

**OPTICAL READOUT METHODS
FOR MEMS CANTILEVER BASED SENSORS**

by

Ulaş Adıyan

**A Thesis Submitted to the
Graduate School of Sciences and Engineering
in Partial Fulfillment of the Requirements for
the Degree of**

Doctor of Philosophy

in

Electrical and Electronics Engineering

Koç University

October 2016

Koç University
Graduate School of Sciences and Engineering

This is to certify that I have examined this copy of a PhD thesis by

Ulaş Adıyan

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Committee Members:

Hakan Ürey, Ph. D. (Advisor)

G. Göksenin Yaralıoğlu, Ph. D.

Hamdi Torun, Ph. D.

Alper Kiraz, Ph. D.

Şükrü Ekin Kocabaş, Ph. D.

Date:

ABSTRACT

Optical readout methods are attractive for micro-electro-mechanical system (MEMS) based sensors as they allow remote readout without electrical connections to the sensor chip and scalable architectures for sensor arrays. Optical readout noise is often the limiting factor in sensor applications. This thesis presents different optical readout methods that can improve the detection sensitivity and decrease the optical readout noise for MEMS sensors specifically for infrared (IR) detection and MEMS oscillator applications.

MEMS based thermo-mechanical IR detection technology with optical readout can play a significant role for wide adaption of thermal detectors due to its low cost. In order to achieve sensitivities near the thermal noise limit, optical readout noise need to be reduced dramatically. For this purpose, firstly we demonstrated sensitivity improvements using a number of single sensor optical readout methods. Secondly, we developed both integrated and free-space based optical readout architectures for sensor arrays.

Interferometric and optical beam deflection methods have been explored for a variety of single MEMS IR detectors. We developed AC-coupled detection methods to reduce the DC noise and increase the sensitivity to detect the thermal or spatial changes in the scene. Detailed noise characterizations of thermo-mechanical MEMS detectors with 35 μm pixels were performed. In addition, a single MEMS pixel with Fabry-Perot cavity type optical readout method was designed and fabricated. Lastly a novel prism-based optical-readout is proposed and demonstrated for a single lever MEMS pixel. The noise equivalent temperature differences (NETD) for different sensor designs were measured below 200 mK, with a best NETD performance of 150 mK. The measured noise levels were comparable to the state-of-the-art thermo-mechanical IR sensors for very small pixels.

In order to improve the performance of the thermo-mechanical MEMS detector arrays, we developed two new approaches: i-) Compact optical Fourier filtering system. A

convergent illumination system was developed, which reduced the size of the system and improved the SNR compared to the conventional 4f optical system. ii-) Two-wavelength based optical readout system. This method provided spatial auto-registration of two different color images on a single RGB camera. The sensitivity and dynamic operation range can be enhanced significantly by using two wavelengths for a non-uniform array.

Integration of MEMS devices with CMOS electronics enables large array operation in a small low-cost package. MEMS-based sensor array with a large number of elements (64x64) is bonded at chip level with CMOS readout IC for the first time. A diffraction grating interferometer-based optical readout is realized by pixel-level illumination of the MEMS chip through the through-silicon via holes and by capturing the reflected light using a photodetector array on the CMOS chip.

Lastly, two non-linear optical readout methods were developed for biological and chemical sensor arrays using dynamic MEMS cantilevers. A single controller is desired to monitor the entire array for tightly packed high density sensor arrays. A separate saturation mechanism and nonlinearity is required for each oscillating cantilever sensor. We used optical non-linearities to drive and sense multiple oscillators with a single controller. In the first method, MEMS cantilevers with embedded diffraction gratings were used in order to parallelize the array for multiple oscillations. In the second method, a prism-based optical readout method was proposed for simple cantilevers. Both methods were successfully implemented to actuate and monitor two nearly identical cantilevers with one actuation coil and photodetector.

Keywords: AC-coupled optical readout, MEMS cantilever sensor arrays, thermo-mechanical IR detectors, bimaterial cantilevers, diffraction grating, prism-based method, non-linear optical readout, closed-loop dynamic operation.

ÖZET

Optik okuma yöntemleri mikro-elektro-mekanik-sistem (MEMS) tabanlı algılayıcılara uzaktan okuma yöntemi olanağı tanıdığı için önemli ölçüde ilgi görmektedirler. Uzaktan okuma elektriksel bağlantı gerektirmez ve algılayıcı dizinleri için kolaylıkla ölçeklenebilir yapılara olanak tanır. Diğer yandan, optik okuma gürültüsü genellikle algılayıcı uygulamaları için hassasiyeti etkiler. Bu tez kapsamında, MEMS kızılötesi algılayıcılarda ve MEMS osilatörlerde algılama hassasiyetini iyileştirecek ve optik okuma gürültüsünü azaltacak yaklaşımlar sunulmaktadır.

MEMS tabanlı, optik okumalı termo-mekanik kızılötesi algılayıcılar düşük maliyetlerinden ötürü ısı dedektörlerin yaygınlaşabilmesinde önemli bir rol oynayabilirler. Isıl gürültü limitlerinde hassasiyet elde edilebilmesi için, optik okuma gürültüsü önemli oranda azaltılmalıdır. Bu amaçla, ilk olarak tekil bir algılayıcı için algılama hassasiyetini iyileştiren optik okuma yöntemleri sunulmuştur. İkinci olarak algılayıcı dizinleri için tümleşik ve tümleşik olmayan düzenekler geliştirilmiştir.

Tekil MEMS kızılötesi algılayıcılar için girişimsel ve hüzme saptırmalı optik okuma yöntemleri incelenmiştir. DC gürültüyü azaltıp, ısı ve uzamsal değişiklikleri algılama hassasiyetini arttıracak AC bağlaştırmalı okuma yöntemleri geliştirilmiş ve 35 μm boyutundaki MEMS algılayıcılar için detaylı bir gürültü analizleri yapılmıştır. Ayrıca, Fabry-Perot boşluğuna sahip bir MEMS algılayıcı için tasarım ve üretimler gerçekleştirilmiştir. Son olarak, prizma tabanlı bir optik okuma sistemi önerilerek MEMS algılayıcılar için uygulanmıştır. Çeşitli algılayıcı modelleri için gürültü eşlenikli sıcaklık farkı (NETD) 200 mK altında ölçülmüş, en iyi performans 150 mK olarak belirlenmiştir.

Termo-mekanik prensiple çalışan algılayıcı dizinlerinin performanslarını iyileştirmek için iki ayrı yöntem geliştirilmiştir: i-) Fourier filtreleme temelli kompakt düzenek. Bu düzenekte, yakınsak aydınlatma kullanılarak düzenek küçültülmüş ve sistemin SNR oranı

4f optik sisteme kıyasla iyileştirilmiştir. ii-) 2-dalgaboylu optik okuma düzeneği. 2-dalgaboylu okuma düzeneğinde ise iki ayrı dalgaboyundaki ışık tek bir RGB kameranın iki ayrı kanalında eş zamanlı olarak aynı MEMS algılayıcıyı oluşturur. Bu düzenek bir biçimli olmayan algılayıcı dizinlerinde hassasiyetin ve dinamik aralığın artırılmasını sağlamıştır.

MEMS örneklerin CMOS elektroniğiyle tümleştirilmesi büyük dizin yapılarının ucuz ve küçük bir paket içerisinde operasyonunu mümkün kılar. Bu tez kapsamında, çok sayıda elemana sahip (64x64) MEMS tabanlı bir algılayıcı dizini, ilk defa çip seviyesinde bir CMOS okuma devresiyle birleştirilmiştir. Dizindeki her eleman, CMOS devresi silikon alt taşına açılmış delikler kullanılarak aydınlatılmıştır. Kırınım ızgaralı yapıların olduğu MEMS algılayıcılarla girişimsel bir optik okuma gerçekleştirilmiş, dedektörlerden yansıyan ışıklar CMOS devresi üzerindeki fotodedektör dizinlerine yönlendirilmiştir.

Son olarak biyolojik veya kimyasal algılayıcılarda kullanılan dinamik MEMS çubuk dizinleri için iki lineer olmayan optik okuma düzeneği geliştirilmiştir. Küçük bir paket halindeki fazla elemanlı MEMS çubuk yapılarını görüntüleyebilmek için tekil bir kontrol yapısının kullanılabilmesi arzu edilen bir durumdur. Bu da her algılayıcı için ayrı satürasyon mekanizmasını gerektirmektedir. Bu noktada, tek bir kontrol yapısıyla dizinleri hareket ettirip görüntüleyebilmek adına lineer olmayan optik okuma düzenekleri kullanılmıştır. İlk yöntemde kırınım ızgaralı çubuklar girişimsel bir okumayı mümkün kılmış ve çoklu salınım için dizinlerin paralel çalışmasını sağlamıştır. İkinci yöntemde ise prizma tabanlı bir optik düzenek basit çubuk yapılar için önerilmiştir. Her iki yöntem de iki eş çubuğun tek bir sürücü ve tek bir dedektör kullanılarak ayrı ayrı salınmalarını sağlamıştır.

Anahtar Kelimeler: AC-bağlaştırıcı optik okuma, MEMS çubuk algılayıcı dizinleri, termo-mekanik kızılötesi dedektör, çift madde çubuklar, kırınım ızgarası, prizma tabanlı okuma, doğrusal olmayan optik okuma, sürdürülebilir salınım.

ACKNOWLEDGMENTS

First and foremost, I would like to express my sincere appreciation to my advisor Prof. Hakan Ürey for his patience, encouragement, support and invaluable guidance throughout my PhD. The joy and enthusiasm he has for his research was a great motivation for me. It was truly a privilege to work with him, and more importantly the experience and knowledge that I learned from him is beyond this thesis work.

I am also thankful to my PhD progress committee members, Prof. Hamdi Torun and Prof. Göksenin Yaralıoğlu. We worked together on MEMS thermo-mechanical detectors with Prof. Hamdi Torun, and I am very grateful for his helps directing this research with numerous advices. In regards to the work related to dynamic mode MEMS cantilevers, I would like to express deep gratitude to Prof. Göksenin Yaralıoğlu for building a very solid background and for his invaluable time, effort and great advices. I would also like to thank the other two members of my oral defense committee, Prof. Ekin Kocabaş and Prof. Alper Kiraz, for their time and support.

A special acknowledgment must also be made to Dr. Fehmi Civitci and Dr. Onur Ferhanoğlu for their endless help and support. They shared their extraordinary knowledge and experience with me, spending a lot of their precious time. They even helped me in the experiments until late nights with enjoyable discussions and great jokes.

I would like to thank all past and present members of OML for providing an enthusiastic research environment and their wonderful friendship. It was a pleasure for me to work with such a great team during my thesis. I would like to thank my previous project partner R. Burak Erarslan for his help and efforts. Selim Ölçer is specially acknowledged for his excellent work in many different parts of the project. I want to thank Dr. Erdem Ulusoy, Kıvanç Hedili, Uğur Aygün, Dr. Emre Heves and Sven Holmström for their help and support during my PhD journey. Last but not least, many thanks go to Deniz Mengü,

Mehdi Kazempour, Yusuf Samet Yarař, Shoaib Soomro, Gölüstan Eren, Dr. Arif Mustafazade, Dr. Kaan Akřit, Serhan Can, Gökhan Saęlam, Vahid Ghouschi, Deniz Ekin Canbay, Ali Bars Gündüz, Nusrah Hussain, Saadeh Mokarian Zanjani, Gamze Yılmaz for their help and friendship.

Very special thank goes to my dear best friend, best man, colleague Dr. Onur Çakmak. We had always great time in the lab, outside or at home by sharing an extremely beautiful friendship, which is certainly one of the most valuable experiences of me. This journey would be incomplete without his wonderful friendship and invaluable support.

The research grants from ASELSAN Inc. and TUBITAK are gratefully acknowledged. I would also like to acknowledge Koç University for the funding I received during my PhD and travel grants for international conferences. I am very thankful to Prof. Tayfun Akın and METU MEMS research group, especially Orhan Akar, for conducting fabrication runs related to this thesis work.

Finally, I would like to thank my excellent parents and wonderful sister with all my love for their love, unlimited support, and everything. I am also very grateful to my second family, TİMİS. I specially thank to all my sisters and brothers, who continuously supported me with their endless love. My last thanks go to the leading role of this story to my wonderful wife, who always supported and encouraged me. Her warm presence put a smile on my face even in very tough situations. It is certain that this thesis would have been impossible without the support of all members of this large family.

I am sorry to anyone I forgot. I owe you a drink.

Table of Contents

LIST OF TABLES	xii
LIST OF FIGURES.....	xiii
NOMENCLATURE	xxiv
1 Introduction	1
1.1 MEMS based Cantilever Sensors	2
1.2 MEMS Sensor Readout Methods	3
1.2.1 Capacitive / Piezoresistive Readout.....	4
1.2.2 Optical Readout.....	7
1.3 Contributions of the Thesis.....	26
2 Design and Fabrication of MEMS based Cantilever Sensors	33
2.1 Thermo-mechanical IR Sensors	33
2.1.1 General Overview	34
2.1.2 Working Principle	40
2.1.3 Design Parameters.....	41
2.1.4 Noise sources	45
2.1.5 Finite Element Analysis	51
2.1.6 Fabricated MEMS Devices.....	58
2.2 Dynamic Mode MEMS Cantilevers	60
2.2.1 General Overview.....	60
2.2.2 Working Principle	62
2.2.3 Fabricated MEMS Devices.....	63
3 MEMS Single Pixel Optical Readout for Thermo-mechanical IR	
Sensors 65	
3.1 Sensor Operation.....	65

3.2	AC-coupled Optical Readout Operation	68
3.3	Diffraction Grating Based Readout	69
3.3.1	Working Principle	70
3.3.2	Experimental Results	72
3.4	Fabry-Perot Interferometric Readout	76
3.5	Performance Improvement using electronic approach	80
3.6	Lever Based Readout	82
3.6.1	Knife-edge optical readout setup	82
3.6.2	Prism-based optical readout setup	84
3.6.3	Simulation Results	86
3.6.4	Single Pixel Characterization	89
3.7	Conclusion	92
4	MEMS Array Readout for Thermo-mechanical IR Sensors.....	95
4.1	4f Optical System	95
4.2	Converging Beam Optical System	97
4.3	4f Optical System using Knife-Edge filtering	101
4.4	Two-Wavelength Readout using LED and Multi-mode fiber	103
4.5	Experimental Results	107
4.6	Conclusions	112
5	Integrated Optical Readout for MEMS-based Sensor Arrays.....	114
5.1	CMOS-based Optical Readout Method	115
5.2	Optical Simulations	119
5.3	MEMS and CMOS Integration	121
5.4	Experimental Results	124
5.5	Conclusion	126
6	Optical Readout for Dynamic Mode MEMS Cantilever Sensor	
Arrays	128	

6.1	Self-sustained oscillations (SSOs) of MEMS cantilever arrays	129
6.1.1	Sensor Array Oscillator Operation	130
6.1.2	Theory of the Two- Cantilever SSO	131
6.1.3	Cross-Coupling Effect.....	137
6.2	Non-linear optical readout with integrated diffraction gratings.....	139
6.2.1	Simulation Results	142
6.2.2	Experimental Results.....	144
6.3	Prism-based non-linear optical readout for MEMS cantilever arrays.....	148
6.3.1	Open-Loop Operation	149
6.3.2	Closed-Loop Operation	155
6.3.3	Experimental Results.....	162
6.4	Conclusion	165
7	Conclusion and Future Work.....	168
	BIBLIOGRAPHY	171

LIST OF TABLES

Table 1-1: Quick overview for the mentioned readout methods.....	15
Table 1-2: Overview for the optical readout methods for MEMS based bimaterial cantilever arrays.	22
Table 2-1: Thermal and mechanical properties of the selected MEMS materials.	44
Table 2-2: The comparison of theoretical performances for each design	57
Table 3-1: Experimentally Determined NETD Values	74
Table 3-2: NETD values for different diffraction orders and the subtracted signal	82
Table 3-3: NETD Values For Different Optical Readout Methods	92
Table 4-1: Converging Beam Optical System Parameters.....	98
Table 4-2: LED Color Selection According to the Coherence Length	105
Table 6-1: Resonance and corresponding oscillation frequencies of the two-cantilever SSO system for changing dominant saturation mechanisms	143
Table 6-2: Resonances and corresponding oscillation frequencies of the two-cantilever SSO where individual resonances are very close.....	146
Table 6-3: Resonances and corresponding oscillation frequencies of the double cantilever SSO where individual resonances are further away.....	148
Table 6-4: Resonances and corresponding oscillation frequencies of the two cantilever SSO where individual resonant frequencies are very close (1 st case) and further away (2 nd case).....	165

LIST OF FIGURES

Figure 1-1: (a) Single clamped beam, cantilever [16] (b) Double clamped beam, bridge [17] (c) Bimaterial cantilever (developed in our group at Koç University).....	2
Figure 1-2: (a) Single MEMS cantilever structure with capacitive readout (b) MEMS cantilever array (3 cantilevers) showing the gold coated area, drive lines and readout pads [33].	4
Figure 1-3: (a) Cross section of a MEMS bimaterial cantilever with capacitive readout (b) SEM image of a part of an MEMS bimaterial cantilever array [35].	5
Figure 1-4: Schematic drawing and microscope image of AFM probe with integrated piezoresistive read-out [38].	6
Figure 1-5: Different parts of optical readout systems for MEMS based cantilevers.	7
Figure 1-6: Embedded diffraction gratings for different MEMS cantilever modalities (a) Dynamic mode MEMS cantilever [41] (b) AFM probe [42] (c) Microphone structure [43] (d) Spiral shaped bimaterial cantilever [44] (e) Bimaterial cantilever with interdigitated fingers [45] (f) Gratings underneath the pixel. (a) and (f) were developed in our group at Koç University.	8
Figure 1-7: MEMS cantilever modalities for optical lever detection (a) AFM probe [46] (b) Dynamic mode MEMS cantilever (developed in our group at Koç University) [41] (c) Bimaterial cantilever with a bottom reflector [47] (d) Bimaterial cantilever with a top reflector [48].	9
Figure 1-8: Integrated readout approaches (a) MEMS accelerometer [49] (b) MEMS bimaterial cantilevers (developed in our group at Koç University and discussed in details in Ch. 5) [50]	10
Figure 1-9: Typical AFM readout method [52].	11

Figure 1-10: The position sensitive detection of AFM using bi-cell and quad detectors [51].	11
Figure 1-11: (a) Schematic of the AFM with optical beam deflection detection method [53] (b) Schematic of an AFM with interferometric readout [54].	12
Figure 1-12: (a) Optical setup for the characterization of membrane-based AFM probes with diffraction gratings (b) The sinusoidal photodiode output with the membrane displacement [55].	13
Figure 1-13: (a) Interdigital cantilever as an AFM probe [56] (b) Fiber-top cantilever with interferometric readout [57] (c) Diagram of the experimental setup for the quad-cell readout [48] (d) Schematic of grating readout for bimaterial cantilevers [58].	14
Figure 1-14: Optical readout setup for the lever based bimaterial cantilever array [59].	16
Figure 1-15: (a) Knife-edge optical readout setup for the lever based bimaterial cantilever array, PH: pin hole; E: extender lens; BS: beam splitter; K: filter; (b) Operation for knife-edge filter, K [60].	18
Figure 1-16: Optical readout setup for a grating (interdigitated fingers) based bimaterial cantilever array [62].	20
Figure 1-17: A two-wavelength (2λ) optical readout setup for diffraction grating based MEMS FPA [64].	21
Figure 1-18: (a) 3D sketch of a parallel measurement setup using a fiber array coupled to PDs for the optical readout. The illuminated MEMS cantilever are shown [67]. (b) Optical beam deflection setup: Using sequentially switched VCSEL array and a PSD for the readout of the cantilever array [68]. (c) The interferometric readout for a cantilever array providing parallel measurement in static mode [69]. (d) An integrated readout scheme for a 2x2 acoustic sensor array [70]. (e) SSO of MEMS cantilevers with diffraction grating readout [71].	24

Figure 1-19: All the systems illustrated above were implemented during this thesis. Important features of each system and contributions are summarized in the boxes.	26
Figure 2-1 (a) SEM of a small part of an FPA showing the structure of each MEMS pixel and the tiling (b) IR images of an electric cooking stove placed at 3m away with different temperatures [45].....	35
Figure 2-2: (a) SEM image of 256x256 FPA (b) The thermal image obtained from the FPA in (a) [72].	36
Figure 2-3: (a) MEMS bimaterial cantilever with a substrate-free FPA. (b) Thermal images using the substrate free FPA [87].	37
Figure 2-4: Schematic of the IR imaging system developed at Koç University [58]	38
Figure 2-5: Fabricated SiNx/Al sensor arrays (a) microscope image of 4x4 array (b) Successfully fabricated sensor [61].....	39
Figure 2-6: IR imaging experiments: (a) IR image of a human hand in front of IR heater captured with SiNx/Al. The dark regions correspond to 700 K temperature where the light regions (regions covered with the hand) correspond to 300K temperature (b) frames of a captured IR video of a moving IR target, entering from left of the screen and moving towards right [61].....	39
Figure 2-7: An example of MEMS based Thermo-mechanical IR single pixel geometry (Top View).	40
Figure 2-8: Design #1: (a) Thermal Gradient of the MEMS pixel when 1 °C is applied to the absorber (Anchors are 0 °C) (b) Mechanical deflection analysis for 1 °C change in the pixel using FEM.	52
Figure 2-9: Design #2: (a) Thermal Gradient of the single sensor element due 1 °C input on the absorber where anchors are fixed at 0 °C. (b) Mechanical deflection analysis for the thermal gradient in (a). (c) Comparison of the tilt angles w.r.t. temperature using the experimental data and the FEM results.	53

Figure 2-10: The geometry of the AC-coupled Design #3.....	55
Figure 2-11: Design # 3: (a) Mechanical deflection analysis for 1 °C change in the pixel for larger pixel (b) Mechanical deflection analysis for 1 °C change in the pixel for smaller pixel.	55
Figure 2-12: 1 W/ m ² heat flux was applied to the absorbers of Design # 3: (a) Transient displacement for Det-1 (b) Transient displacement for Det-2.	56
Figure 2-13: Design #4: (a) Thermal Gradient of the MEMS pixel when 1 °C is applied to the absorber (Anchors are 0 °C) (b) Mechanical deflection analysis for 1 °C change in the pixel using FEM.	57
Figure 2-14: Fabrication steps for thermo-mechanical MEMS detector: (1) Patterning of gold grating (2) Polyimide spinning and definition of anchors (3) SiNx and Al deposition (4) Al patterning (5) TiN deposition (6) TiN and SiNx patterning (7) Release .	58
Figure 2-15: SEM images of the 4 different designs. Design #1 and #2 were fabricated as arrays. Design #3 and #4 were fabricated as single test structures.	59
Figure 2-16: Dynamic mode operation of a cantilever sensors [97].	60
Figure 2-17: Schematic of the working principle of the MEMS cantilever with EM actuation and optical readout.	62
Figure 2-18: The fabrication flow of MEMS cantilevers with diffraction gratings.....	63
Figure 2-19: (a) Optical microscope images of the nickel cantilevers. The thickness is 2 μm. Top picture shows a portion of a cantilever array. Bottom picture is the zoomed view of one of the cantilevers. (b) Optical microscope image of fabricated array of cantilevers without diffraction gratings.	64
Figure 3-1: a) Side-view of an IR pixel illustrating grating readout b) Side-view of an IR pixel illustrating lever readout	66

Figure 3-2: Intensity of light going to diffraction orders as a function of the distance from the membranes to the diffraction gratings (Assuming an initial gap (g_0), $\pm\lambda/8$ movements to achieve maximum and minimum target temperatures)	67
Figure 3-3: AC signals (A, B, and C) modulated at a certain frequency with different DC levels depending on the top reflector position.....	68
Figure 3-4: Experimental setup of single pixel optical readout: (a) IR Optics Part (b) Visible Light Optics Part.....	71
Figure 3-5: a) 10 Hz AC signal for 50 °C temperature difference b) Noise levels of the optical readout system with the contribution of the PD, Laser and MEMS device.	73
Figure 3-6: (a) Visible image of the target (b) Thermal image of the target.....	75
Figure 3-7: (a) Side-view of an IR pixel illustrating the Fabry-Perot readout (b) The reflectance of the Fabry-Perot cavity Intensity of light going to diffraction orders as a function of the distance from the top mirror to the bottom half reflector.	77
Figure 3-8: (a) AC coupled photodetector signal obtained using a chopper blade (at 30°C) rotating at 4 Hz placed in front of an IR target (at 50°C) for the Fabry-Perot optical readout system (b) Noise levels of the Fabry-Perot optical readout system.	78
Figure 3-9: (a) Single MEMS pixel on the CCD image with the zoomed in version showing the beam reflected light profile. (b) Signal obtained from the single pixel from a temperature difference of $\Delta T = 20$ °C for OFF-ON-OFF states with 29x29 CCD pixels. (c) Signal obtained from the single pixel from a temperature difference of $\Delta T = 20$ °C for OFF-ON-OFF states with 5x5 CCD pixels.(d) Signal obtained from the single pixel from a temperature difference of $\Delta T = 20$ °C for OFF-ON-OFF states with 3x3 CCD pixels.	79
Figure 3-10: DC reduction using electronic approach	80
Figure 3-11: The response of the IR target (50 °C) modulated at 10 Hz for the 0 th and - 1 st diffraction orders with the difference signal.	81

Figure 3-12: Experimental setup for the characterization of single sensor element using Knife-edge method, KEM. The CCD was used to check the alignment of laser with the selected sensor for single MEMS pixel operation.....	83
Figure 3-13: Experimental setup for the characterization of single sensor element using Critical Angle Method, CAM. The CCD was used to check the alignment of laser with the selected sensor for single MEMS pixel operation.....	85
Figure 3-14: Beam propagation simulation results (Sample intervals in space domain are $dx=dy=2\text{ }\mu\text{m}$.) showing the cross-sections ($y=0$) of the beams according to the two different target temperatures (25°C and 525°C) for (a) Knife-edge method, KEM (b) Critical angle method, CAM. (c) Reflectivity of a glass ($n=1.51$) – air interface ($n=1$) for TM polarization. (d) Reflection matrix at the prism (glass-air) interface. (e) Comparison of normalized power changes for both approaches at PD w.r.t. different target temperatures. (f) Results for the normalized power changes at PD w.r.t. different target temperatures using CAM for different illumination angles.	87
Figure 3-15: (a) Single MEMS pixel on CCD image (b) Zoomed in single pixel image area, which will be used for the IR detection characterization (c) Signal obtained from the single pixel in front of an IR target (at 75°C) for OFF-ON-OFF states.....	90
Figure 3-16: (a) AC coupled photodetector signal obtained using a chopper blade (at 25°C) rotating at 10 Hz placed in front of an IR target (at 50°C) for knife-edge method (KEM) and Critical angle method (CAM). (b) Noise levels of the optical readout system for both methods.	91
Figure 4-1: 4f Optical System: (a) Schematic (b) Experimental setup.....	96
Figure 4-2: Converging Beam Optical System: a. Schematic b. Experimental setup....	97
Figure 4-3: Beam width analyses for the converging optical setup at the Fourier Plane	99

Figure 4-4: a. Ray tracing of Converging Beam Optical System with a rectangular aperture on grating structure using Zemax Optical Software b. Detector Image.....	100
Figure 4-5: More compact form of the converging beam optical setup.....	101
Figure 4-6: 4f Optical Setup using knife-edge filter	102
Figure 4-7: (a) Side-view of an IR pixel illustrating grating 2λ readout (b) Intensity of light going to diffraction orders as a function of the gap (g).	103
Figure 4-8: (a) Spectrum of different color LED light sources (b) The quantum efficiency (QE) of the R and G channel of the RGB camera and the spectrums of yellow and red LED light sources.	104
Figure 4-9: Block diagram of the post-processing algorithm for two wavelength setup.	106
Figure 4-10: Two-wavelength optical readout system: (a) Schematic (b) Experimental setup.	107
Figure 4-11: (a) A small part of the MEMS FPA (160x120) imaged on the CCD (b) Image of 3x3 IR Pixels.....	108
Figure 4-12. Direct heating experiment (15 °C heating) results for the marked pixel as a red square: a. using the conventional 4f system b. using converging beam optical system	109
Figure 4-13 A soldering iron was moved from left to right. Background subtraction was applied to both images.	110
Figure 4-14: (a) Image captured from a CCD output of a circular IR target at 1000 °C (b) Image captured from a CCD output of a black TEC at 80 °C. Background subtraction was applied to both images.	111
Figure 4-15. (a) Image of the 64x64 array (b) Response of Pixel #1 to $\Delta T=5$ °C (c) Response of Pixel #2 to $\Delta T=5$ °C	112
Figure 5-1: (a) Schematic of the integrated device. (b) Side view of one sensor.	114

Figure 5-2: (a) SEM pictures of $35\mu\text{m} \times 35\mu\text{m}$ MEMS sensors. (b) Microscope image of a larger array.	116
Figure 5-3: CMOS ROIC, Photodetector and hole configuration.....	117
Figure 5-4: (a) SEM image of backside of CMOS. (b) Microscope image showing the light transmission through via holes. (c) Microscope image of post-processed CMOS chip with via holes. (d) SEM image of a single hole from backside of CMOS.....	118
Figure 5-5: CMOS characterization data.	119
Figure 5-6: (a) The propagated beam at the grating plane. (b) The diffraction orders at the photo-detector (PD) plane for $2\mu\text{m}$ gap. (c) The cross section of the beam at the PD plane for three different gap values.....	121
Figure 5-7: The grinded and non-grinded dies.....	122
Figure 5-8: Decreasing surface roughness using refractive index matched epoxy.....	123
Figure 5-9: Photograph of the alignment setup.....	123
Figure 5-10: Experimental setup to test the integrated system	124
Figure 5-11: Experimental characterization of the integrated system.....	125
Figure 5-12: (a) Integrated sensor array platform in the vacuum chamber (b) The response of the integrated sensor array to a modulated IR source.	126
Figure 6-1: The system block diagram of a sensor array operating in self-sustained oscillation mode.	131
Figure 6-2: Two cantilevers SSO block diagram with separate saturation blocks belonging to the each branch.....	132
Figure 6-3: The location of the roots of two cantilever SSO system when gain is swept from zero to 1×10^{-5} . S1 has the following properties $f_1=100$ kHz, $f_2=103$ kHz. Red stars indicate the SSO frequencies of S1. S2 has the following properties $f_1=100$ kHz, $f_2=100.5$ kHz. The Q and the spring constants of the cantilevers in both systems are 100 and 1 N/m, respectively.	134

Figure 6-4: The analytical solution of the equation of motion (22) of the two-cantilever SSO system. The cantilevers have two different resonant frequencies (ω_1, ω_2). Both axes are scaled by the frequency of Low Resonant Cantilever (ω_1). ω_1 is assumed fixed and the High Resonant Frequency is varied (ω_2). Vertical axis shows the solutions of (22) for the two-cantilever SSO system (ω_{SSO}). Spring constants (=1 N/m) and the Q-factors (Q=100) of cantilevers are assumed equal. Red stars show the SSO frequencies of S1 illustrated in Figure 6-3. 135

Figure 6-5: Cross-coupling between the SSO frequencies of two cantilevers oscillating in an SSO system. This figure shows the change in the oscillation frequency of the cantilever with low SSO frequency due to a change for the cantilever with high resonant frequency. 138

Figure 6-6: a-) Cross-section of a cantilever with an integrated diffraction grating. 0th and $\pm 1^{\text{st}}$ diffraction orders are shown. A photodiode (PD) is used to monitor the +1st diffraction order. b-) The system overview of the nonlinear optical readout of the two-cantilever SSO system. Neutral density (ND) filter to attenuate and equalize outputs of channels; Spatial filter: two square openings to select the desired cantilevers. Inset shows top view of a cantilever array overlaid with laser illumination area. 140

Figure 6-7: Interferometric response curve according to the calculated and the experimental data. Experimental data is obtained by moving a super strong magnet from the closest point to the cantilevers to a farther location. g_0 shows the nominal gap between the cantilever and the substrate. Gaps those are different from the nominal value results in reduced sensitivity. 142

Figure 6-8: Nickel cantilevers were used in the experiments. The thickness is 2 μm . Top picture shows a portion of a cantilever array. Bottom picture is the zoomed view of one of the cantilevers. 144

Figure 6-9: Frequency response of two cantilevers that have very similar resonant frequencies. Oscillation frequencies (f_1, f_2, f_3) from Table 6-2 are also added to the figure.	146
Figure 6-10: Spectra of SSO system when individual cantilevers and both cantilevers are oscillated. The individual oscillations were obtained by selectively blocking the light diffracted from the cantilevers.	147
Figure 6-11: Frequency response of two cantilevers that have resonances further away from each other. Oscillation frequencies (f_1, f_2, f_3, f_4) from Table 6-3 are also added to the figure.	148
Figure 6-12: (a) The system overview of prism-based optical readout system for open-loop cantilever operation (b) Reflectivity of a glass ($n=1.5168$) – air interface ($n=1$) for TM polarization [136].	150
Figure 6-13: Simulations for prism-based optical readout system: (a) Initial Beam Profile ($\theta_{inc} = 41.1^\circ$) at the prism's glass-air interface with respect to incident angle. (b) Normalized intensity (I) with respect to incident angle for different NAs. (c) Optical intensity change (dI) with respect to incident angle change ($d\theta$) for different NAs. The responsivity values of the conventional optical beam deflection (OBD) readout for two different NAs are also provided.	152
Figure 6-14: Open loop operation of a single cantilever using prism-based optical readout system (a) Input: Cantilever excitation at 30 kHz with a peak cantilever displacement of 1 μm . (b) Optical intensity curve with the cantilever displacement range for different incident angles. (c) Time domain output for the given input. (d) Frequency domain output for the given input.	154
Figure 6-15: (a) Optical microscope image of fabricated array of cantilevers (b) The system overview of prism-based optical readout system for closed-loop cantilever operation.	156

Figure 6-16: Closed-loop operation analysis using a single cantilever for different incidence angles: (a) Block diagram of the single cantilever SSO system that is used in Simulink Model. Simulation results: (b) Gain of the optical readout system for the SSO operation with respect to different incident angles (The gain was selected to be 20% larger than the critical gain value). (c) Peak displacements for the SSO operation with respect to different incident angles. (d) Total harmonic distortion (%) with respect to different incident angles.....158

Figure 6-17: (a) Block diagram of the system that is used in Simulink Model. Simulation results: (b) Frequency response of two cantilevers that have closer resonant frequencies (Only one oscillation frequency observed.) (c) Frequency response of two cantilevers that have resonances separated by more than 3dB bandwidth (d) Effect of phase and incident angle on the oscillation frequency. Phase shift in the electronics shift both resonances simultaneously while different incident angles shift each resonance separately. 160

Figure 6-18: Experimental results for two cantilevers that have closer resonant frequencies: (a) Closed-loop SSO operation (b) Open-loop frequency sweeps. Experimental results for two cantilevers that have resonances further away: (c) Closed-loop SSO operation (d) Open-loop frequency sweeps.....163

NOMENCLATURE

AC	Alternating Current
AFM	Atomic Force Microscopy
CAM	Critical Angle Method
CBOS	Converging Beam Optical System
CCD	Charge Coupled Device
CMOS	Complementary Metal-Oxide-Semiconductor
CTE	Coefficient of Thermal Expansion
DC	Direct Current
FEM	Finite Element Methods
FOV	Field of View
FPA	Focal Plane Array
IC	Integrated Circuit
IR	Infrared
KEM	Knife-Edge Method
LED	Light Emitting Diode
LUT	Look-Up-Table
LWIR	Long wave Infrared
MEMS	Micro-electro-mechanical Systems
MWIR	Mid wave Infrared
NEP	Noise Equivalent Power
NETD	Noise Equivalent Temperature Difference

NIR	Near Infrared
OBD	Optical Beam Deflection
OPD	Optical Path Difference
PCB	Printed Circuit Board
PD	Photodetector
PSD	Position Sensitive Detector
RIE	Reactive Ion Etching
RMS	Root Mean Square
ROIC	Read-out Integrated Circuit
SBR	Signal to Bias Ratio
SEM	Scanning Electron Microscope
SNR	Signal to Noise Ratio
TE	Transverse Electric
TEC	Thermo-Electric Cooler
TM	Transverse Magnetic
VCSEL	Vertical-Cavity Surface-Emitting Laser

1 Introduction

The invention of piezoresistivity at Bell Labs [1] in 1954 inspired the researchers to develop silicon based sensors [2]. After that silicon technology has been gradually employed due to its superior mechanical and electrical properties [3], which gave rise to the foundation of the micro-electro-mechanical systems (MEMS) technology [2]. MEMS technology can be defined as miniaturized mechanical and electro-mechanical structures, which are produced using lithography-based microfabrication, mostly borrowed from the standard IC processing technologies [4]. MEMS or microsystems, literally, are very small systems with micron sizes up to a few mm [4] and therefore has the advantage of being low-weight, mass producible, low cost and having high performance [5]. Since it has mechanical and electrical parts, the functionality of the MEMS devices can involve many different disciplines such as sensing [6], actuation [7], control [8], signal processing [9], telecommunications [10], data storage [11] and displays [12].

While MEMS have wide application areas, this thesis work is mostly interested in sensor applications. The working principles of the MEMS sensors are based on measuring the physical property changes of the sensor according to the specific input. MEMS sensors attracted the researchers due to its sensitivity, precision and reliability with the developments in the microfabrication technologies [13]. Various MEMS structures with different mechanical, electrical and optical technologies can be used for sensing applications. Among these sensor technologies, MEMS cantilevers have become one of the most important sensor technology after the invention of the atomic force microscopy (AFM) [14]. The advances in low cost and mass producible MEMS cantilever technology revolutionize the development of the physical, biological and chemical sensors [13].

1.1 MEMS based Cantilever Sensors

MEMS cantilevers offer a measurement platform for physical, chemical or biological inputs. They can have different geometries such as single clamped beams (cantilevers), double clamped beams (bridges), or other suspended structures (bimaterial cantilevers) depending on the desired application (Figure 1-1) [15].

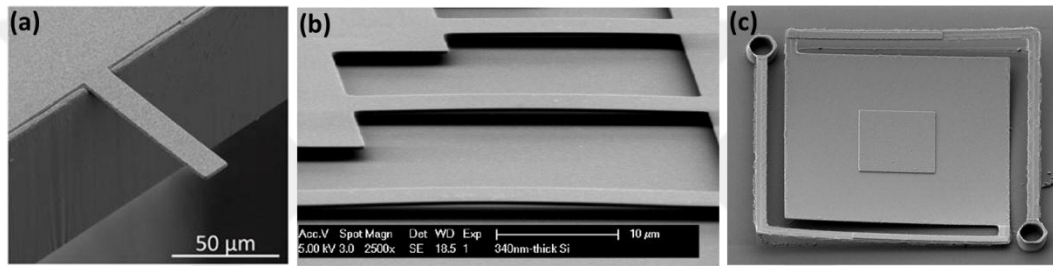


Figure 1-1: (a) Single clamped beam, cantilever [16] (b) Double clamped beam, bridge [17] (c) Bimaterial cantilever (developed in our group at Koç University).

MEMS cantilevers have enabled the detection of the chemical vapors previously using specific coatings on the cantilever [15]. Dynamic mode cantilevers were used as chemical sensors by tracking the resonant frequencies of the cantilevers to detect humidity, hazardous materials, and explosive chemicals [18-20]. In dynamic mode cantilever operations, resonant frequency, quality factor, deflection amplitude or phase can be monitored [13]. Similarly biological sensing applications can be implemented to the MEMS cantilevers. Since MEMS cantilevers can operate in liquid environment, they are excellent biosensors. Typically, these sensors track the shifts in the resonant frequencies according to the added biological mass to the cantilever [21-23].

MEMS cantilevers can also operate as high sensitive physical MEMS sensors [13, 15]. The physical parameters of a sample such as viscosity, density, pressure, temperature can be detected using MEMS cantilevers [13]. Cakmak et al. presented a MEMS viscosity sensor [24] and density sensor [25] using dynamic mode MEMS cantilevers by tracking

the resonant frequencies of the cantilevers using phase-locked loop (PLL) systems. Other than dynamic mode MEMS cantilevers, suspended diaphragms were generally used as pressure sensors, which operates in static mode [6]. Additionally, MEMS cantilevers can also be used as temperature or thermal sensors, which detect IR radiation using the thermo-mechanical principle [26]. IR radiation induces a temperature change on the bimaterial cantilevers, which has a movable, suspended membrane. The movement of the membrane can be detected with different readout methods. This type of physical sensors also works in static mode [27].

In this thesis work, static mode suspended bimaterial cantilevers are studied for IR detection and dynamic mode single clamped cantilevers are examined for closed-loop dynamic operation of biological and chemical sensors.

1.2 MEMS Sensor Readout Methods

As earlier mentioned, the real-time measurements of cantilever sensors are actually based on the measurement of cantilever deflection with sub-nanometer resolution [15]. The measurement of these small displacements can be conducted either in static (e.g., bimaterial cantilevers) or in dynamic mode (e.g., single clamped cantilevers) [13]. The readout system is crucial to sense the changes with high accuracy by measuring the cantilever deflection. There are mainly two different readout systems for MEMS cantilevers: electrical and optical readout systems [28]. Capacitive [29] and piezoresistive readout [30] methods are typical electrical readout methods, which are used to measure the deflections of cantilevers [15]. On the other side, optical readout methods can mainly be classified as interferometric [31] or optical beam deflection methods [32]. It is noteworthy to mention that all these readout systems can also be implemented to cantilever arrays [15]. In the upcoming subsections, these readout methods will be explained in details.

1.2.1 Capacitive / Piezoresistive Readout

Capacitive readout stands on the capacitance change between two plates that is placed on the fixed substrate and the moving cantilever. When the cantilever deflects due to the applied input, the gap between the plates change, so does the capacitance [33]. Figure 1-2 shows a MEMS cantilever based chemical sensor with a single element and in a small array form with 3 cantilevers. The cantilever legs, the bond pads and drive lines were coated with gold to perform the capacitive readout. A capacitive readout circuit with low-noise amplifiers was employed to measure the deflection of the cantilever by means of measuring the capacitance change. The displacement resolution of the MEMS cantilevers with capacitive readout was reported around 100 pm in Ref. [34].

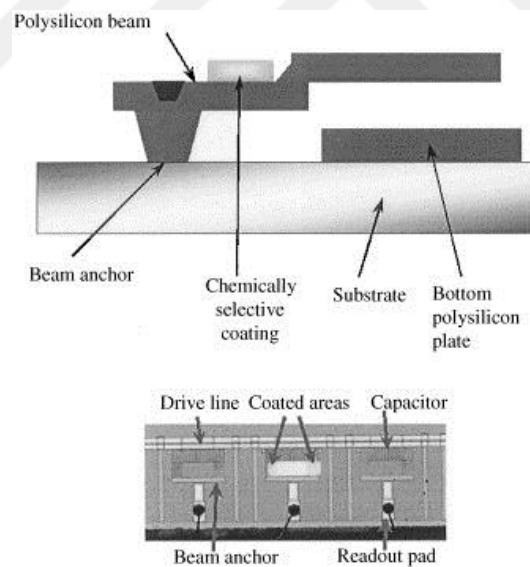


Figure 1-2: (a) Single MEMS cantilever structure with capacitive readout (b) MEMS cantilever array (3 cantilevers) showing the gold coated area, drive lines and readout pads [33].

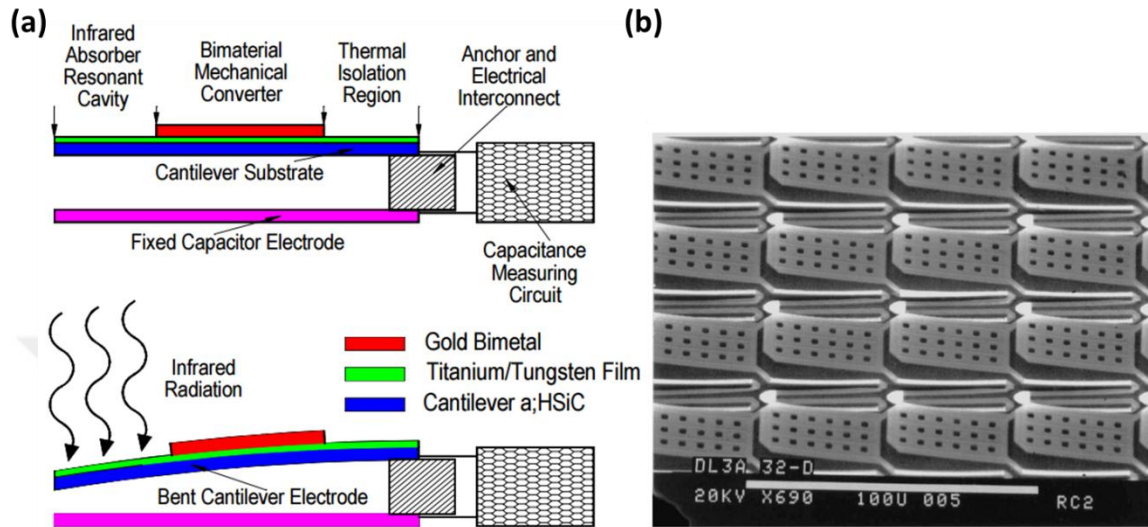


Figure 1-3: (a) Cross section of a MEMS bimaterial cantilever with capacitive readout (b) SEM image of a part of a MEMS bimaterial cantilever array [35].

The capacitive readout was also utilized for MEMS bimaterial cantilevers by Sarnoff Corporation [36]. Figure 1-3 shows the MEMS bimaterial cantilever structure with capacitive readout showing all functional layers of the structure with the SEM image of an array [35]. They claimed a very high sensitive IR sensor showcasing a theoretical NETD performance of 5 mK. Although this IR sensor technology offers 5mK theoretical NETD performance, the measured NETDs of the best pixels were around 2 K due to the noise limitations of their readout circuit [35].

Capacitive methods may have sensitivity advantage and they can be implemented to nano-scale devices. However, the variations in the dielectric medium of the MEMS cantilevers can be a dominant noise source for the capacitive readout [15]. In addition, the fabrication of these devices are complicated because of the need of pre-amplifiers and CMOS integration [37].

Piezoresistive readout methods are important alternatives for the electrical readout methods. MEMS cantilevers, which are coated with piezoresistive materials, change their electrical resistivity as a result of mechanical deformation [38].

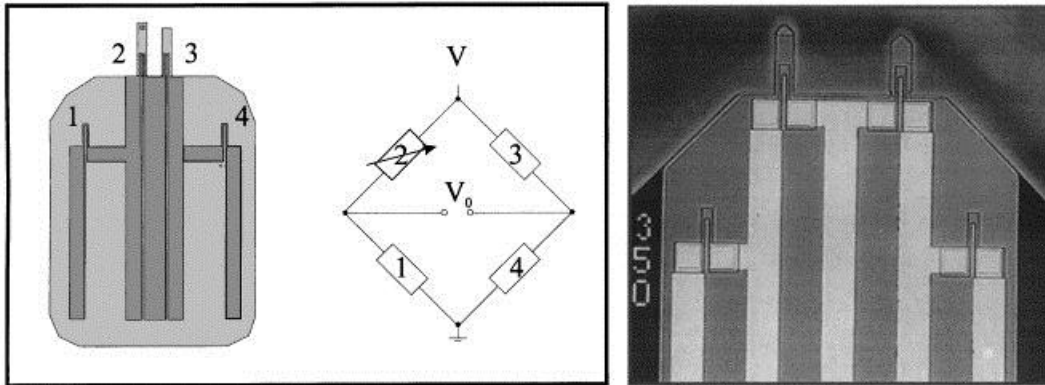


Figure 1-4: Schematic drawing and microscope image of AFM probe with integrated piezoresistive read-out [38].

Figure 1-4 displays an AFM probe with MEMS based cantilevers, which is suitable for piezoresistive readout. Two resistors that are fixed on the substrate with the two resistors on the cantilevers form a Wheatstone bridge to enable the detection changes in the resistivity. The two resistors on the cantilevers are utilized for a differential readout. The cantilever displacement resolution was determined as 30 pm for a measurement bandwidth of 10 Hz [38].

Piezoresistive MEMS cantilevers were also used as uncooled IR detectors [39]. Datskos et al. also demonstrated an IR detection scheme using MEMS bimaterial cantilevers with piezoresistive readout [40].

Although the piezoresistive MEMS cantilevers allow sensitive detection and array implementation in many different mediums, they suffer from heat dissipation and thermal drifts related to the current flow through the cantilever [15]. Furthermore, the deposition of

piezoresistive layer degrades the mechanical performance [37]. Eventually, all electrical readout methods require electrical connection to the MEMS device, which causes additional noise due to self-heating and complicates the fabrication. In contrast, optical readout methods enable high sensitive and remote detection for the cantilevers with simple design considerations and easier fabrication processes.

1.2.2 Optical Readout

Optical readout methods are very attractive for MEMS based cantilever sensors as they allow remote readout without electrical connections to the sensor chip and scalable architectures for sensor arrays. In addition, optical readout enables the MEMS sensors to operate in different mediums such as liquid environments [37]. The optical readout of a MEMS cantilever consists of two different parts. This thesis introduces the first part as the cantilever (or pixel) embedded optics, which defines the pixel level operation; and the second part as the free-space optics, which includes optical elements (lenses, apertures, etc.) to transmit the optical output light to the detector (Figure 1-5).

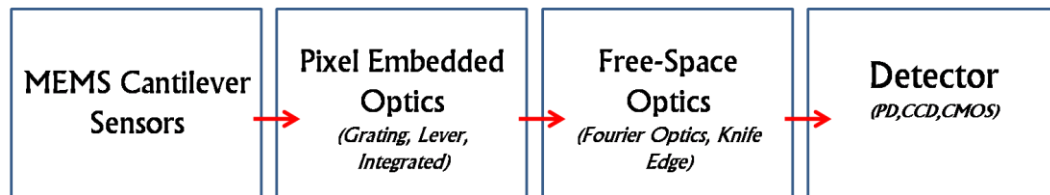


Figure 1-5: Different parts of optical readout systems for MEMS based cantilevers.

The pixel embedded optics for the MEMS based cantilevers can be classified in three groups: diffraction grating based cantilevers; lever based cantilevers and integrated approaches. Previous studies demonstrated various implementations of the embedded optics with different cantilever geometries.

Figure 1-6 displays different MEMS cantilever geometries such as dynamic mode MEMS cantilevers, AFM probes, microphone structures and bimaterial cantilevers with embedded diffraction gratings. The diffraction gratings can be located on or underneath the cantilever to facilitate the optical readout.

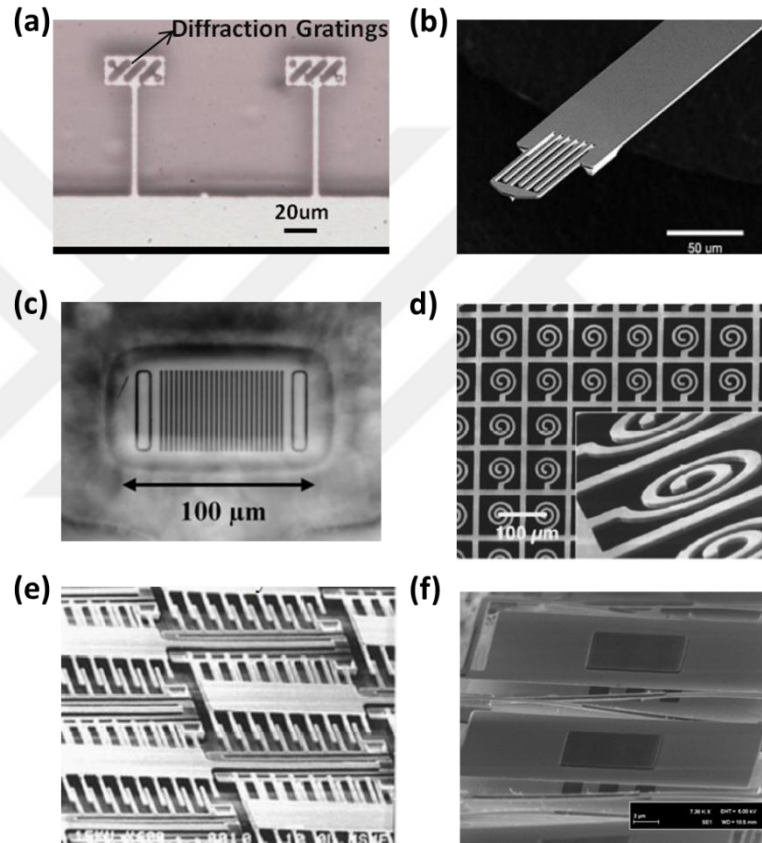


Figure 1-6: Embedded diffraction gratings for different MEMS cantilever modalities (a) Dynamic mode MEMS cantilever [41] (b) AFM probe [42] (c) Microphone structure [43] (d) Spiral shaped bimaterial cantilever [44] (e) Bimaterial cantilever with interdigitated fingers [45] (f) Gratings underneath the pixel. (a) and (f) were developed in our group at Koç University.

Similarly, Figure 1-7 shows a variety of MEMS cantilevers including AFM probes, dynamic mode cantilevers and bimaterial sensors. In the optical lever based cantilevers, the

reflector surfaces for the optical readout can be the cantilever itself or a separate reflective layer on top or bottom of the cantilever.

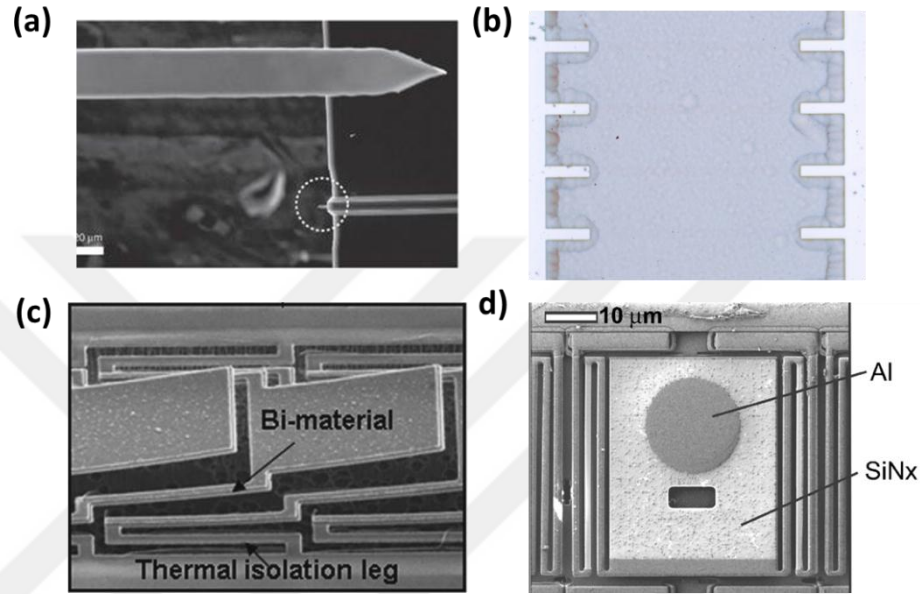


Figure 1-7: MEMS cantilever modalities for optical lever detection (a) AFM probe [46] (b) Dynamic mode MEMS cantilever (developed in our group at Koç University) [41] (c) Bimaterial cantilever with a bottom reflector [47] (d) Bimaterial cantilever with a top reflector [48].

Lastly, Figure 1-8 illustrates the integrated optical readout schemes for a single MEMS device and an array of bimaterial cantilevers. In Figure 1-8a, a vertical-cavity surface-emitting laser (VCSEL) was centered under the diffraction gratings of a single MEMS accelerometer device, and the photodetectors (PD) on the readout chip captures the reflected 1st diffraction orders from the diffraction gratings [49]. In the second system, an array was integrated with a CMOS read-out integrated circuit (ROIC), where the pixel level illumination was performed through the via holes post-processed on CMOS chip. Similarly the reflected 1st orders from the diffraction gratings were captured on the PDs on the CMOS ROIC. This system was developed by our group at Koç University and

discussed in details in Chapter 5 [50]. The integrated scheme does not require any free space optical components, and they provide an ultimate compactness for the sensor system.

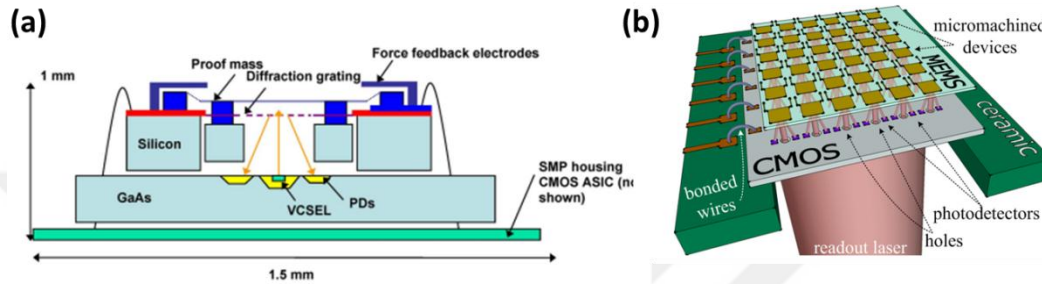


Figure 1-8: Integrated readout approaches (a) MEMS accelerometer [49] (b) MEMS bimaterial cantilevers (developed in our group at Koç University and discussed in details in Ch. 5) [50]

In the upcoming subsections of the optical readout methods, the optical readout operation with embedded and free space optics will be discussed for single sensor operation and array operations.

1.2.2.1 Single Sensor Readout

AFM and static or dynamic mode MEMS cantilever sensors with optical readout are the typical examples of the single sensor operation. Figure 1-9 shows the typical AFM readout setup with simple cantilever geometry. As probe tip scans the surface, the cantilever has a mechanical deformation. The laser is focused on to the single cantilever, and the reflected beam from the reflective surface of the cantilever is detected via a position sensitive detector (PSD) [15]. Generally a bi-cell or quad detector is used to measure the deflection of the cantilever probe. As shown in Figure 1-10, the bi-cell is used to measure the vertical displacement of the cantilever, whereas the quad cell is used to measure the vertical and horizontal deformation at the same time [51]. In bi-cell readout, the difference in the signals obtained from both cells (A-B) is used for the measurement.

Similarly, in the quad cell readout the signals obtained from lower cells are subtracted from the upper cells, $(A+C)-(B+D)$ (Figure 1-10).

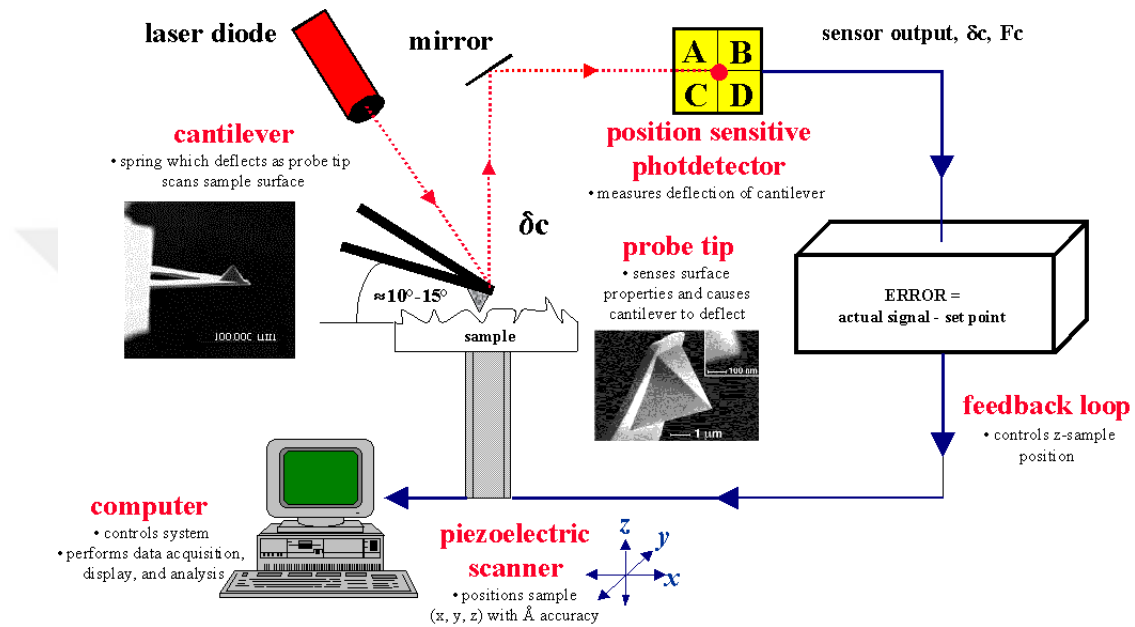


Figure 1-9: Typical AFM readout method [52].

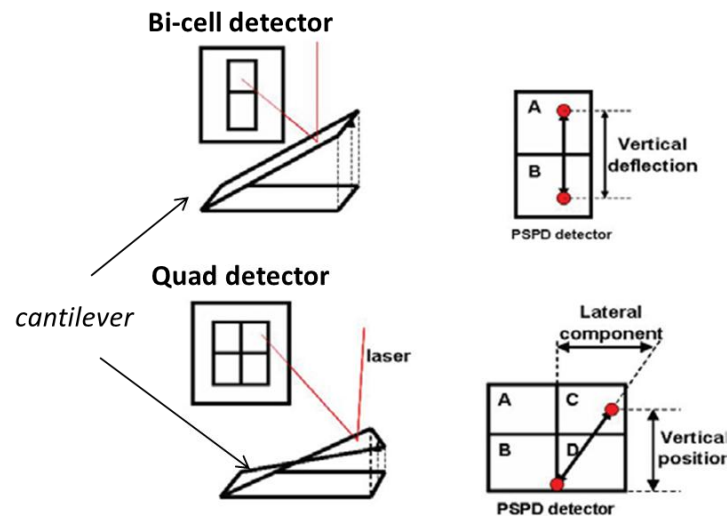


Figure 1-10: The position sensitive detection of AFM using bi-cell and quad detectors [51].

Figure 1-11 refers to the free-space optics part of an AFM system that was introduced in the previous section. The development of the free-space optical setups, even for a single sensor, can enable better detection sensitivity. Figure 1-11a displays an optical beam deflection setup for AFM operation [53]. A collimated laser beam was firstly shaped using a square aperture. Then the light beam was focused on the single cantilever after passing through a beam splitter. The reflected light from the cantilever was directed to a bi-cell detector using the same beam splitter. Quarter wave plate and polarizing beam splitter was used to eliminate the irrelevant reflections, which can enhance the detection sensitivity. The ultimate vertical resolution reported for the optical beam deflection method is $10 \text{ fm}/\sqrt{\text{Hz}}$ [15].

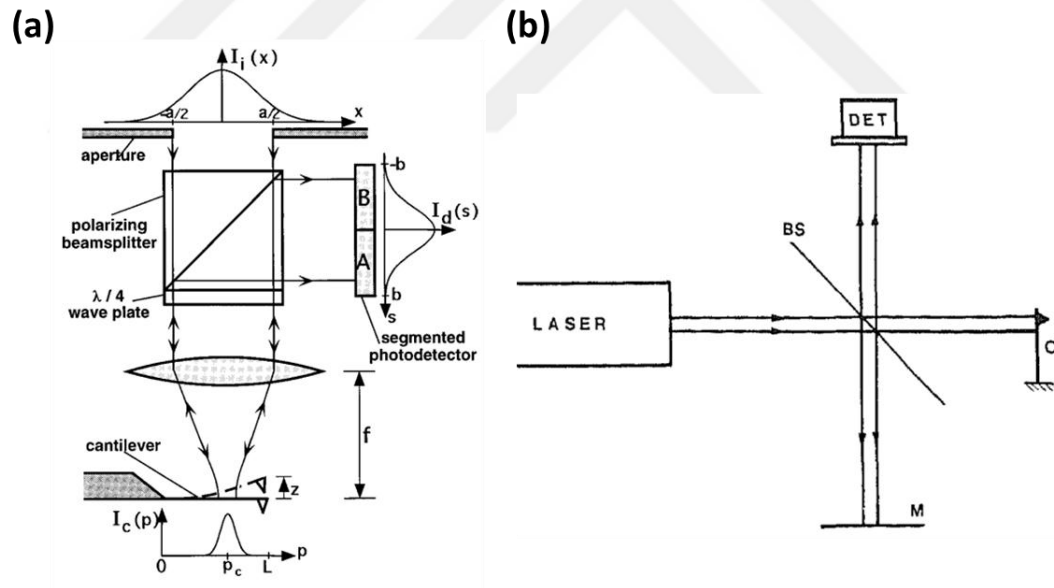


Figure 1-11: (a) Schematic of the AFM with optical beam deflection detection method [53] (b) Schematic of an AFM with interferometric readout [54].

Same cantilever geometry can be used for AFM applications using Michelson interferometry as illustrated in Figure 1-11b [54]. The interference of the reflected light beam from the reference mirror and the cantilever surface will cause

destructive/constructive interference depending on the position (or phase information) of the reflectors. In addition to this interferometric scheme, which is performed with the help of the free-space optical elements, the embedded gratings on the cantilevers can also enable interferometric readout.

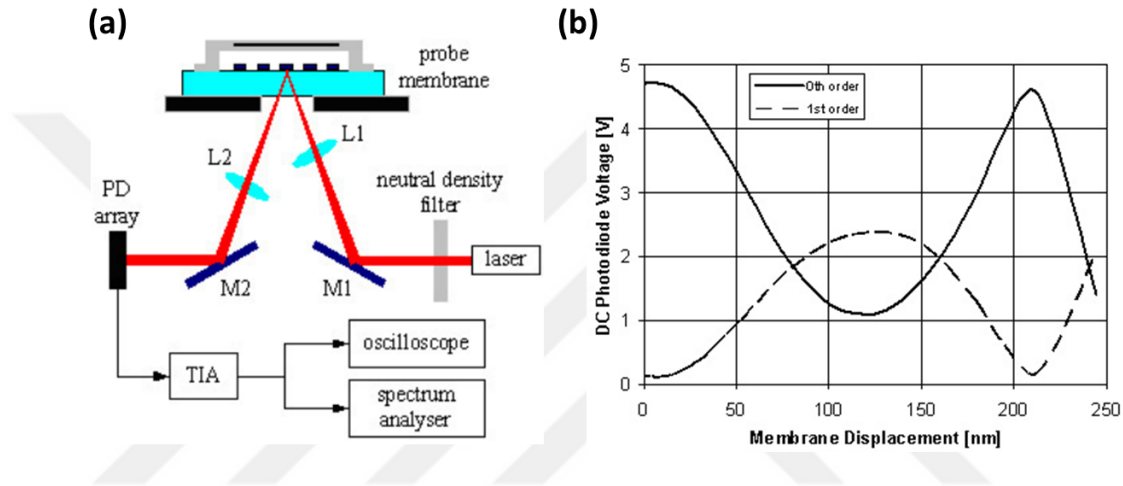


Figure 1-12: (a) Optical setup for the characterization of membrane-based AFM probes with diffraction gratings (b) The sinusoidal photodiode output with the membrane displacement [55].

Figure 1-12a shows the experimental setup for the characterization of membrane-based AFM probes with grating readout. The reflected 0th or 1st orders, which have a sinusoidal characteristic, can be monitored to detect the displacement using a detector (Figure 1-12b). The noise floor of the system for the mechanical displacement was reported below 10 fm/ $\sqrt{\text{Hz}}$, which is an extremely low value for displacement sensors [55].

There are various different sensor designs for interferometry and beam deflection readout methods. Figure 1-13a shows an interdigitated cantilever design as an optical displacement sensor monitoring the 0th or 1st diffraction orders [56]. Figure 1-13b displays another interesting technology, which is called fiber-top cantilever. The cantilever mounted on top of a fiber enables the interference of the reflected light from fiber-to-air, air-to-

cantilever, and cantilever-to-metal interfaces, which is used for optical readout [57]. This method provides atomic resolution without dealing with optical alignment.

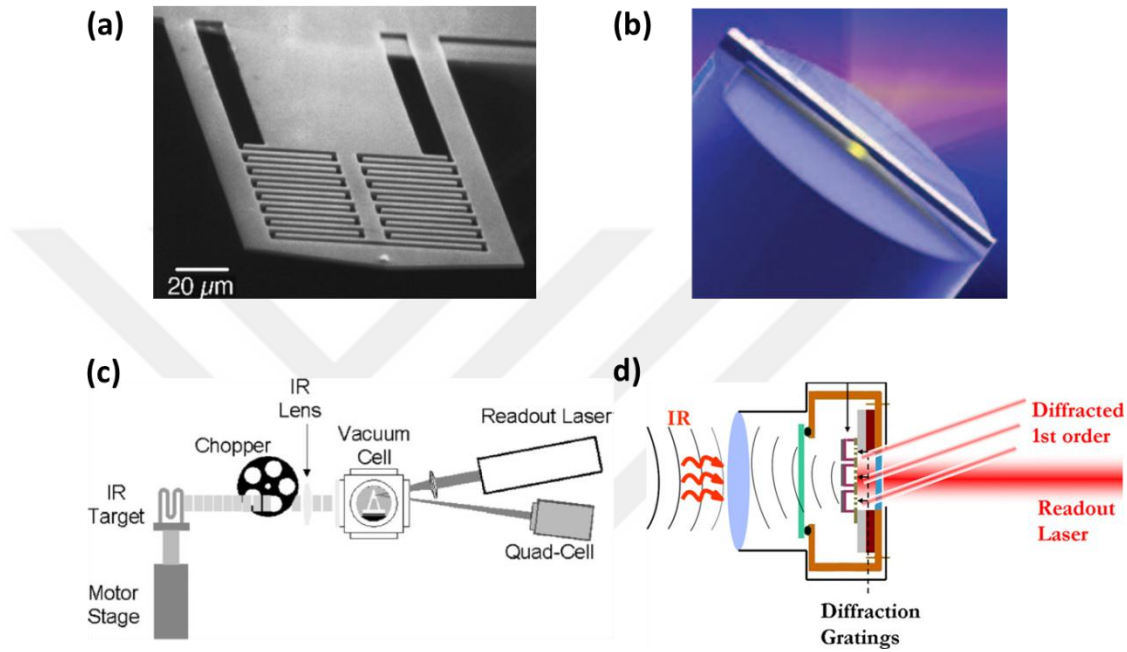


Figure 1-13: (a) Interdigital cantilever as an AFM probe [56] (b) Fiber-top cantilever with interferometric readout [57] (c) Diagram of the experimental setup for the quad-cell readout [48] (d) Schematic of grating readout for bimaterial cantilevers [58].

The single cantilever readout schemes were also applied for thermo-mechanical IR detectors. Figure 1-13c displays a diagram of the experimental setup for the bimaterial cantilever employing pixel level lever readout using a quad detector [48]. Similarly, our group from Koç University presented a grating readout scheme demonstrating the pixel level illumination for bimaterial cantilevers, which is also applicable to arrays [58].

The presented pixel level optical methods reveal high sensitivity in mechanical displacement measurements compared to the electrical methods. In addition, optical readout methods are easily applicable to the cantilevers, because they don't require any electrical connections to the sensor chip. Therefore they are scalable for larger arrays.

Furthermore, it can easily be operated in various different media, except for opaque liquids, due to the remote access property.

Table 1-1: Quick overview for the mentioned readout methods.

Method	Resolution [pm/ $\sqrt{\text{Hz}}$]	Pros	Cons
Capacitive	100 [34]	✓ Readout does not change mechanical properties of cantilever ✓ Nano scale devices are implementable	- Requires electrical connections - Complex fabrication - Variations in the dielectric medium create noise
Piezoresistive	10 [38]	✓ Sensitive detection ✓ Array implementation in many different mediums	- Requires electrical connections - Suffer from heat dissipation and thermal drifts - Piezoresistive coating degrades the mechanical performance
Optical beam deflection	0.01 [15]	✓ High sensitivity ✓ Simple read-out (No electrical connections, remote access) ✓ Scalability ✓ Operation in many different mediums	- Operation in opaque liquids - Not suitable for nano-cantilevers
Optical interferometry	0.01 [55]		

On the other hand, optical methods require decent alignment, especially for larger arrays and they are not suitable for nm-sized cantilevers [37]. An overview for the readout methods are presented in Table 1-1 considering the single cantilever operation [37].

1.2.2.2 Array Readout

In the previous subsection (1.2.2.1), optical readout schemes for single MEMS cantilevers were presented. As earlier mentioned optical readout can be employed to the arrays, which is very important from the perspective of parallel measurements or imaging. In this subsection, the optical readout setups from the literature of MEMS cantilever sensor arrays are presented. Firstly, the array imaging implementations for thermo-mechanical IR detectors, in other words bimaterial cantilevers, are discussed. Then, a mixture of different implementations for the array readout is presented.

i- Optical readout methods for lever based bimaterial cantilever arrays:

Optical beam deflection (OBD) methods are used for the readout of the lever based bimaterial cantilevers.

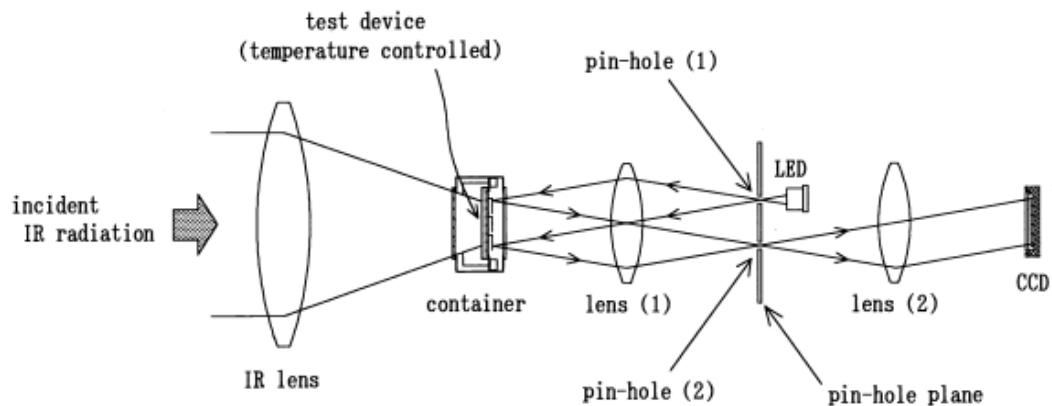


Figure 1-14: Optical readout setup for the lever based bimaterial cantilever array [59].

In order to enable the array operation, free space optical elements such as lenses and apertures are needed for Fourier filtering and imaging using a 2D detector array such as a CCD or CMOS camera. In addition, the imaging operation of large arrays requires a decent optical alignment to avoid the cross-talk and undesirable light reflections from different surfaces of any element in the sensor system for a high quality imaging. Typically LED light sources are preferred in OBD readout for facilitating better imaging of the array.

Nikon Corp. demonstrated IR imaging operation using lever based bimaterial cantilever sensor array with the optical readout setup displayed in Figure 1-14 [59]. The IR imaging operation with optical readout starts with imaging an object on the MEMS focal plane array (FPA) using an IR lens. This creates mechanical deformations at the pixels of the FPA. They implemented an optical beam deflection setup for monitoring these deformations, where they used an LED as the visible light source. After beam shaping through the 1st pinhole, the light was collimated using the 1st lens that illuminates the entire FPA. The parallel light reflected from the FPA was transmitted through the 1st lens again and focused on the same plane with the LED light source, which is called the Fourier Plane. The spot at the Fourier Plane contains the information of each pixel of the MEMS FPA, which was spatially filtered using the 2nd pinhole. This spatial filtering allows the optical power variation of the output due to the tilted bimaterial cantilevers, when exposed to IR radiation. As a last step, the MEMS FPA was imaged on the CCD using the 2nd lens [59]. So the IR image of the object was converted to a visible image on the CCD camera thanks to the optical readout.

Figure 1-15a shows another optical setup for the lever based bimaterial cantilever arrays with the knife-edge filtering operation [60]. They claim that knife-edge filtering operation results in better readout sensitivity as compared to the aperture based techniques. IR part of the readout setup is same with the previous setup. Similarly, they were using LED as the light source.

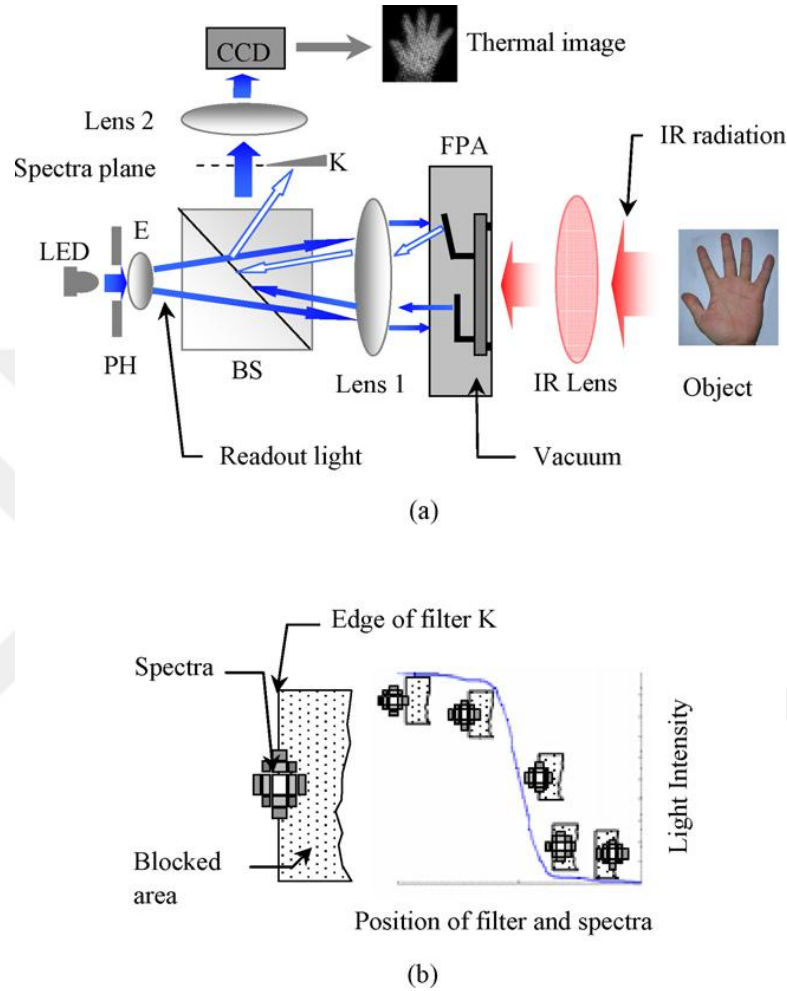


Figure 1-15: (a) Knife-edge optical readout setup for the lever based bimaterial cantilever array, PH: pin hole; E: extender lens; BS: beam splitter; K: filter; (b) Operation for knife-edge filter, K [60].

Firstly, the light beam was transmitted through a beam expander, E, and then collimated with the 1st lens to illuminate the whole array. Reflected light was focused by using the 1st lens again, which was then reflected by a beam splitter towards the knife-edge plane. Knife-edge filter is a spatial filter, which operates at the focus point (spectral plane) of the 1st lens. Figure 1-15b illustrates the performance of the knife-edge filter depending

on the performance. One should arrange the location of the filter's edge on the brightest part of the focused spot to obtain the highest responsivity [60]. The light reflected from the IR absorbed tilted pixels was blocked by the knife-edge filter, which enables the optical power modulation. Lastly, the 2nd lens images the deformed FPA on the CCD, which shows an IR image of a human hand.

ii- Optical readout methods for diffraction grating based arrays:

Interferometric optical readout methods are also implemented for the bimaterial cantilever arrays. As discussed in Section 1.2.2.1, interferometric methods offer high detection sensitivity. In addition, they have other advantages over the OBD methods such as immunity to saturation and vibrational effects [58]. Since interferometric readout has a cyclic nature, the sensor output doesn't saturate for very high temperature objects. The sensor output can be corrected for high temperature objects by tracking the peaks and dips of the sinusoidal output.

Furthermore, the ambient vibrations, which may be coupled to the sensor chip through the substrate, can degrade the performance of the lever based cantilevers. However, since the interference occurs due to the optical path difference resulted from the gap between the substrate and the membrane, the vibrations coupled to both surfaces doesn't affect the output of the interferometric readout [61].

Generally, the pixel embedded diffraction gratings are used for the interferometric readout and the operation of the array readout requires free space optical elements and a decent alignment for imaging the array appropriately. Typically, high coherent light sources, lasers, are used to enable the interferometric readout, which may be a drawback for the imaging operation related to undesired reflections.

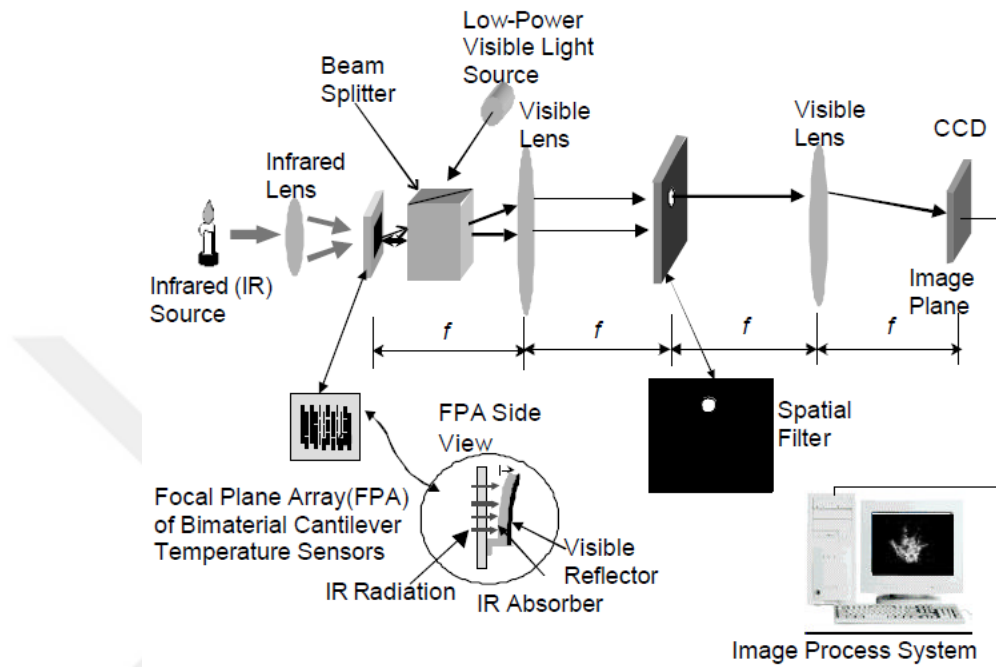


Figure 1-16: Optical readout setup for a grating (interdigitated fingers) based bimaterial cantilever array [62].

Figure 1-16 shows the 4-f optical readout setup for a grating based bimaterial cantilever array [62]. The interdigitated fingers on the pixel enable the interferometric readout. The IR optics part is similar with the previous setups. In the visible optics part, a collimated laser beam irradiates the FPA using a beam splitter. The reflected diffraction orders were transmitted to a 4f optical system, where the distances from the FPA to the 1st lens, from the 1st lens to the pinhole (spatial filter), from the pinhole to the 2nd lens and from the 2nd lens to the CCD adjusted to the focal lengths, f , of the lenses. Therefore the Fourier transform of the transmittance function produces a waveform at the spatial filter plane of the FPA. Similarly the wave function captured on the CCD is the inverse Fourier transform of the wave function at the spatial filter plane, which forms the image of the FPA. Generally the 1st diffraction orders are used for imaging and detection in these systems. They are filtered at the Fourier plane (spatial filter plane) with the help of a pinhole

aperture [62, 63]. This filtering operation is extremely important for a better visualization of the FPA and better detection sensitivity.

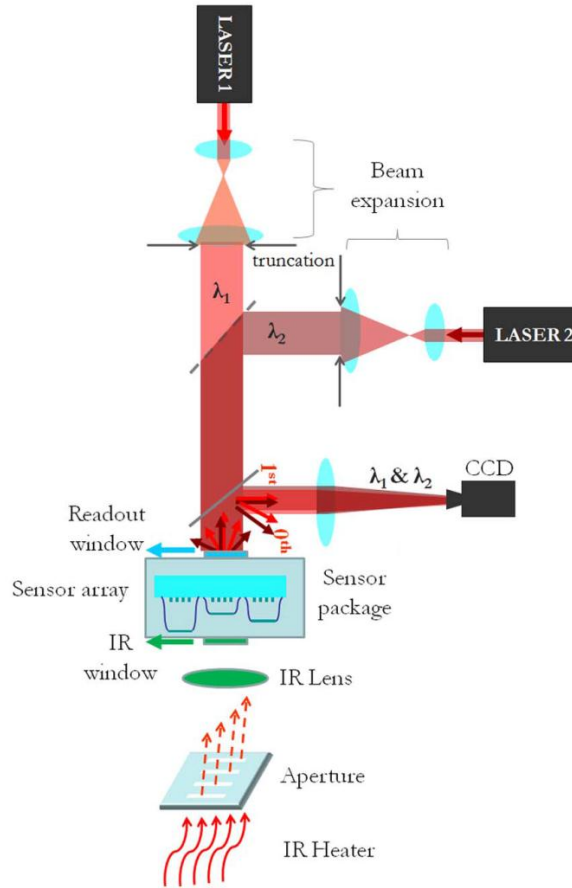


Figure 1-17: A two-wavelength (2λ) optical readout setup for diffraction grating based MEMS FPA [64].

Secondly another novel optical readout method based on a two-wavelength (2λ) approach for diffraction grating based bimaterial cantilever array was previously presented by our group at Koç University [64]. This impressive work aims to improve the detection sensitivity of the thermo-mechanical detectors by using two light sources with different wavelengths. As illustrated in Figure 1-17, the bimaterial cantilevers can have different gaps between the substrate and the membrane due to the imperfections in the fabrication

process. This can result in different sensitivity levels for the optical output signal due to the non-linear regions of the sinusoidal output. In this scenario, 2nd light source was used to achieve better sensitivity [64]. The expanded and collimated light beams from different laser sources with different wavelengths illuminates the FPA and the reflected +1st diffraction orders were collected at the CCD using a single lens. Fourier filtering was also implemented to the system after the imaging lens.

Table 1-2: Overview for the optical readout methods for MEMS based bimaterial cantilever arrays.

Optical beam deflection	Optical interferometry
✓ High sensitivity - Measured NETD = 100 mK (50 μm pixels, Dynamic range of CCD (NA), f/1 IR lens) [65] - Measured NETD = 183 mK (60 μm pixels, 12 bit CCD, f/0.7 IR lens) [66]	✓ High sensitivity - Measured NETD=200 mK (65 μm pixels, 12 bit CCD, f/1 IR lens)
✓ Simple read-out (No electrical connections, remote access to chip)	✓ Simple read-out (No electrical connections, remote access to chip)
✓ Scalability	✓ Scalability
✓ 3-masks may be enough for fabrication	✓ 4-mask fabrication process
✓ Low coherent light source (LED)	- High coherent light source (Laser)
✓ Size reduction of the pixel is more flexible.	- Size reduction of the pixel is limited by grating size.
✓ Improves pixel absorption area due to the less area requirements of top reflector.	- Top reflector area is also limited by the grating size.
- Vulnerability to vibrational effects	✓ Immunity to vibrational effects
- High temperature objects may cause saturation problem.	✓ Immunity to saturation for high temperature objects.

After showing two typical readout methods for the MEMS bimaterial cantilever arrays, the overview of these systems are needed to be done, which is summarized in Table 1-2. The references showing the previous studies were used for the sensitivity comparison, where the other performance criteria were pointed out according to the findings of this thesis work.

iii- Optical readout methods for MEMS cantilever arrays for other applications:

Figure 1-18 shows a variety of MEMS sensor arrays with optical readout. In Figure 1-18a, MEMS cantilevers, which operate in dynamic mode, were illuminated with a laser source using a diffractive optical element. A fiber array collects the reflected light from the cantilevers and enables the optical power modulation as a knife-edge filter at the edge of the fiber. The fiber array was coupled to PDs to detect the light modulation according to the dynamic deformation of the cantilevers [67].

Figure 1-18b displays an optical beam deflection setup, which uses sequentially switched VCSEL array and a single PSD for the readout of the cantilever array. The elements of the VCSEL array were sequentially switched on and off. Each cantilever was functionalized differently, which enables the sensing of different chemicals with each cantilever [68]. The interferometric readout in Figure 1-18c provides parallel measurements in static mode. In one arm of the interferometer a mirror mounted on a translator was utilized, whereas the MEMS cantilevers were located to the end of the second arm. A camera was employed for the detection of static deformations [69].

Figure 1-18d demonstrates an integrated readout scheme for a 2x2 acoustic sensor array with embedded diffraction gratings. The VCSEL located under the sensor illuminates the grating from backside, and the reflected 1st diffraction orders were collected at the PDs located on the readout circuit [70]. Diffraction gratings were also used in a different multi-channel application, which is based on the self-sustained oscillations of the cantilevers

(Figure 1-18e). The laser was focused by forming a line on the MEMS cantilevers using a cylindrical lens. The reflected light from the cantilevers were collected at the same PD.

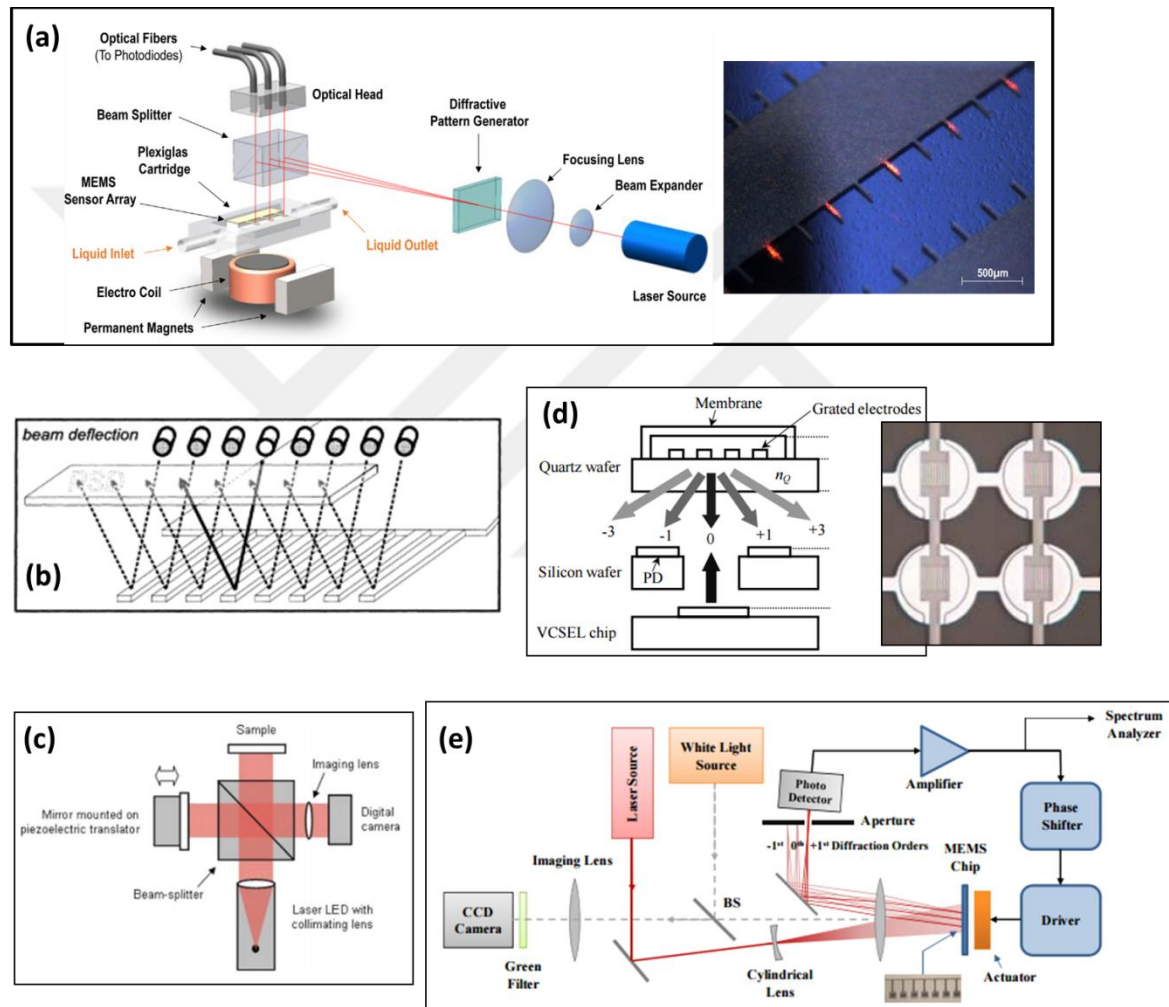


Figure 1-18: (a) 3D sketch of a parallel measurement setup using a fiber array coupled to PDs for the optical readout. The illuminated MEMS cantilever are shown [67]. (b) Optical beam deflection setup: Using sequentially switched VCSEL array and a PSD for the readout of the cantilever array [68]. (c) The interferometric readout for a cantilever array providing parallel measurement in static mode [69]. (d) An integrated readout scheme for a 2x2 acoustic sensor array [70]. (e) SSO of MEMS cantilevers with diffraction grating readout [71].

The output of the system was fed back to the actuator using an amplifier and phase shifter, which enables closed-loop dynamic operation of MEMS cantilevers with diffraction grating readout [71]. The parallelization of the dynamic MEMS cantilevers are challenging due to the bandwidth requirements of the detectors. However, approaches as parallel fiber array or closed-loop dynamic operation implementations make the parallelization simply implementable.

Consequently, optical readout methods provide many different modalities for MEMS sensor array applications. On the other hand, optical readout noise is often the limiting factor in sensor applications. So in order to reduce the effects of these limitations, this thesis presents different optical readout methods that can enhance the detection sensitivity and decrease the optical readout noise for MEMS sensors specifically for infrared (IR) detection. In addition, non-linear optical methods were used in order to enable parallel measurements of dynamic mode MEMS cantilever in a simple closed-loop system.

1.3 Contributions of the Thesis

Figure 1-19 summarizes all the systems, which were implemented during this thesis work. Important features of each system and the contributions of this thesis are also provided. The main focus of this thesis is on improving the detection sensitivity and reducing the optical readout noise for MEMS thermo-mechanical IR detectors and detector arrays. Furthermore, the capabilities of non-linear optical readout methods were analyzed for the parallelization of dynamic mode MEMS cantilever arrays.

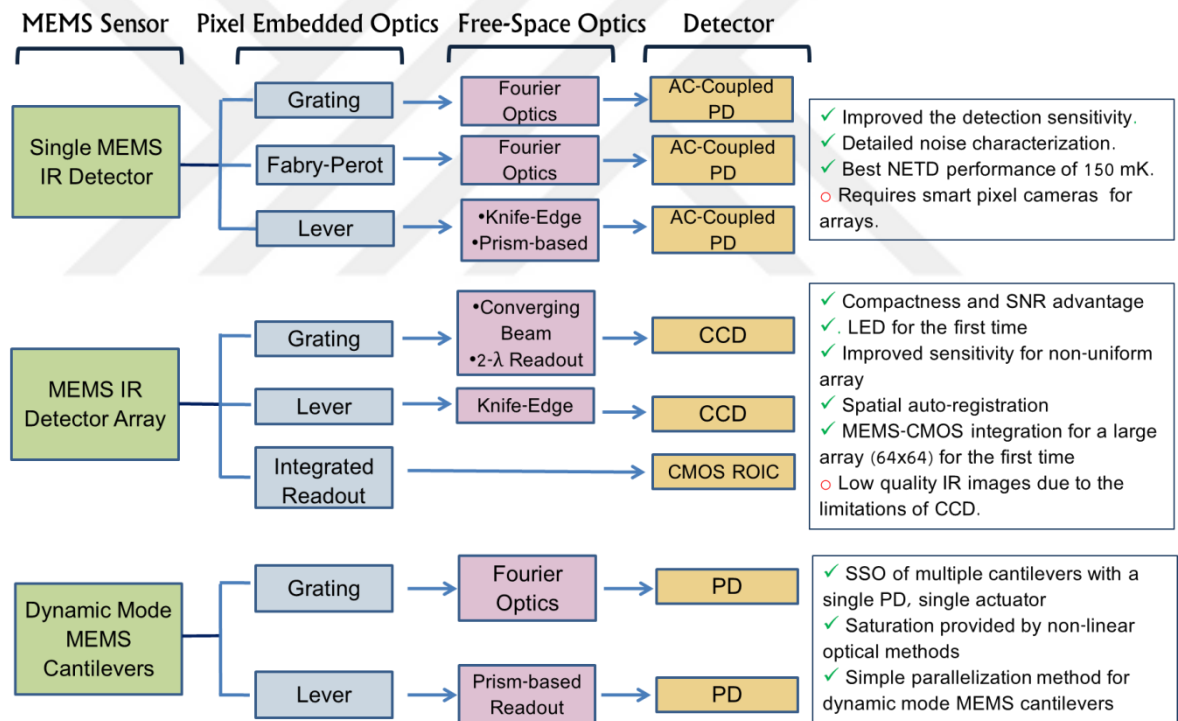


Figure 1-19: All the systems illustrated above were implemented during this thesis. Important features of each system and contributions are summarized in the boxes.

The contributions of this thesis work are also explained below as a detailed list. The related publications are also provided.

✓ *MEMS Single Pixel Optical Readout for Thermo-mechanical IR Sensors:*

The limiting performance factor for the thermo-mechanical detector is the optical readout noise that arises from the CCD sensor array and the laser. In addition, bias on the diffracted light limits the dynamic range and increases the DC noise. Performance of MEMS sensor arrays with optical readout have also been limited by this large DC bias that accompanies a small AC signal. Therefore, an AC-coupled optical readout method was developed for 35 μm pitch IR thermo-mechanical MEMS detectors to reduce the DC term and increase the sensitivity.

This fabricated 35 μm pitch design has one of the smallest pixel sizes among the IR thermo-mechanical MEMS detectors in the literature. Although small pixel pitch offers fabrication of large formatted arrays, there are challenges associated with decreasing the pixel pitch such as low fill factor, lower thermal isolation and reduced responsivity due to shorter bimaterial legs. So, in order to increase the sensitivity, the optical readout noise was reduced using this AC-coupled optical readout method.

In addition, detailed noise characterization of the pixel and the readout system was implemented for the first time. The NETD of the diffraction grating based MEMS detector was measured as 216mK using f/0.86 lens with this AC-coupled optical readout. The AC-coupled optical readout method was also implemented for 35 μm -pixel pitch lever based MEMS detectors. The NETD of the lever based MEMS detector was measured as 200 mK using f/0.86 lens. Furthermore, a thermal image of a 45 $^{\circ}\text{C}$ object was obtained using a single MEMS pixel combined with a scanning configuration.

Secondly, a Fabry-Perot cavity type optical readout method was designed and fabricated with two parallel reflector layers on top of the substrate and the membrane respectively for a 50 μm single MEMS pixel. The IR detection was implemented in the linear region of the optical output, which increases the opto-mechanical sensitivity

significantly. The NETD of the detector was measured as 178 mK using the same f/0.86 IR lens with an AC-coupled photodetector.

As a third approach, a novel prism-based optical readout method, which uses a single prism to detect the incoming TM polarized wave just below the critical angle, was developed. The change of the inclination angle results in an increase in the reflectivity at the prism's glass-air interface. The NETD for a single sensor was measured as 154 mK for the proposed critical angle approach using f/0.86 IR lens. This approach shows a significant improvement for the sensitivity of the IR sensor.

Both methods utilize an AC-coupled readout method for a single MEMS pixel using a photodetector (PD), which responds only to changes in the scene. Consequently, these different AC-coupled optical readout approaches decreased the optical readout noise and increased the sensitivity of the detectors significantly compared to the previous approaches. Despite the reduced pixel size, the measured noise levels are comparable to the state-of-the-art thermo-mechanical IR sensors due to the AC-coupled optical readout [65, 66, 72, 73]. Moreover, this method can be scaled using smart pixel cameras for read sensor arrays with low-noise and high-dynamic range.

Relevant Publications:

- **U. Adıyan**, F. Civitçi, O. Ferhanoglu, H. Torun, and H. Urey, "A 35-Pitch IR Thermo-Mechanical MEMS Sensor with AC-Coupled Optical Readout," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 21, pp. 87-92, 2015.
- **U. Adıyan**, F. Civitci, O. Ferhanoglu, H. Torun, and H. Urey, "MEMS bimaterial IR sensor array with AC-coupled optical readout," in *Optical MEMS and Nanophotonics (OMN)*, 2015 International Conference on, 2015, pp. 1-2.

- **U. Adiyen**, F. Civitci, O. Ferhanoglu, H. Torun, and H. Urey, "A Prism-Based Optical Readout Method for MEMS Bimaterial Infrared Sensors," *IEEE Photonics Technology Letters*, vol. 28, pp. 1866-1869, 2016.
- **U. Adiyen**, F. Civitci, O. Ferhanoglu, H. Torun, and H. Urey, "A Fabry-Perot Optical Readout Method for Thermo-Mechanical MEMS Detectors," (*in preparation*)

✓ *MEMS Array Optical Readout for Thermo-mechanical IR Sensors:*

35 μm pitch, 320x240 and 64x64 thermo-mechanical imaging arrays with diffraction grating based optical readout were tested for real time video applications. A compact, converging optical readout setup was developed for a diffraction grating based optical readout of a MEMS thermal sensor. This was achieved by using an off-axis converging laser beam illumination that forms the Fourier plane near the imaging lens. This approach has important advantages such as reducing number of optical components and minimizing the optical path compared to the previous approaches. The system was optimized considering parameters such as laser converging angle, laser beam size at MEMS chip, and magnification of the imaging system. Furthermore, an image processing algorithm for single pixel was developed to characterize the single pixel performance using a CCD. Image and real time video acquisition was demonstrated for 35 μm pitch thermo-mechanical imaging arrays for the first time. Although the pixel size was reduced according to the previous works, the imaging of the arrays was successfully achieved with a fine spatial filtering at the Fourier plane.

Secondly, a novel two-wavelength optical readout for grating based thermo-mechanical MEMS arrays was demonstrated by using two LEDs with different colors butt-coupled to a multi-mode fiber. LED light source was used for the first time with diffraction grating based thermo-mechanical MEMS arrays. This system provided spatial auto-registration of two different color images on an RGB camera. The -1st diffraction orders of these colors

were simultaneously monitored with different channels (R and G) of the RGB camera. This simultaneous monitoring of the MEMS pixels with different channels solves the previous approaches' registration problems. The sensitivity of the MEMS array was improved by using the channel data with higher sensitivity for each MEMS detector under a thermal load.

Relevant Publication

- **U. Adıyan**, R. B. Erarslan, O. Ferhanoglu, H. Torun, and H. Urey, "Diffraction grating-based optical readout for thermal imaging," in *SPIE Optical Systems Design*, 2012, pp. 855026-855026-8.
- **U. Adıyan**, F. Civitci, R. B. Erarslan, O. Ferhanoglu, H. Torun, and H. Urey, "Simultaneous two-wavelength readout for thermo-mechanical MEMS detectors," in *Optical MEMS and Nanophotonics (OMN), 2014 International Conference on*, 2014, pp. 169-170.

✓ *Integrated Optical Readout for MEMS-based Sensor Arrays:*

A micro electro-mechanical system (MEMS) based sensor array integrated with CMOS-based optical readout was demonstrated. The integrated architecture has several unique features. MEMS devices are passive and there are no electrical connections to the MEMS sensor array. A CMOS-based readout IC was integrated to the MEMS chip. This integrated approach eliminates the free-space optical components and minimizes the optical path as much as possible. It is the most compact form of MEMS based thermo-mechanical IR imaging system. In order to achieve this integration, a model for the optical readout principle was developed using Fourier optics for the thickness optimization of the MEMS substrate. MEMS chip was thinned down by a grinding process to enable integrated optical readout. The roughness of the grinded MEMS chips was decreased by

using refractive index matched epoxy in the integration. Two chips are aligned with 1-2 μm accuracy and integrated. Test of the integrated optical setup for different sensor inputs was performed.

Relevant Publications:

- R. B. Erarslan, **U. Adiyen**, S. Z. Lulec, S. Olcer, Y. Temiz, Y. Leblebici, et al., "Design and characterization of micromachined sensor array integrated with CMOS based optical readout," *Sensors and Actuators A: Physical*, vol. 215, pp. 44-50, 2014.
 - R. B. Erarslan, S. Z. Lulec, **U. Adiyen**, S. Olcer, Y. Temiz, Y. Leblebici, et al., "MEMS sensor array platform integrated with CMOS based optical readout," in *Micro Electro Mechanical Systems (MEMS), 2013 IEEE 26th International Conference on*, 2013, pp. 181-184. [12]
- ✓ *Multiple Cantilever Resonator using single actuator, single detector and optical nonlinearities:*

Firstly, an experimental setup was developed to conduct simultaneous self-sustained actuated MEMS cantilever sensor arrays with diffraction gratings. MEMS array oscillators typically require a separate detector and feedback loop for each oscillator. It was shown theoretically and experimentally that the grating based optical readout induces non-linearity, which enables simultaneous operation of an array of oscillators using only one actuator, one detector and single electronic feedback-loop. The multiple oscillations were obtainable if the cantilever resonant frequencies were separated from each other by at least 3dB bandwidth.

As a second approach, a prism based optical readout for MEMS cantilever arrays was developed. The non-linear reflectivity arisen from the internal reflection at the right-angle prism's hypotenuse plane enables the measurement of cantilever deflections. A laser beam

illuminates multiple cantilevers, and then it is partially reflected by the prism. The reflectivity of the prism's glass-air interface changes with the cantilever deflection and modulates the laser intensity at the photodetector. The detection sensitivity of the optical readout system was determined by the initial angle of incidence at the prism's hypotenuse plane, numerical aperture of the illumination system and the polarization of the laser beam. In addition, the gain saturation mechanism for the oscillators was provided by the optical non-linearity in the prism readout, which eliminates the requirement for separate sensing electronics for each cantilever. It was shown both theoretically and experimentally that self-sustained oscillations of two MEMS cantilevers with simple rectangular geometry is achievable using only one actuator, one detector and single electronic feedback-loop. The prism based optical readout eliminated the need of diffraction gratings, which is the main advantage compared to the previous approach. Simultaneous self-sustained oscillations of two cantilevers were demonstrated in closed-loop with resonant frequencies in the range 25-30 kHz.

Relevant Publication:

- S. Z. Lulec, **U. Adiyen**, G. G. Yaralioglu, Y. Leblebici, and H. Urey, "Cantilever array oscillators with nonlinear optical readout," in *Optical MEMS and Nanophotonics (OMN)*, 2015 International Conference on, 2015, pp. 1-2.
- S. Z. Lulec, **U. Adiyen**, G. G. Yaralioglu, Y. Leblebici, and H. Urey, "MEMS cantilever sensor array oscillators: Theory and experiments," *Sensors and Actuators A: Physical*, vol. 237, pp. 147-154, 2016.
- **U. Adiyen**, F. Civitci, G. G. Yaralioglu, and H. Urey, "Prism-based optical readout for MEMS Cantilever Array Oscillators," (accepted, *Sensors and Actuators*, 2016).

2 Design and Fabrication of MEMS based Cantilever Sensors

2.1 Thermo-mechanical IR Sensors

Observing and identifying the objects in darkness, foggy and in different adverse conditions is extremely desirable in various applications. Infrared (IR) technology plays a key role for these applications. Far-IR (8-14 μm wavelength range) technology is very suitable to operate in adverse conditions such as darkness, because the waves at these wavelengths do not attenuate much in the atmosphere [62]. Therefore, IR detection and imaging technology for these wavelengths is very important for various applications such as security, surveillance, medical and vision enhancement [61]. Even though this technology was firstly utilized in military application, IR imaging (especially thermal detectors) has been widely used for the last few years in civilian applications such as medical diagnostics, security, automotive, food inspection, etc. [27].

Two major IR detector technologies are used in IR imaging: the photon detectors and thermal detectors. Photon detectors are very fast and they offer high sensitive IR detection compared to the thermal detectors [74]. However, these detectors requires cooling to cryogenic temperatures, because the thermal noise has an exponential dependency to the band gap (E_g) and temperature (T) of the material: $\exp(-E_g/(k_B T))$, where k_B is the Boltzmann constant [75]. According to this exponential relation, one needs to decrease the temperature to decrease the thermally induced transitions and the noise. Since a dewar with a liquid nitrogen mechanism is used to achieve cryogenic temperatures, these photon detectors are bulky and very expensive [74]. Thus, they are mainly used in costly, military applications [27].

The second major IR detection technology is thermal detectors, which are less sensitive and slow compared to the photon detectors. However, since they don't require any cooling,

they are smaller and 100 times less expensive than the photon detectors [27]. The operation principle of the thermal detectors is based on inducing a temperature change on the detector depending on the incident IR radiation emitted from an object [75]. This temperature change on the detector, changes a physical property of the sensor such as electrical resistance (in bolometers), electrical polarization (in pyroelectric detectors), thermally induced electrical current (in thermopiles), and thermo-mechanical displacement (in thermo-mechanical detectors) [27]. Consequently, the change of the physical property is converted to an electrical signal using different readout schemes, which is converted to thermal image of the object at the end [76].

The most widely used technology for the thermal detectors are the microbolometers. The microbolometer technology have been offering high sensitivity (NETD ~ 50 mK) and high resolution arrays (3 Megapixels) after the developments in the microelectronics and the microfabrication technologies [77]. This mature technology has 95% share in the thermal detectors market; however it's still been accepted as a high cost technology with the prices above US\$1000 for a 1000 pixel IR camera due to its fabrication complexity [27, 77]. Decreasing the cost further can help the IR detection technology to be widely used in civilian applications, which can make it a mass consumable technology. Thermo-mechanical detection technology, which is a part of this thesis, is the most prominent technology to decrease the costs of the thermal detectors due to simpler fabrication procedure and its optical readout property by using CCDs around US\$1 [27].

2.1.1 General Overview

The principle of thermo-mechanical detectors is based on the bending of the bimaterial cantilevers due to absorbed IR radiation emitted from the target [78]. This mechanical motion can be detected via optical [79] or electrical [80] methods. This IR detection technology offers high sensitivity with a low cost and simple fabrication process [27].

Many MEMS based thermo-mechanical detectors have been developed for IR detection in the last two decades. The first MEMS thermo-mechanical detector was developed by Datskos et al. [40] in 1996 by using the bimetallic effect with piezoresistive readout. After that, they achieved IR imaging of an object using a single piezoresistive microcantilever by scanning the sensor at the image plane [39]. Manalis et al. fabricated an array of thermal micromachined bimorphs, which is suitable for IR imaging in 1997 [44]. Perazzo et al. demonstrated IR imaging results for the first time using the MEMS based bimaterial cantilever array with optical readout [45]. The optical readout for this cantilevers are based on diffraction gratings. There are fixed and movable fingers on one MEMS pixel. After the temperature of the pixel changes with the absorbed IR radiation, the pixel moves and changes the optical path difference (OPD).

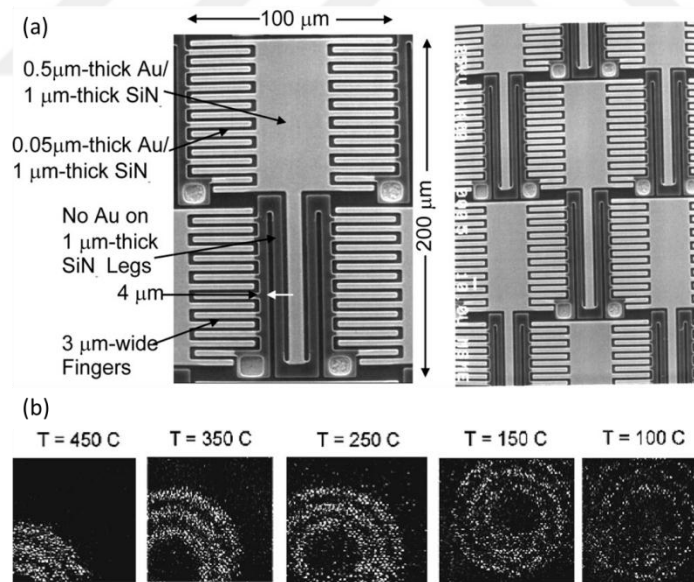


Figure 2-1 (a) SEM of a small part of an FPA showing the structure of each MEMS pixel and the tiling (b) IR images of an electric cooking stove placed at 3m away with different temperatures [45].

The mechanical structure of the pixels and the tiling of the array is given in Figure 2-1a. Figure 2-1b displays an IR image acquired from the array for different temperatures and positions of an electrical cooking stove. They can detect 100 °C with an NETD of 10 K. The same group presented an IR image of a human hand with an NETD of 200 mK using a 300x300 FPA [81].

Nikon Corp. demonstrated a thermo-mechanical based IR detector array (266x194) with optical readout having a pixel pitch of 55 μ m x 55 μ m [59]. They obtained an IR image of a person from raw image using a CCD camera. Oak Ridge National Laboratory has been working on thermo-mechanical IR detectors since 1990's [26, 48, 72, 82]. They designed and fabricated MEMS based thermo-mechanical detector arrays (256x256) with 75 μ m pixel pitch, and demonstrated an NETD performance of 500 mK [72]. Figure 2-2a shows the SEM image of the mechanical structure of their MEMS detector within an array. They obtained IR images from humans at room temperature (Figure 2-2b).

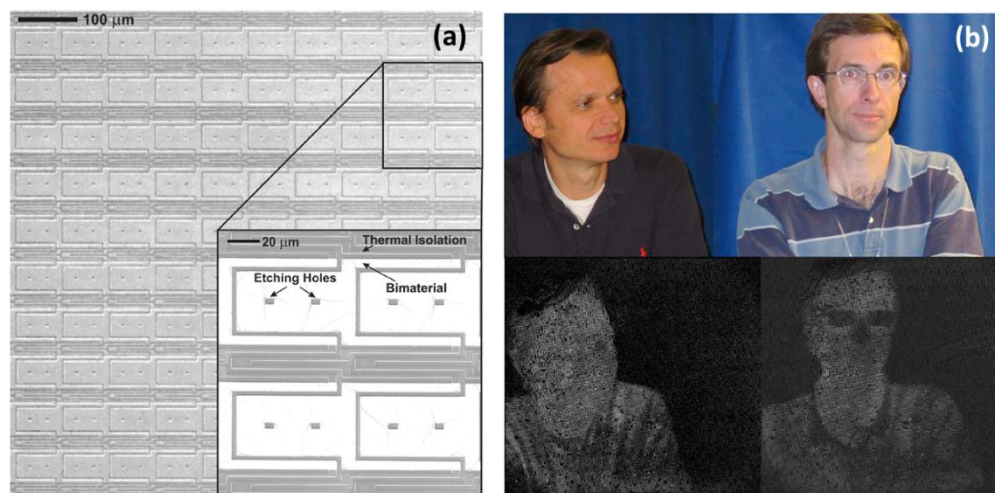


Figure 2-2: (a) SEM image of 256x256 FPA (b) The thermal image obtained from the FPA in (a) [72].

Agiltron Corp. presented an IR image of a human hand using a thermo-mechanical detector array (160x120) with optical readout in 2005 [83]. The pixel pitch is 50 μm and the measured NETD from a single MEMS pixel is 140 mK. Agiltron Corp. has still been working on MEMS based bimaterial cantilevers for IR and THz detection [27]. Chinese Academy of Sciences (CAS) has been working on thermo-mechanical detectors since 2000's [66, 84-87]. The MEMS pixels illustrated in Figure 2-3a has a pitch of 60 μm , and the substrate-free array size is 160 $\times$ 160. The measured NETD is 330 mK using a 12 bit CCD camera in the optical readout [20]. Figure 2-3b displays the IR images obtained from this substrate free array. Ilmenau Technology University in Germany has been studying on these detectors since 2012 [73, 88]. They reported an array with a size of 40x30 and the measured NETD is 600 mK using an 8 bit CCD camera [88].

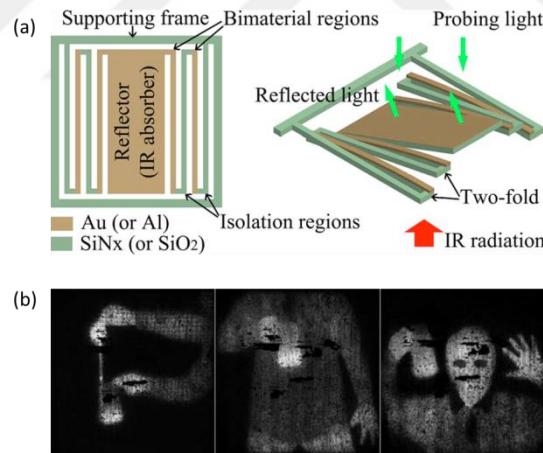


Figure 2-3: (a) MEMS bimaterial cantilever with a substrate-free FPA. (b) Thermal images using the substrate free FPA [87].

The previously mentioned studies from different groups generally implemented optical readout methods (interferometric or optical beam deflection methods). However as explained earlier, capacitive readout methods can also be used with these thermo-mechanical structures. Sarcon Microsystems and Sarnoff Corporation [35, 36, 80, 89] had

worked on these detector until 2008, where the moving pixel was utilized as a plate of the capacitor. These structures requires electrical connection to the MEMS chip and they are costly for this reason [27].

Thermo-mechanical IR detection technology has been going on at Koç University since 2005 [90]. Figure 2-4 shows the whole system. The IR radiation coming from an object is focused on the FPA using an IR lens. It changes the temperature of the MEMS FPA, which is anchored to a glass substrate. The temperature change leads to a mechanical motion due to the bimetallic effect of the legs of each MEMS pixel, which changes the position of a top reflector. The movement of the top reflector is easily detectable using interferometric optical readout [58].

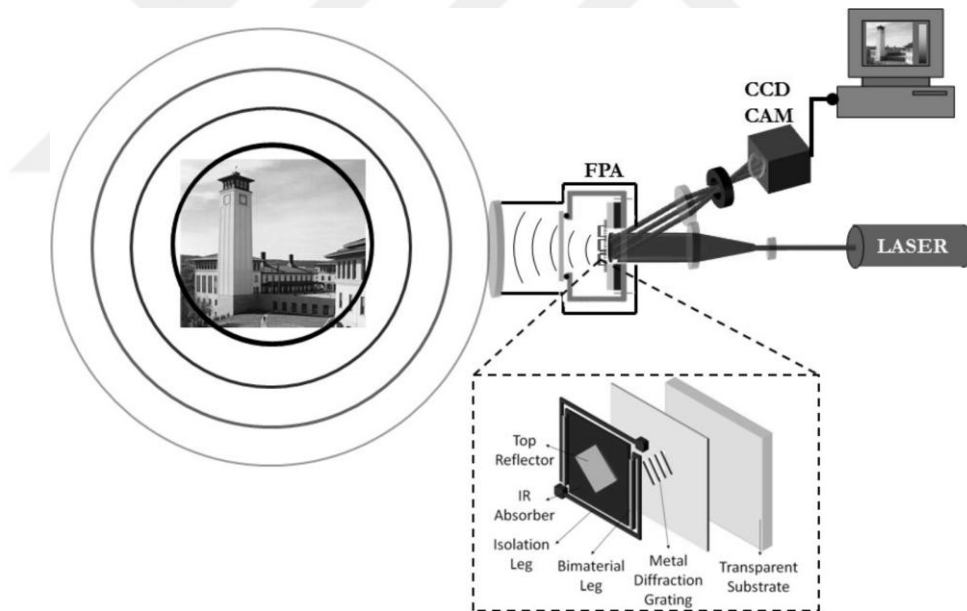


Figure 2-4: Schematic of the IR imaging system developed at Koç University [58]

Figure 2-5a shows a microscope image of a small part of a 160x120 SiNx/Al array. Figure 2-5b displays an SEM image of a successfully released MEMS pixel made of the same materials with another geometry [61].

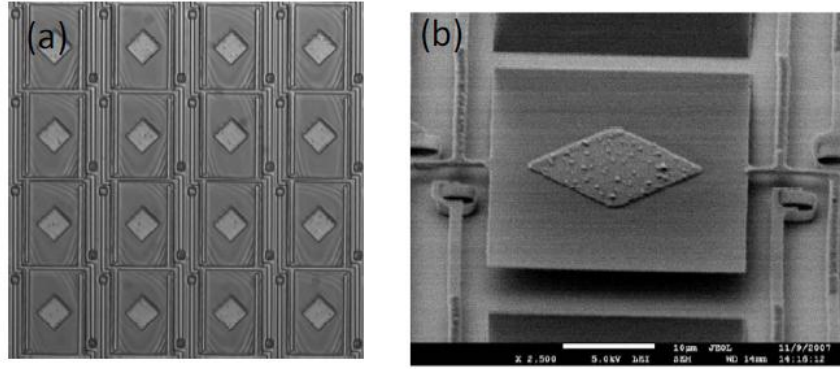


Figure 2-5: Fabricated SiNx/Al sensor arrays (a) microscope image of 4x4 array (b) Successfully fabricated sensor [61].

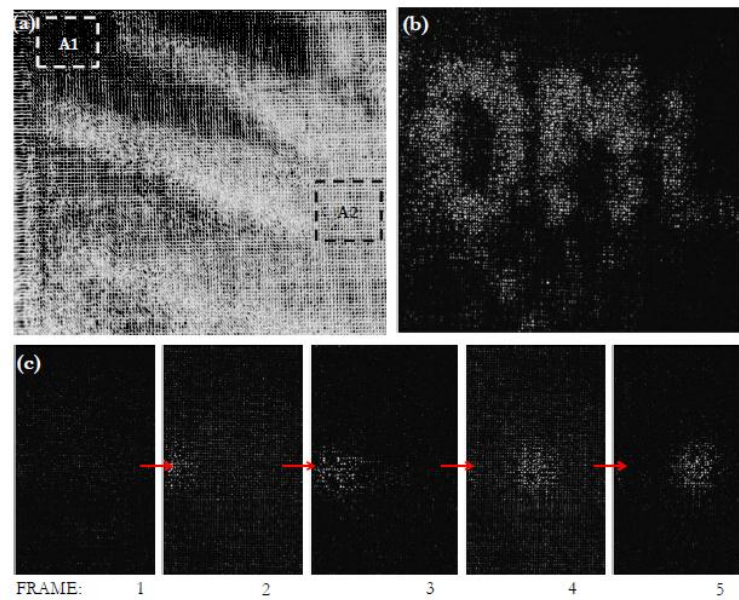


Figure 2-6: IR imaging experiments: (a) IR image of a human hand in front of IR heater captured with SiNx/Al. The dark regions correspond to 700 K temperature where the light regions (regions covered with the hand) correspond to 300K temperature (b) frames of a captured IR video of a moving IR target, entering from left of the screen and moving towards right [61].

Figure 2-6a shows an IR image of a human hand, which was placed in front of an IR heater (~ 700 K temperature) at approximately 1 meter away from the SiNx/Al sensor array. Figure 2-6b illustrates an IR image of a printed circuit board (PCB), which is placed in front of the same heater, on which “OML” text is carved. Lastly, Figure 2-6c shows an IR source (Custom IR source by Bruker (~ 1200 K temperature) moving from left to right. Although uniform arrays were successfully fabricated, due to the optical readout limitations (noisy 8 bit CCD camera and laser) the NETD was measured around 20 K with an 8 bit CCD camera [61]. As early mentioned, one of the main objective of this thesis work is to get rid of the limitations of the optical readout noise, to increase the sensitivity and decrease the NETD value.

2.1.2 Working Principle

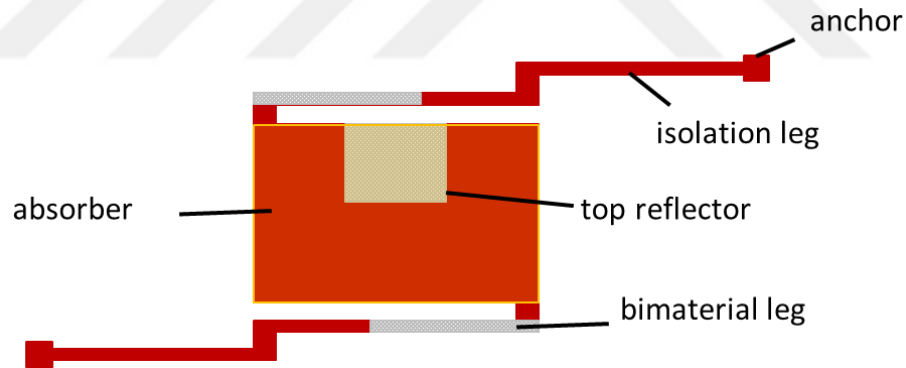


Figure 2-7: An example of MEMS based Thermo-mechanical IR single pixel geometry (Top View).

Figure 2-7 illustrates a MEMS based thermo-mechanical IR detector with an example geometry. The thermo-mechanical detectors measure the temperature change on the device by measuring the mechanical deformation. They are micromachined membranes anchored to a transparent substrate via bimaterial and isolation legs. Each membrane is

identical and forms a pixel in an array. Each pixel has an absorber layer on the detector to better absorb the Far-IR radiation and a top reflector for facilitating the optical readout.

Generally a thin metal layer is used on top of the pixel to absorb the IR radiation. The material of the top reflector is often same with the metal layer used in the bimaterial legs for the sake of the simplicity in the fabrication. Bimaterial legs are made of materials that have large mismatch in the coefficients of thermal expansion (CTE) to induce mechanical deflection with the temperature difference on the detector. The isolation legs and the membrane are typically made of dielectric materials with a good absorbance property in Far-IR and low thermal conductivity (e.g., SiN_x and SiO₂) [26, 58].

This structural material should form a good thermal mismatch pair in combination with the metal layer of the bimaterial leg. Free-standing structures can be fabricated using these materials with thicknesses of a few tens of nanometers that result in large displacements [91].

2.1.3 Design Parameters

There are many design parameters for MEMS based thermo-mechanical IR detectors to consider for maximizing the sensor performance in terms of sensitivity and speed. Each design parameter is summarized below [62].

2.1.3.1 IR Optics

The detector is designed to absorb the incident IR radiation in the Far-IR wavelengths (8 – 14 μm). A germanium (Ge) coated IR lens, which has a transmittance specifically in this wavelength range, is used to image the target object onto the sensor array. Collection efficiency of the IR lens depends on the F-number (F#) of the lens. Smaller F#'s are desired to capture more radiation.

After the IR radiation is focused onto the sensor using the IR lens, it is absorbed through the absorber of the detector. In order to increase the performance, absorbance

should be maximized. Generally a thin metal layer (a few nm) is deposited onto the pixel, which behaves like a transparent medium for the incoming IR wave. Absorption can further be increased using a reflective layer on the substrate. This reflective layer should be located quarter wavelength (around 2.5 μm) away from the thin metal layer to form a resonant cavity [92]. In the experimental setups of this work, a Ge coated IR lens with an F# of 0.86 was used. In addition, the absorber layer was formed of 5-10 nm thick thin films (e.g., Au, Al or TiN).

2.1.3.2 Heat transfer in the sensor

In order to convert the IR radiation to a temperature change on the detector efficiently, one needs to isolate the MEMS detector from the substrate, which may work as a heat sink. Isolation legs of the detector are used for this purpose. Thus, the geometry and the material selection for the isolation leg are extremely important. However, a very good isolation has drawbacks in terms of the speed of the sensor, namely the time constant. The time constant depends on the heat capacity (C) and the thermal conductance (G) of the MEMS sensor (Equation (1)).

$$\tau = \frac{C}{G} = \frac{\rho c V}{k A / L} \quad (1)$$

C , the heat capacity, depends on the volume of the MEMS sensor structure (V), the densities (ρ) and the heat capacitances (c) of the materials selected for the design. G , the thermal conductance, majorly depends on the thermal conductivity (k), cross sectional area (A), and the length (L) of the isolation leg. Consequently, the sensor performance depends strictly on the isolation of the sensor; however one needs to design the sensor fast enough to work with at least 15 fps CCD cameras for real time applications. A trade-off analysis needs to be done according to the requirements of the sensor [93].

2.1.3.3 Thermo-mechanical sensitivity of the sensor

The thermo-mechanical displacement response of the detector with respect to the temperature change should be maximized in order to increase the sensitivity. Equation (2) shows the thermo-mechanical displacement for a bimaterial cantilever. The displacement of a singly clamped bimaterial leg (δ) depends on the length (L) and thicknesses (h_1, h_2) of the bimaterial leg, the mechanical properties of the materials such as thermal expansion coefficients (α_1, α_2) and Young's modulus (E_1, E_2), and lastly the temperature difference ΔT on the legs [90].

$$\delta = \frac{3 \cdot E_1 \cdot E_2 \cdot h_1 \cdot h_2 \cdot (h_1 + h_2) \cdot (\alpha_1 - \alpha_2) \cdot \Delta T \cdot L^2}{(E_1 \cdot h_1 + E_2 \cdot h_2) \cdot (E_1 \cdot h_1^3 + E_2 \cdot h_2^3) + 3 \cdot E_1 \cdot E_2 \cdot h_1 \cdot h_2 \cdot (h_1 + h_2)^2} \quad (2)$$

It is apparent that the mismatch between thermal expansion coefficients of the materials, directly changes the displacement, e.g. the more the difference, the larger the deflection. Increasing the bimaterial leg and obviously the temperature difference also enhances the thermo-mechanical displacement. Nevertheless, in more complex geometries, one needs to use Finite Element Methods (FEM) to obtain the thermo-mechanical displacement of the detector with respect to temperature.

2.1.3.4 Material Selection

Material selection is another important part to facilitate high sensitive detection. For instance, in order to have high thermo-mechanical responsivity, CTE's of the structural layer and the metal layer should have a good enough mismatch. In addition, thermal conductivity of the structural material should be low enough to enable a good isolation. Heat capacity is another important parameter to determine the time constant of the sensor.

The candidate material pairs for the thermo-mechanical detectors are presented in Table 2-1. The first selected material pair for the design and fabrication of the MEMS

sensor is Silicon nitride (SiN_x) - Aluminum (Al). They have a good mismatch in CTEs, and SiN_x has a low thermal conductivity (Table 2-1) [93]. As Young's modulus of SiN_x implies, the sensor structures made of SiN_x have good enough solidity.

Parylene C - Titanium (Ti) are the second candidate for the material pair. Parylene C, which is a soft polymer ($E=3.2$ Gpa), has a good CTE mismatch with Ti and its thermal conductivity is extremely small. This can help to decrease the length of the isolation legs and even the size of the detector. However, the fabrication of the structures with Parylene C is not as easy as SiN_x due to its softness [61].

Nevertheless, both material pairs are used in different designs and fabricated [93].

Table 2-1: Thermal and mechanical properties of the selected MEMS materials.

Material	CTE: α (10^{-6} K^{-1})	Thermal conductivity: k (W/m.K)	Heat capacity: c (J/kg.K)	Young's modulus: E (GPa)
SiN_x	0.8	18.5	690	180
Al	25	237	908	69
Parylene C	35	0.082	1000	3.2
Ti	8.6	22	530	116

2.1.3.5 Array perspective

The pixel pitch is an important parameter for the MEMS arrays to produce a small size chip with large number of elements. Therefore, decreasing the pixel pitch is desirable for array implementations. Fill factor is another important parameter, which exhibits the effective absorbance area of each pixel, from the array perspective. One can increase the fill factor by decreasing the length of the legs. Tiling of the pixels is another important parameter for the arrays. Tiling should be implemented by adjusting the pixel period with a small enough empty space between the pixels.

2.1.4 Noise sources

The sensitivity of the thermo-mechanical detectors basically depends on the overall noise performance of the detector system. The noise-equivalent temperature difference (NETD) is the mostly used figure of merit, which evaluates the performance of IR detection systems. The NETD of an IR detection system determines the minimum detectable temperature difference for a target [61, 90]. It can simply be calculated by dividing the target temperature difference to the corresponding SNR of the detection system to obtain the minimum detectable temperature difference for an $\text{SNR} = 1$ [78]. In the SNR calculations, the thermal detection sensitivity determines the signal level for a given temperature difference of target. For our detectors, it is mainly the optical intensity change at the PD or CCD due to the absorbed radiation from the target.

The overall noise of the detection system appears as the second parameter that defines the SNR. There are many different noise sources that contribute to the overall noise of the thermo-mechanical detection systems. Background fluctuation noise and temperature fluctuation noises are known as the fundamental limits for all thermal detectors that are arisen from the continuous heat exchange by conduction, convection and radiation between the detector and its surroundings [61]. Another fundamental limitation, which is unique for thermo-mechanical detectors, is the thermo-mechanical noise. It is based on the continuous exchange of the mechanical energy stored in the released detector and the thermal energy [90]. The last noise source is defined as optical readout noise, which is often the most dominant noise source for the thermo-mechanical detectors with optical readout. The optical readout system suffers from the detector (CCD, PD) and light source (laser intensity noise). Although, the thermo-mechanical noise sets the noise limit for our detector system theoretically, the optical readout noise appeared as the most dominant noise source by far as it was pointed out in different studies [58, 63, 78, 84].

These noise sources are explained separately in the upcoming subsections.

2.1.4.1 Background Fluctuation Noise:

The background fluctuation noise refers to the disturbance on the detector system resulted from the temperature changes in the background. The temperature change in the background causes heat exchange between the detector and its environment through radiation. The working principle of all thermal detectors is based on absorbing the IR radiation. Accordingly, they are also good emitters for the same wavelengths [62]. Therefore, it is not possible to avoid from the radiative heat exchange between the detector and the environment by nature. Furthermore, this statement is valid for all thermal detectors independent from the detection technology [90].

In order to quantify the effect of the background fluctuation noise, the NETD figure of merit can be utilized (Equation (3)).

$$NETD_{BF} = \frac{8F_{\#}^2}{\eta\tau_0(dP/dT)_{\lambda_1-\lambda_2}} \sqrt{\frac{2k_B\sigma_TB(T_D^5 + T_B^5)}{A_d}} \quad (3)$$

The $NETD_{BF}$ depends on the $F_{\#}$ (f-number of the IR lens), η (the absorbance of the detector), τ_0 (transmittance of the detection system through atmosphere and IR lens), $(dP/dT)_{\lambda_1-\lambda_2}$ (radiated power change per temperature change for the far IR wavelengths between $\lambda_1=8 \mu\text{m}$ and $\lambda_2=14 \mu\text{m}$ per unit area [SI unit: $\text{W m}^{-2}\text{K}^{-1}$]), k_B (Boltzmann's constant: energy-temperature relation at the particle level [SI unit: JK^{-1}]), σ_T (Stephan-Boltzmann constant: gives the radiated power per unit area with the 4th power of temperature [SI unit: $\text{Wm}^{-2}\text{K}^{-4}$]), B (measurement bandwidth [SI unit: Hz]), T_D and T_B (Detector and background temperatures respectively [SI unit: K]) and A_d (effective detector area [SI unit: m^2]).

2.1.4.2 Temperature fluctuation noise

In addition to the temporal fluctuations of temperature due to the radiative heat exchange, the thermal conduction turns out to be another source of the noise for thermal detection systems. Basically, there are two conductive heat exchange mechanism in the thermo-mechanical detectors. The first one is thermal conduction from the detector to substrate through the air molecules (G_{air}), and the second one is along the legs of the detector that are anchored to the substrate (G_{leg}) [62]. G_{air} is often larger than the G_{leg} under atmospheric pressure due to the pixel geometry, where the absorber area is much larger than the cross-sectional area of the leg [62]. In order to reduce the effect of the thermal conductance of air, all the thermal detectors typically operate at low pressures ($\sim 1\text{mTorr}$) [58]. Under these low pressures, the total thermal conductance of the detector can be assumed as $G = G_{leg}$. Therefore, the dominant heat exchange mechanism is caused by the thermal conduction through the legs of the detector, which constitutes as another fundamental limitation for all thermal detectors. Since there are temporal fluctuations of temperature at the membrane and the substrate by means of thermal conduction, it is called the temperature fluctuation noise.

Equation (4) shows the expression of the NETD related to the temperature fluctuation noise.

$$NETD_{TF} = \frac{8F_{\#}^2 T_D \sqrt{k_B B G}}{\eta \tau_0 A_d (dP/dT)_{\lambda_1 - \lambda_2}} \quad (4)$$

Some of the parameters used in this expression (Equation (4)) were also explained in the previous subsection (2.1.4.1). Since the thermal fluctuation noise is based on thermal conduction, radiative parameters (σ_T, T_B) doesn't affect the $NETD_{TF}$. Additionally, thermal conductance (G) is used in Equation (4) apart from the previous parameters due to the mentioned conductive heat exchange.

2.1.4.3 Thermo-mechanical noise

Thermo-mechanical noise is a fundamental noise source for specifically thermo-mechanical IR detectors apart from background and temperature fluctuation noise. Thermo-mechanical IR detectors, which are released bimaterial cantilever structures, can easily be exposed to vibrational noises originated from thermal energy ($k_B T$) or the surrounding [62]. Basically, the temporal vibrations resulted from the thermal energy causes the thermo-mechanical noise through the continuous exchange of the accumulated mechanical energy on the detector [61].

Thermo-mechanical noise is often the dominant noise source among the other fundamental noise sources for thermo-mechanical detectors [90]. Equation (5) shows the expression of the NETD related to the thermo-mechanical noise.

$$NETD_{TM} = \frac{8F_{\#}^2 G}{\eta \tau_0 A_d \frac{dz}{dT_d} (dP/dT)_{\lambda_1 - \lambda_2}} \sqrt{\frac{k_B T_D B}{k Q f_0}} \quad (5)$$

$\frac{dz}{dT_d}$ (SI unit: mK^{-1}) refers to the thermo-mechanical sensitivity, which gives the displacement of the mechanical structure for the temperature difference on the detector. FEM simulations are very useful to obtain the thermo-mechanical sensitivity regarding the specific bimaterial cantilever geometry. k (SI unit: N/m), Q (which is assumed as 500 in vacuum condition [26]), f_0 (SI unit: Hz) refers to the stiffness, mechanical quality factor and the natural resonance frequency of the bimaterial cantilever respectively. It is noteworthy to mention that it is possible to reduce the thermo-mechanical noise by optimizing the stiffness, natural frequency, thermo-mechanical sensitivity, the thermal conductance of the detector in the design process.

2.1.4.4 Optical readout noise

As previously mentioned in Section 1, the optical readout noise is the limiting factor for the thermo-mechanical detector systems. The detector noise (typically a CCD camera or PD) and the laser noise constitutes the optical readout noise. The CCD noise simply originates from the dark (related to dark current) and shot noise (related to illumination), and the noise related to the quantization. Typically the shot noise is larger compared to the other detector noise contributions [90]. We will use the signal to noise ratio of the detector (SNR_{CCD}) according to the bit depth specifications of the CCD for the noise analysis. For instance, an 8-bit CCD camera can simply have a maximum SNR_{CCD} of 255 assuming a noise level of 1, which is an ideal case. In order to emphasize this ideal case, we will use the effective bit depth terminology.

Similarly, the specifications of the laser by means of the laser intensity noise should be extracted from the specifications of the laser used. For instance, we used a low-noise laser (Coherent Ultra-Low Noise Diode Laser) with an RMS noise of 0.06 %. This RMS noise sets a limit for the laser intensity noise.

$$\beta = \frac{1}{I_0} \frac{dI}{dz} \quad (6)$$

Another important parameter for the optical readout noise is the opto-mechanical (β) sensitivity, which indicates the intensity change of the optical system output with respect to the deflection of the bimaterial cantilever structure. Equation (6) expresses the opto-mechanical sensitivity; where $\frac{dI}{dz}$ is the optical intensity change with respect to cantilever displacement and I_0 is the constant amplitude related to the laser output. Increasing the opto-mechanical sensitivity, decreases the NETD related to the optical readout. Eventually, the NETD related to CCD is shown in Equation (7) [62]:

$$NETD_{CCD} = \frac{1}{(SNR)_{CCD} \beta \frac{dz}{dT_d} \frac{\Delta T_D}{\Delta T_T}} \quad (7)$$

where $\frac{\Delta T_D}{\Delta T_T}$ denotes the detector to target temperature ratio, which is explicitly given in Equation (8) [61].

$$\frac{\Delta T_D}{\Delta T_T} = \frac{\eta \tau_0 A_d (dP/dT)_{\lambda_1 - \lambda_2}}{4 F_{\#}^2 G} \quad (8)$$

Similarly, the NETD calculation related to the laser noise is expressed in Equation (9) [62].

$$NETD_{Laser} = \frac{1}{(SNR)_{Laser} \beta \frac{dz}{dT_d} \frac{\Delta T_D}{\Delta T_T}} \quad (9)$$

Consequently, the optical readout noise is the superposition of the CCD noise and the laser intensity noise as it is illustrated in Equation (10).

$$NETD_{OPT} = \sqrt{NETD_{CCD}^2 + NETD_{Laser}^2} \quad (10)$$

2.1.4.5 Total noise

The all previously mentioned noise sources contribute to the total noise and determine the sensitivity of the detector system. All these noise sources are independent random processes, therefore the root mean square value of the noise sources are calculated as the whole system NETD in Equation (11).

$$NETD = \sqrt{NETD_{BF}^2 + NETD_{TF}^2 + NETD_{TM}^2 + NETD_{OPT}^2} \quad (11)$$

So far, the design parameters, the noise sources and the most important figure of merit NETD were explained for thermo-mechanical detectors. In order to increase the overall performance of the detector system and reduce the NETD, different sensor structures should be designed and simulated using FEM software with an aim of optimizing parameters such as thermal conductance, thermo-mechanical sensitivity, stiffness, resonant frequency and time constant. Next subsection describes the finite element analysis implemented for different sensor geometries to obtain these important design parameters.

2.1.5 Finite Element Analysis

FEM software can be used to extract the necessary design parameters for theoretical calculations. ANSYS was used for the simulations with the SOLID98 element type. Since the geometries of the MEMS structures are relatively simple, rectangular blocks were used to define the geometry. Mesh sizes were manually adjusted such that the solution doesn't change with a further decrease of the mesh size.

Firstly, modal analyses were implemented to the designs in order to check the natural frequencies. The first modes of the natural frequencies for all designs are greater than 17 kHz, which is sufficiently larger than the frequency of the detector operation and the environmental vibrations [61]. In addition, the structures were designed such that the first three modes were well separated to ensure the thermo-mechanical operation in the first mode [93]. As a second important parameter, the stiffness of the structure was calculated by applying a pressure load to the structure, which results in a displacement. The stiffness can be calculated by dividing the force related to the pressure load to the corresponding

displacement value. The other important parameters such as thermo-mechanical displacement and thermal conductance are also extracted from FEM simulations.

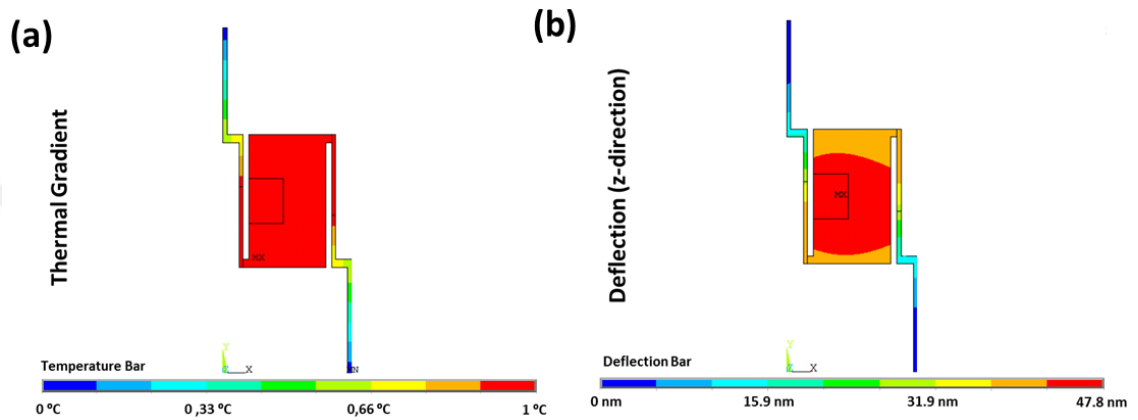


Figure 2-8: Design #1: (a) Thermal Gradient of the MEMS pixel when 1 °C is applied to the absorber (Anchors are 0 °C) (b) Mechanical deflection analysis for 1 °C change in the pixel using FEM.

Figure 2-8 shows an exemplary MEMS design (Design #1) with a pixel size of 35 μm . The pixel is made of 150 nm-thick Al and 150 nm-thick SiNx that form bimaterial legs with a length of 20 μm . The isolation leg is 42 μm long excluding the joints and the anchor. The isolation legs are longer as compared to the bimaterial legs to minimize the thermal conductance for better performance. The design is immune to environmental vibrations due to its high mechanical resonant frequency of ~ 18 kHz, according to FEM modal analysis. The stiffness for this design was calculated as ~ 0.002 N/m. Figure 2-8 shows two important design parameters: the temperature distribution and the resulting thermo-mechanical deflection of a pixel based on FEM analysis. A thermal gradient along the pixel is observed when a temperature load of 1 °C is applied on the absorber, as illustrated in Figure 2-8a. This results in an out-of-plane deflection of 47.8 nm, as illustrated in Figure 2-8b. Our unique mechanical design, capable of out-of-plane, piston-like movement, is compatible with our grating interferometer based optical readout, owing

to the crosswise configuration of the legs [94]. This out-of-plane motion is ensured through the two-end-fixed design that is composed of two legs, each having two joints.

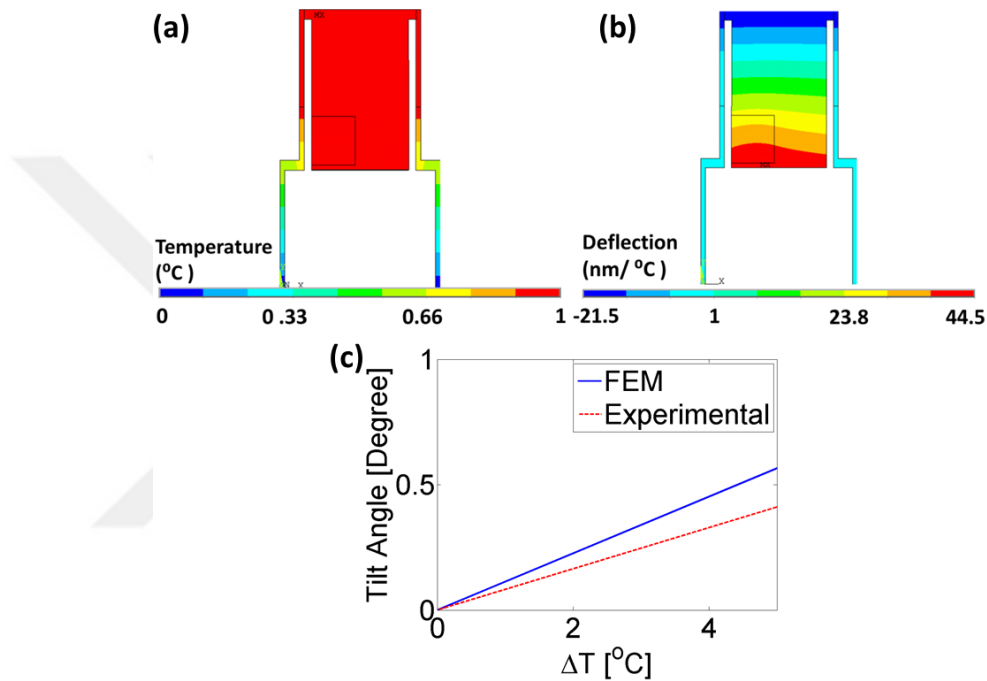


Figure 2-9: Design #2: (a) Thermal Gradient of the single sensor element due 1 °C input on the absorber where anchors are fixed at 0 °C. (b) Mechanical deflection analysis for the thermal gradient in (a). (c) Comparison of the tilt angles w.r.t. temperature using the experimental data and the FEM results.

Figure 2-9 shows another MEMS sensor geometry (Design #2), which is suitable for optical lever based readout. The dimensions of the structure are similar with the previous geometry. The pixel is 35 μm in pitch size and made of 150 nm-thick Al and 150 nm-thick SiNx forming the bimaterial layer. The lengths and thicknesses of the legs are optimized considering the thermal isolation and induced thermo-mechanical displacement as a result of the temperature change on the sensor. The thermal conductance (G) was calculated by applying a heat flux to the absorber and looking at the corresponding temperature change,

which was resulted in $G=1.2 \times 10^{-7}$ W/K thermal conductance. This value is mostly depending on the length of the isolation legs, which are around 40 μm [95]. The thermal time constant of the design in Figure 2-9 was calculated as 1.5 ms that is suitable for real-time imaging. In addition, the 20 μm -long bimaterial legs provide $> 40 \text{ nm}/^\circ\text{C}$ thermo-mechanical responsivity (Figure 2-9). IR induced temperature change on the sensor creates a thermal gradient along the pixel, as illustrated in Figure 2-9a that induces a tilt over the sensor with respect to its substrate (Figure 2-9b). Furthermore, the thermo-mechanical responsivity was also verified with heating experiments under a white light interferometer (WLI) device. MEMS device were directly heated up using a thermo-electric cooler (TEC). Measurements under WLI revealed a tilt angle vs. temperature change of $0.08^\circ/1^\circ\text{C}$ as opposed to the simulation result of $0.11^\circ/1^\circ\text{C}$ (corresponding to thermo-mechanical displacement gradient over the MEMS reflector), extracted from FEM (Figure 2-9c). The deviation between the measured values and the simulated ones can be attributed to the deviation of the geometry and material properties from the theoretical values.

Figure 2-10 shows an AC-coupled design (Design # 3) that consists of two different pixels, which has similar shapes. The working principle of this differential MEMS detector is based on the speed difference of two similar MEMS pixels. A differential signal will be obtained by eliminating the DC, when the MEMS detector is exposed to an IR radiation. In order to have different speeds, there should be a difference between the time constants of the MEMS sub-pixels (Det-1 and Det-2). Since Det-1 has smaller pixel pitch (35 μm pixel pitch), the heat capacity of this pixel is smaller compared to Det-2 (50 μm pixel pitch). Therefore Det-1 works faster than Det-2. The lithographic resolution is 1.5 μm , which corresponds to the width of the legs and the fingers. The grating period is 3 μm . The lengths of the bimaterial and isolation legs are same for both sub-pixels, which are made of SiNx-Al pair to have the same amount of thermo-mechanical displacement per temperature

and equal thermal conductance. But the heat capacities are different, so does the time constants.

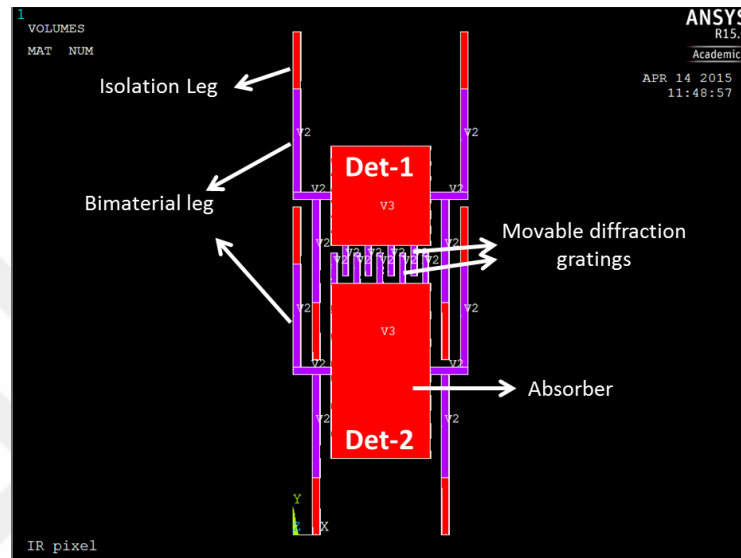


Figure 2-10: The geometry of the AC-coupled Design #3

1 °C temperature change on the sensor creates a same amount out-of-plane motion (45nm/K) for both sensors as it can be seen from Figure 2-11.

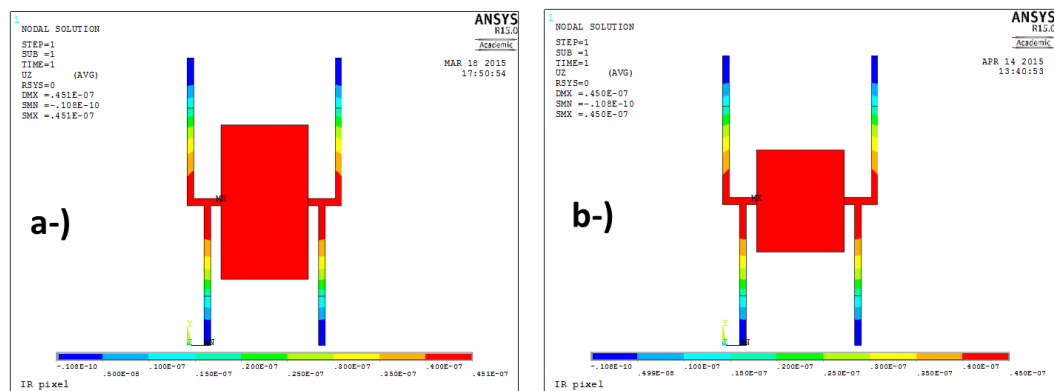


Figure 2-11: Design # 3: (a) Mechanical deflection analysis for 1 °C change in the pixel for larger pixel (b) Mechanical deflection analysis for 1 °C change in the pixel for smaller pixel.

In order to find the time constants, transient analysis in ANSYS was implemented.

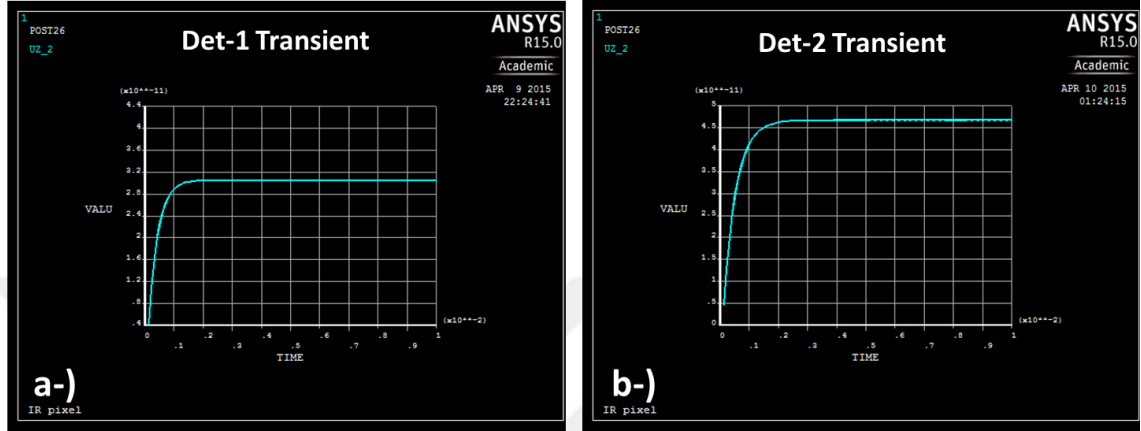


Figure 2-12: 1 W/m^2 heat flux was applied to the absorbers of Design # 3: (a) Transient displacement for Det-1 (b) Transient displacement for Det-2.

When 1 W/m^2 heat flux was applied to the sub-pixels of Design #3, transient responses for deflection was obtained as illustrated in Figure 2-12. The time constant for Det-1 was calculated as 0.386 ms. The slower detector (Det-2) has a time constant of 0.512 ms. The stabilized deflection values for 1 W/m^2 heat flux are 0.031 nm and 0.048 nm respectively. This difference is related to the absorber area difference. Nevertheless, the system still produces a differential signal thanks to having different time constants for sub-pixels.

Lastly, a design for Fabry-Perot readout that is capable of out of plane motion was analyzed. Design #4, which is illustrated in Figure 2-13, is similar with Design #1 that has a piston like motion. The pixel pitch is $50 \text{ }\mu\text{m}$, the fill factor is 60%. The lengths of the bimaterial and the isolation legs are $30 \text{ }\mu\text{m}$ and $68 \text{ }\mu\text{m}$ respectively at one side. A thermal gradient along the pixel is observed when a temperature load of $1 \text{ }^\circ\text{C}$ is applied on the absorber, as illustrated in Figure 2-13a. This results in an out-of-plane deflection of 75 nm, as illustrated in Figure 2-13b. This high thermo-mechanical responsivity helps to increase the sensitivity of the sensor.

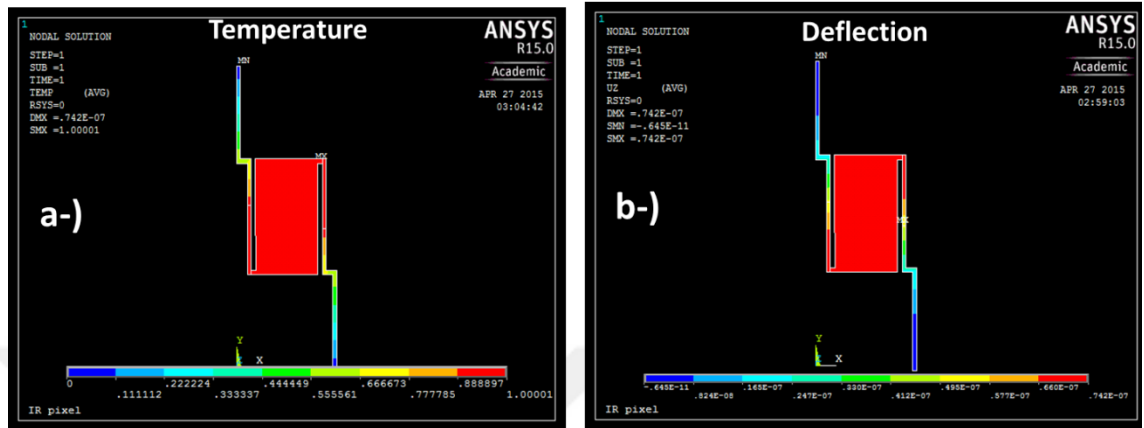


Figure 2-13: Design #4: (a) Thermal Gradient of the MEMS pixel when 1 °C is applied to the absorber (Anchors are 0 °C) (b) Mechanical deflection analysis for 1 °C change in the pixel using FEM.

4 different designs were studied using FEM analysis. The geometry of the MEMS designs were optimized according to the defined parameters. The theoretical performances of the optimized MEMS designs are summarized in Table 2-2.

Table 2-2: The comparison of theoretical performances for each design

Design	Embedded Readout	Pixel Pitch [μm]	Fill factor (β)	NETD _{MEMS} [mK]	NETD _{Opt} [mK]	NETD [mK]	Time Constant (τ) [ms]
Design #1	Diffraction Grating	35	60%	20	147	148	1.4
Design #2	Lever Readout	35	60%	22	172	173	1.5
Design #3	Differential Detector	85	50%	20	140	141	➤ 0.386 (Det-1) ➤ 0.512 (Det-2)
Design #4	Fabry-Perot Readout	50	%60	9	62	63	3

The optical readout noise is calculated assuming an effective 12-bit CCD camera. Design #4 with Fabry-Perot optical readout has the best NETD performance due to 50 μm pixel pitch, high thermo-mechanical sensitivity and reduced optical readout noise, which is related to the opto-mechanical sensitivity. Additionally, since SiNx and Al were used as material pair, the selected designs have small time constants.

2.1.6 Fabricated MEMS Devices

Although Figure 2-14 illustrates the typical fabrication steps for MEMS thermo-mechanical IR detectors with diffraction gratings (Design #1), these fabrications steps are more or less similar for the other designs (Design #2, #3, #4).

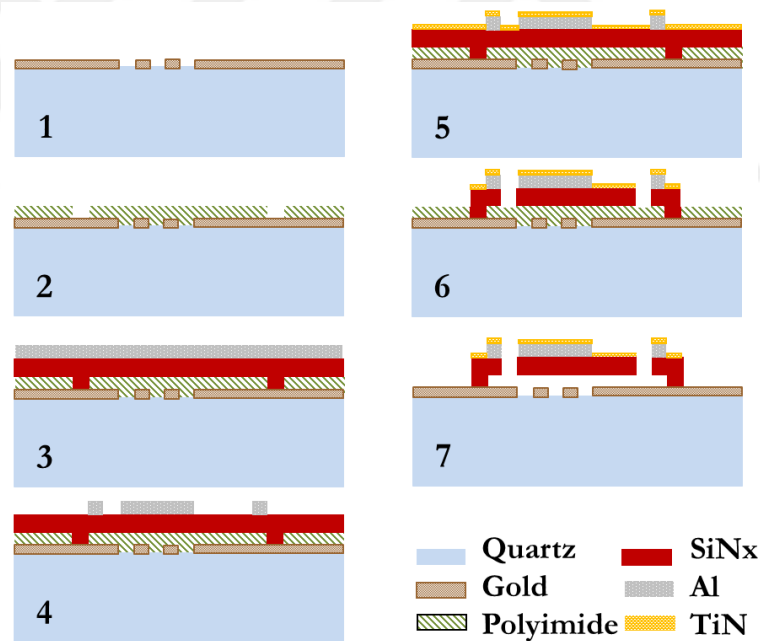


Figure 2-14: Fabrication steps for thermo-mechanical MEMS detector: (1) Patterning of gold grating (2) Polyimide spinning and definition of anchors (3) SiNx and Al deposition (4) Al patterning (5) TiN deposition (6) TiN and SiNx patterning (7) Release

Firstly, a gold layer is evaporated and patterned as a diffraction grating onto a quartz substrate using a lift-off process. Then, a polyimide layer is deposited as a sacrificial layer

and patterned. After that, the structural SiNx and Al layers are deposited and then Al is patterned to form the top reflector and bimaterial legs. A thin layer of Titanium Nitride (TiN) is further deposited on top of the structural nitride layer to enhance IR absorption. Then SiNx and TiN is patterned using the same mask and the structure is released using oxygen plasma etching [78]. The fabrication was carried out at the clean room facilities of METU-MEMS.

Figure 2-15 shows SEM images of the successfully fabricated designs. Design #1, which has a grating based readout, was fabricated as an array. The reflectors on top of the pixel bodies are placed hexagonally in the array to mitigate the optical cross talk during array readout [78]. The lever based design, Design #2, was fabricated as an array too. The differential detector (Design #3) and the Fabry-Perot detector (Design #4) were fabricated as single test structures.

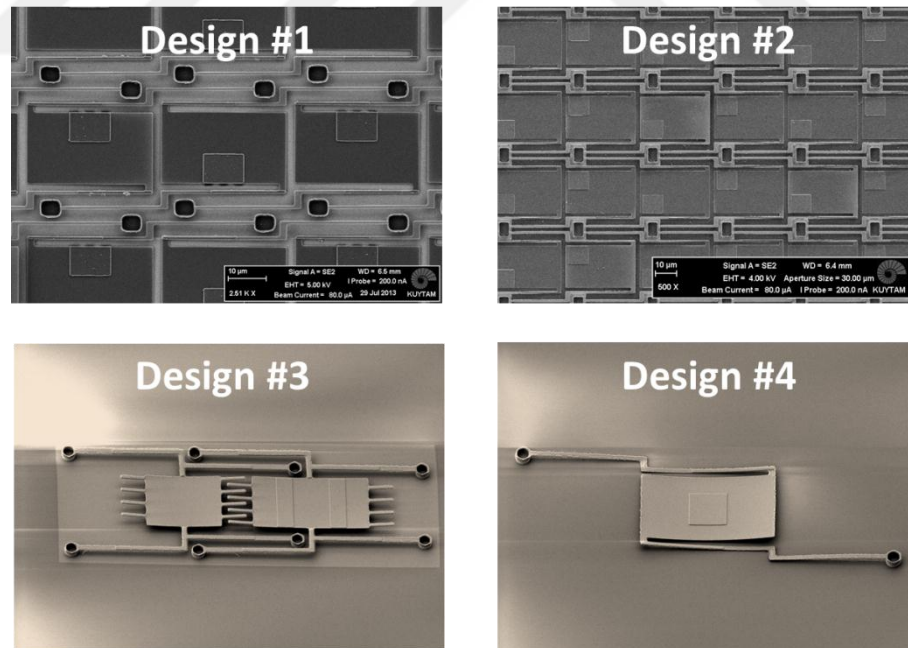


Figure 2-15: SEM images of the 4 different designs. Design #1 and #2 were fabricated as arrays. Design #3 and #4 were fabricated as single test structures.

2.2 Dynamic Mode MEMS Cantilevers

As earlier mentioned, the main part of this thesis work is related to thermo-mechanical MEMS detectors with optical readout. Nevertheless, the optical readout methods can be implementable for any kind of sensor to measure the displacement of the sensor, which can include dynamic mode MEMS cantilevers that are used in chemical and biological sensors.

2.2.1 General Overview

In dynamic mode MEMS cantilever systems, a MEMS structure is oscillated at its resonant frequency and the shift in the resonant frequency is monitored for the chemical and biological sensing applications [15, 96]. These cantilever based chemical and biological sensors can operate either in static or in dynamic mode. This thesis work focuses on dynamic mode MEMS cantilevers.

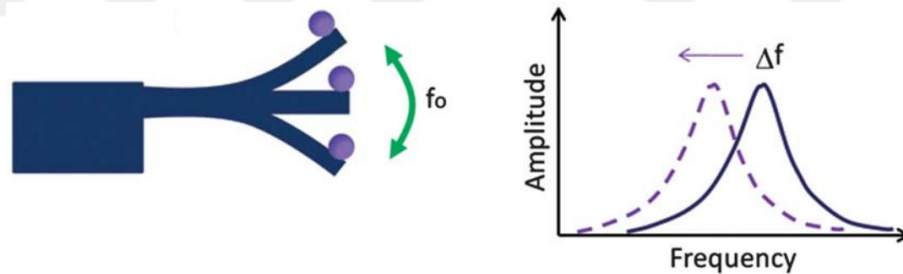


Figure 2-16: Dynamic mode operation of a cantilever sensors [97].

Figure 2-16 shows a dynamic mode operation of a MEMS cantilever. When an object is bound to the tip of the cantilever, the resonant frequency of the cantilever changes. Shifts in the resonant frequency can occur for different biological inputs such as change in the properties of the liquids, namely viscosity and density [24, 25]. Generally, these sensing applications require a frequency sweep for tracking the resonance frequency [15]. Alternatively, lock-in amplifiers or phase-locked loops can be utilized for real-time measurements of the MEMS cantilevers in air or different liquids [24]. There are some

drawbacks of operating the cantilever in liquid, which decreases resonant frequency, quality factor and the sensitivity of the detection system [98]. However there are various studies solving this issue by offering novel mechanical structures or measurement methods. For instance, the quality factor and sensitivity challenges in liquid were overcome by operating the liquid channel cantilevers in air, which is called suspended microchannel resonators [99]. In addition, the measurement systems can provide high sensitive and stable detection architectures that can operate with low quality factor cantilever systems.

There are many different actuation and readout methods for cantilever based sensors [13]. Typical actuation methods for the MEMS cantilevers are thermal, piezoelectric, electrostatic and electromagnetic actuations, and the most common readout methods are optical, capacitive and piezoelectric methods [15]. In this thesis work, electromagnetic actuation with optical readout is utilized for dynamic mode MEMS cantilevers. Specifically, dynamic MEMS cantilevers will be used to maintain oscillations in a closed-loop system without the need of any external AC signal generator for frequency sweeping. This operation is called as self-sustained oscillation (SSO) of MEMS cantilevers.

In an SSO system that uses a cantilever as the mechanical structure, the oscillation frequency locks to the resonant frequency of the cantilever with the help of a feedback loop that contains a saturation mechanism [100]. The main advantages of this closed-loop operation are the simplicity of the electronics, the possibility to parallelize the system easily [71] and the opportunity for larger measurement bandwidths [101] compared to the open-loop techniques. The feedback loop, which consists of a differentiator and an amplifier, is typically very simple for the fundamental mode oscillation where the system output is delayed, amplified and fed back to the cantilever for the excitation at resonance [102]. Therefore, the closed-loop operation does not require time-consuming frequency sweep and it can provide larger measurement bandwidths, which enable measurement of rapidly changing nanoscale mass distributions using a cantilever oscillator [103].

2.2.2 Working Principle

Figure 2-17 shows the working principle of a MEMS cantilever array with electromagnetic (EM) actuation and optical readout. The EM actuation of the nickel cantilevers are achieved using an electro-coil. In addition, permanent magnets are placed under the cantilevers in order to saturate magnetization of the Ni cantilevers [24]. In this system, diffraction grating based optical readout is utilized to measure the dynamic deflections of the cantilever. Typically 1st diffraction order is used for this measurement. An external signal generator is often used with a lock-in amplifier to track the resonant frequency of the system in the post-detection stage. Alternatively, PLL or self-excitation systems can be used in a closed-loop system that connects the post-detection electronics to the actuation mechanism. Frequency counter or spectrum analyzer can be used to monitor the frequency of the cantilever system output [23].

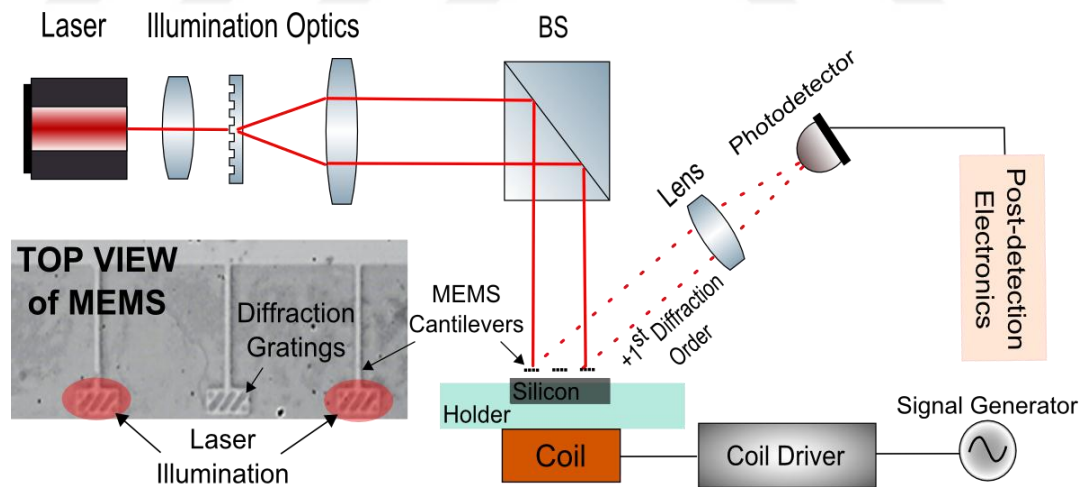


Figure 2-17: Schematic of the working principle of the MEMS cantilever with EM actuation and optical readout.

2.2.3 Fabricated MEMS Devices

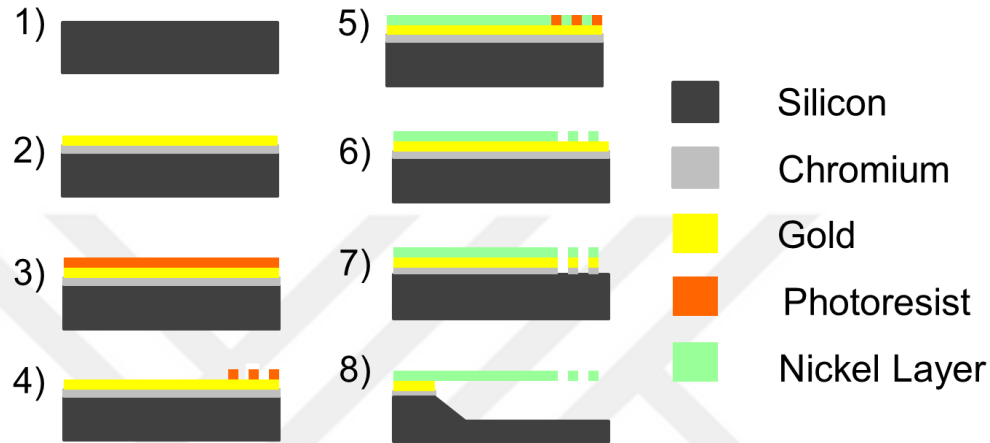


Figure 2-18: The fabrication flow of MEMS cantilevers with diffraction gratings.

The fabrication flow of the MEMS cantilevers with diffraction gratings is given in Figure 2-18. Cantilevers are fabricated using a single mask process, starting with the deposition of a chromium and gold layer. After defining the diffraction gratings, a nickel layer is electroplated. Wet etching process is used for releasing the cantilevers [41, 104].

Figure 2-19 shows the optical microscope images of the nickel cantilevers with different geometries. In Figure 2-19a, nickel cantilevers with diffraction gratings are displayed. The lengths and thicknesses of the cantilevers are $75\ \mu\text{m}$ and $2\ \mu\text{m}$ respectively. The resonant frequencies of the cantilevers with diffraction gratings are around 20 kHz in air. Cantilever geometry without diffraction grating, which has a simple form, is illustrated in Figure 2-19b. The length and the width of these cantilevers are $200\ \mu\text{m}$ and $50\ \mu\text{m}$ respectively. The thicknesses of these cantilevers are approximately $1.5\ \mu\text{m}$. The resonant frequencies of these cantilevers are in the range of 25 to 30 kHz.

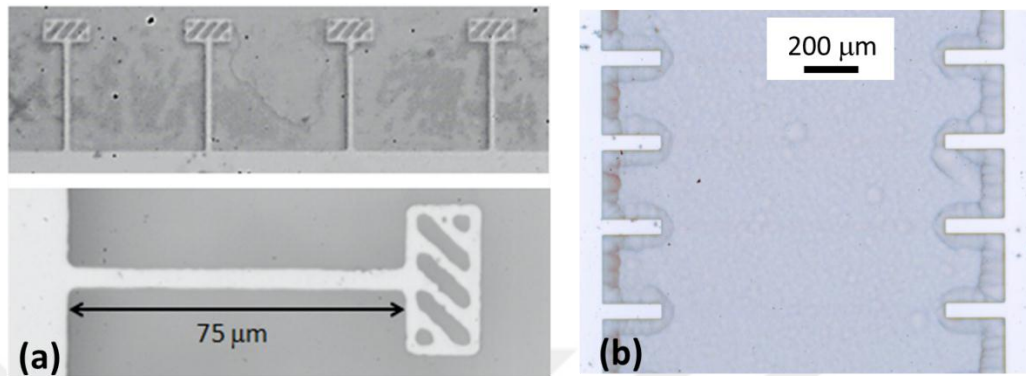


Figure 2-19: (a) Optical microscope images of the nickel cantilevers. The thickness is $2\ \mu\text{m}$. Top picture shows a portion of a cantilever array. Bottom picture is the zoomed view of one of the cantilevers. (b) Optical microscope image of fabricated array of cantilevers without diffraction gratings.

3 MEMS Single Pixel Optical Readout for Thermo-mechanical IR Sensors

This chapter presents different optical readout methods for a variety of single MEMS detectors to improve the detection sensitivity and the noise performance. Interferometric optical readout method for diffraction-grating based and optical beam deflection methods for lever based thermo-mechanical IR sensors will mainly be discussed. Since the performance of MEMS sensor arrays with optical readout is limited by a large DC bias light that accompanies a small AC signal, different optical readout systems to reduce the DC term and the related noise using an AC-coupled detection scheme is introduced. Detailed noise characterization of the single pixel is performed. In addition a novel prism-based optical-readout is proposed for the optical beam deflection method. This approach is compared with the conventional knife-edge method. Both methods utilize an AC-coupled readout method for a single MEMS pixel using a photodetector (PD), which responds only to changes in the scene.

The organization of the chapter is as follows: In the first sub-section the sensor operation is explained. After the AC-coupled operation is introduced, diffraction grating based optical readout will be explained with the experimental results. Then, some different approaches (Fabry-Perot readout, electronic approach etc.) employing the AC-coupled detection will be presented. After that, the lever based readout for optical beam deflection methods is explained with the simulation and experimental results.

3.1 Sensor Operation

The incident IR radiation emitted from a target leads to a mechanical bending that change the position of the reflector on top of the MEMS IR pixel. Optical readout, which is implemented from the backside of a transparent substrate with a light source illumination, is used to detect this mechanical bending. Figure 3-1a illustrates the side view of an IR

pixel with grating readout, where a diffraction grating based interferometer is formed under each detector pixel to facilitate optical readout. Typically the $\pm 1^{\text{st}}$ diffraction orders are used to monitor the sub-micron mechanical displacement with sub-nanometer precision [91]. Figure 3-1b shows the side view of an IR pixel with optical lever readout, which can be used as another approach without the need of embedded diffraction gratings. The deflection of this one end fixed sensor changes the tilt angle of the cantilever. This angle variation deflects the incident beam according to the induced tilt [26].

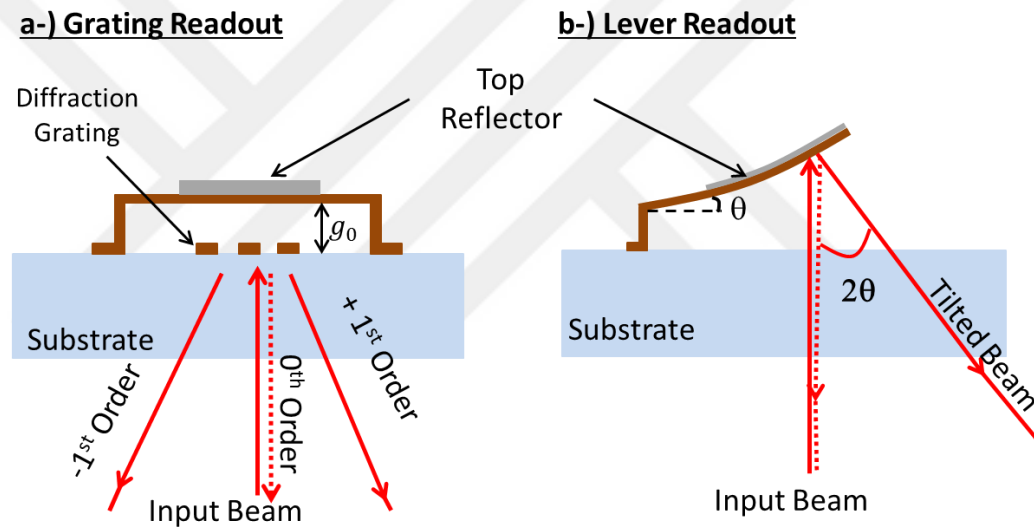


Figure 3-1: a) Side-view of an IR pixel illustrating grating readout b) Side-view of an IR pixel illustrating lever readout

The diffraction grating based optical readout is an interferometric method, which the diffraction orders have a sinusoidal behavior with respect to the gap. Figure 3-2 shows the normalized intensities of 0^{th} (black solid line) and $+1^{\text{st}}$ diffraction order (red solid line) as a function of normalized gap. Since the diffracted order intensities has a period of $\lambda/2$, the displacement can be detected within half the period, or when the sensor bends $\pm\lambda/8$ to each side, as illustrated in Figure 3-2. The dashed line in Figure 3-2 is a linearization of the intensity curve for the quarter cycle as spotted in the gray box. So, the average sensitivity

of the optical readout can be extracted from this linear line, within the range of the sensor gap from $g_0 - \lambda/8$ to $g_0 + \lambda/8$. Consequently, the slope of the linearized curve determines the sensitivity of the optical readout.

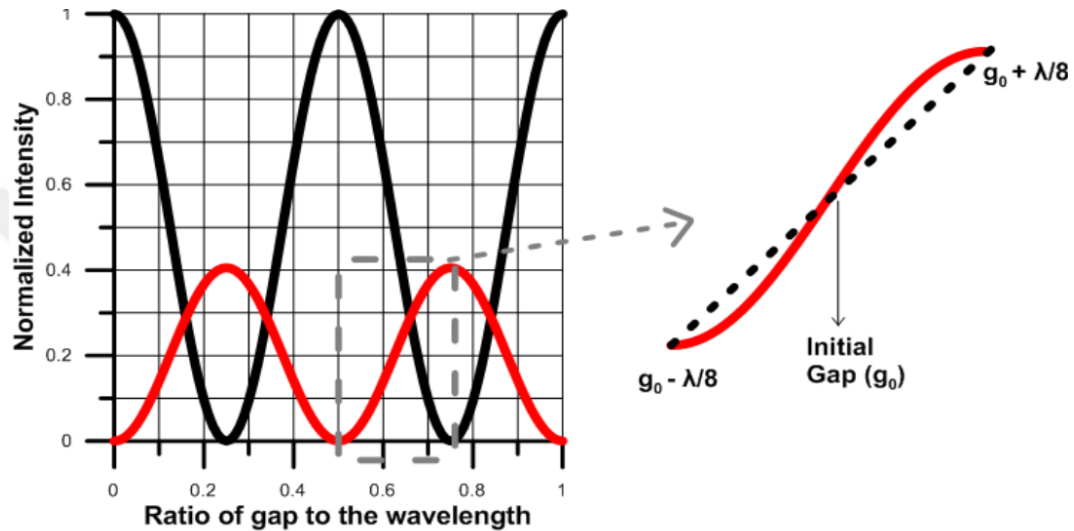


Figure 3-2: Intensity of light going to diffraction orders as a function of the distance from the membranes to the diffraction gratings (Assuming an initial gap (g_0), $\pm\lambda/8$ movements to achieve maximum and minimum target temperatures)

As previously mentioned in Section 1, optical lever readout for the thermo-mechanical IR sensors has the same working principle with AFM [32, 105]. For one end fixed cantilever-type IR sensors, the thermo-mechanical motion induces a small tilt and can be detected via position sensitive detectors or spatially filtering. Generally a position sensitive detector [105] or a quadrant photodetector [106] is utilized in the optical system for the detection of the deflected beam (Figure 1-9). This translation of the cantilever beam can easily be monitored. This design does not require diffraction gratings, which simplifies the fabrication steps, improving effective absorption area since the area of the top reflector can be reduced, and eliminates the need for pixel surface planarization to avoid the tilt errors.

3.2 AC-coupled Optical Readout Operation

MEMS based thermo-mechanical IR detectors with optical readout are the most prominent candidates among the other alternatives due to its low cost [27]. Optical readout which is used in the technologies such as AFM (Atomic Force Microscopy), is the most sensitive (sub-picometer) readout method as far as is known [107]. But, the thermal detector arrays could not reach to the full potential so far, firstly because of the limits of the light source and CCD/Photodetector and secondly the other limits that haven't been considered so far [27]. In the present systems, the DC component of light uses an important portion of the dynamic ranges of CCD or photodetectors. Moreover, this issue has negative effects on the sensitivity of the detection system.

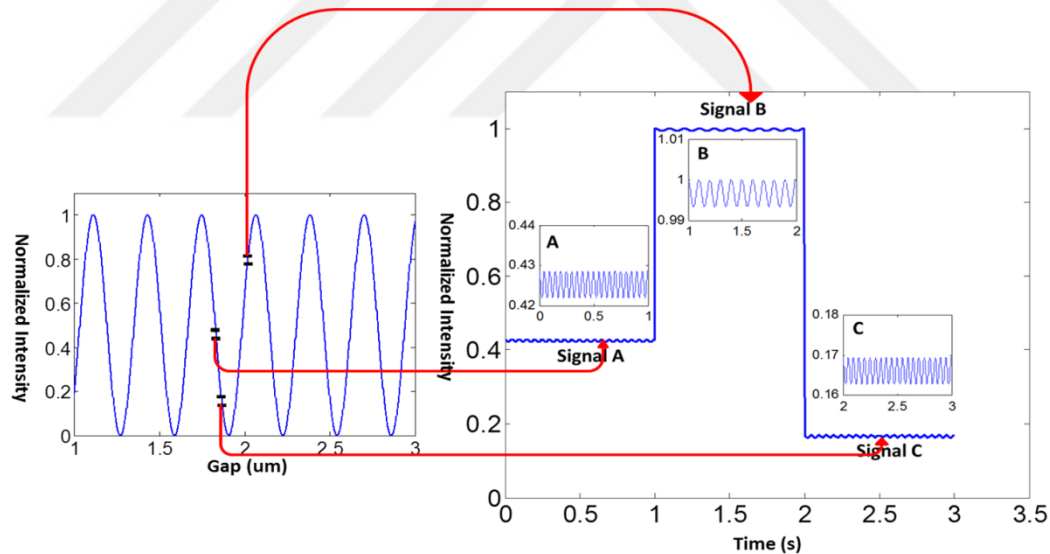


Figure 3-3: AC signals (A, B, and C) modulated at a certain frequency with different DC levels depending on the top reflector position.

For instance, the DC component of the light depends on the position of the top reflector of the MEMS for diffraction-grating based IR detectors. In addition, the IR target can be modulated at a certain frequency in order to obtain an AC signal. In this case, the

position of the reflector determines the detection sensitivity, and the signal-to-bias ratio (SBR) as previously mentioned.

Figure 3-3 shows 3 different AC signals (A, B, and C) modulated at a certain frequency. These 3 different signals have three different DC levels depending on the gap as it's shown. The SBRs of signal A, B, and C are 1/128, 1/300 and 1/50 respectively. For example, an 8 bit CCD camera (assuming an SNR of 255/1 as the best case) is not sufficient to detect the signal A and B. 7 bits are reserved for the DC component of the light for signal A, where only 1 bit is usable for the AC signal. It is not possible to detect signal B, because the entire DC component uses the whole dynamic range of the CCD. Since the signal C has the largest SBR, it has a better detection sensitivity compared to the Signal A, B. Therefore, AC-coupled optical readout methods can decrease the system noise and increase the sensitivity of the MEMS based thermo-mechanical detectors significantly. Moreover, it is possible to use the dynamic range of the CCD or the photodetectors effectively with AC-coupling. Consequently, AC coupled optical readout methods help to get rid of the optical readout noise limitations and to reach the fundamental limits of the MEMS device by decreasing the DC component of the optical output light.

In addition, the AC coupled optical readout method is favorable for single element operation, but for the array structures a custom smart pixel camera can be used. Such cameras [50] include photodiodes, trans-impedance amplifiers, bandwidth limiting and DC eliminating filters, together with analog multiplexers and decoders for pixel selection.

3.3 Diffraction Grating Based Readout

The diffraction grating interferometer based readout method has been previously employed in thermo-mechanical detectors as previously mentioned [58, 63]. In the diffraction grating based readout, the $\pm 1^{\text{st}}$ diffraction orders are generally used to monitor the mechanical displacements due to having less DC component compared to the 0^{th} order [61]. Therefore using the $\pm 1^{\text{st}}$ diffraction orders in these systems brings a significant

enhancement for the optical readout sensitivity by reducing the DC component of the light [62]. In addition, still the limiting performance factor for the thermo-mechanical detector is the optical readout noise that arises from the CCD sensor array and the laser [48, 61, 62, 73, 84].

3.3.1 Working Principle

Since CCD noise poses a significant limit, characterization for the performance of the MEMS device alone is hampered. In order to isolate the optical noise from the performance of the MEMS sensor, we propose an AC coupled optical readout setup, as illustrated in Figure 3-4. Accordingly, the IR target is modulated using a rotating chopper. The modulated IR radiation is focused on the MEMS device using an IR lens, with a focal length of 50 mm (Figure 3-4a). The visible optics part of the experimental setup is given in Figure 3-4b. Firstly, the illumination system focuses the laser light onto a single MEMS pixel. We use an ultra-low noise red laser preceding a 5x magnifier. After beam-shaping with a circular aperture, we focus the laser on an individual array element using a 100 mm focal length lens. We then image the 1st diffraction orders reflected back from the MEMS device on the CCD with a single lens and an aperture at the Fourier plane, while also monitoring the intensity of the 1st order with a photodetector (PD). This PD, which is connected to a wide band-pass filter having a center frequency of 10 Hz, rejects the DC component of the diffracted light. We fine tune the focusing until a single diffracted spot appears at the CCD screen. After tight focusing onto a single element, we gather the relevant intensity data from the PD in response to the chopped IR target.

Since the MEMS FPAs are tailored for real time imaging applications, the system is designed to work with a 30 fps CCD camera. Therefore a low noise preamplifier is utilized just after the PD, implementing a unity gain Low Pass Filter (LPF) with a 30 Hz cutoff frequency.

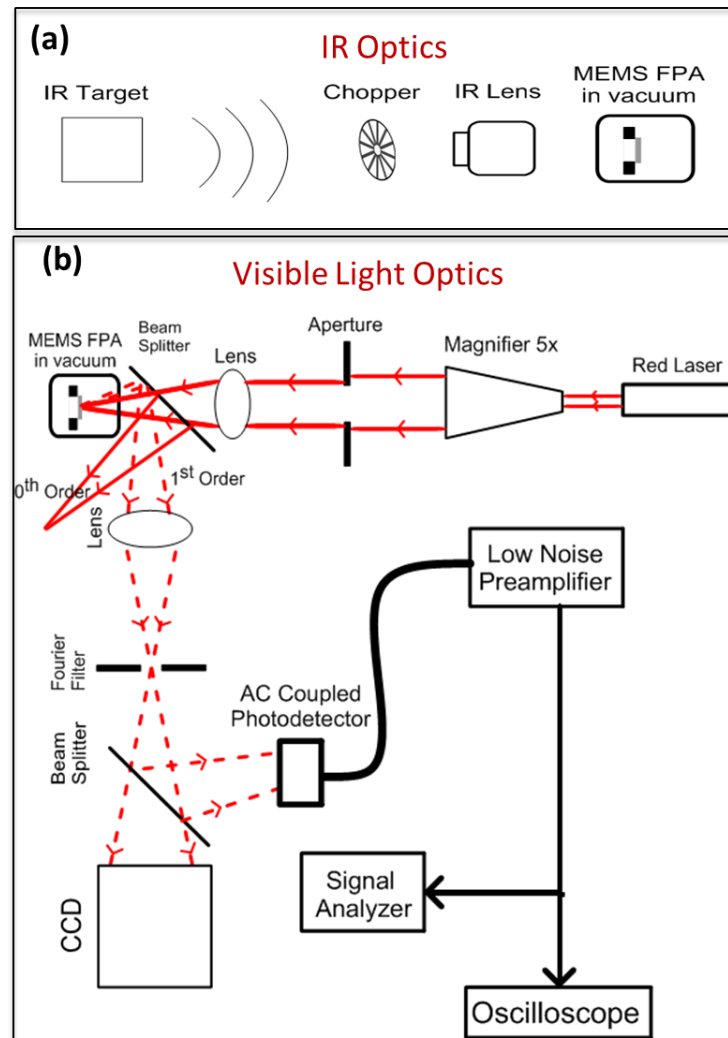


Figure 3-4: Experimental setup of single pixel optical readout: (a) IR Optics Part (b) Visible Light Optics Part

An oscilloscope and a signal analyzer are connected to the low noise preamplifier. The oscilloscope is used in measuring the signal level when the MEMS device is exposed to a chopped blackbody source. Secondly, while the IR target is blocked, the noise measurement of the system is held using both the oscilloscope and the signal analyzer to mutually cover the entire frequency range of 0-30 Hz. A Thermoelectric cooler (TEC)

module is used as an IR target that is placed before a rotating chopper to carry out the AC coupled readout.

3.3.2 Experimental Results

In the experiments, the TEC module was heated up to 75 °C where the background temperature was 25 °C. The response of the selected MEMS pixel to the TEC module, which was chopped at 10 Hz, is given in Figure 3-5a. The peak-to-peak signal level (Vs) was 220 mV for the temperature difference of $\Delta T = 50$ °C. The thermal time constant was also deduced as 15ms based on the signal, which is an important figure of merit to understand the capability of the system for 30-fps real time applications.

The noise measurement was performed in three steps, through isolating one noise component at a time. Firstly, the laser was blocked in order to measure the noise of the PD. Secondly the contribution of the laser intensity noise was checked, while the MEMS was by-passed with a switch mirror. Then, the intensity of the beam collected at the PD was adjusted to that of the 1st diffracted order using neutral density filters. Finally, the entire system noise was measured including the MEMS device, which was used in the calculation of the NETD.

Figure 3-5b depicts the noise levels of the PD, laser and MEMS. When the laser was turned on, the noise increased particularly for the lower frequencies (< 10 Hz), due to a combination of laser intensity noise and low frequency vibrations associated with our setup. The total noise is further above both PD and laser noise sources, as expected, due to contribution from the MEMS noise sources. Thermo-mechanical, background fluctuation and temperature fluctuation noises are among MEMS related noise sources, which are the fundamental limitations of the uncooled thermo-mechanical IR detectors [14].

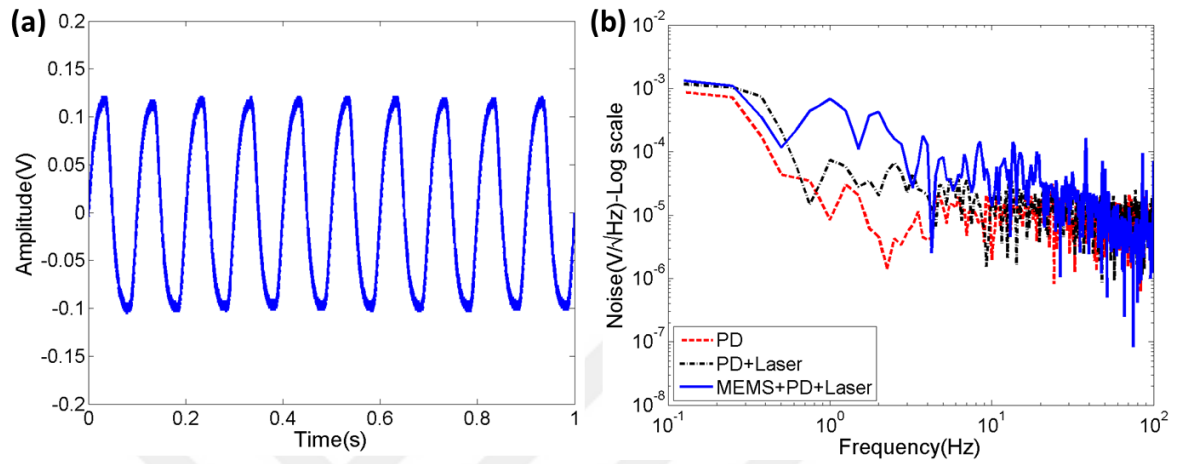


Figure 3-5: a) 10 Hz AC signal for 50 °C temperature difference b) Noise levels of the optical readout system with the contribution of the PD, Laser and MEMS device.

After the noise measurements, the total noise (MEMS+PD+Laser) between 0-30 Hz was integrated for extracting SNR and NETD of the system. The noise spectrum was limited to 0- 30 Hz as an ideal case to characterize the system as if one can capture 15 Hz video content for real time video applications. The SNR calculation is given in Equation (12), where V_s is the peak to peak signal level and Noise refers to the total noise measured for the system, as illustrated in Figure 3-5b. The noise power was then integrated, where the lower bound ($f1$) was taken as 0 and the upper bound ($f2$) as 30 Hz. Once SNR is determined, NETD can be calculated by taking the ratio of $\Delta T = 50$ °C to the SNR by using Equation (13). The NETD of the selected pixel, whose signal and noise levels are given in Figure 3-5, was calculated as 216 mK.

$$SNR = V_s / \sqrt{\int_{f1}^{f2} Noise^2} \quad (12)$$

$$NETD = \Delta T / SNR \quad (13)$$

As an alternative way, the NETD was also calculated according to the output given in Figure 3-5a without limiting the noise spectrum to 0-30 Hz while calculating the total noise. In this case the signal level is the mean of the peak to peak signal amplitude for different cycles at 10 Hz in Figure 3-5a. Similarly, the noise is the standard deviation of the peak to peak signal amplitudes for different cycles as different measurements. NETD was calculated as 303 mK using this approach that sets an upper bound for the noise performance. NETD calculation procedure was also applied to PD+Laser (optical) noise data (Figure 3-5b) to determine the contribution of optical readout noise. Then noise sources associated with MEMS and optical readout were extracted using:

$$NETD_{TOTAL} = \sqrt{NETD_{OPT}^2 + NETD_{MEMS}^2} \quad (14)$$

The $NETD_{OPT}$ was calculated as 166 mK whereas the $NETD_{MEMS}$ was found as 140 mK, as illustrated in Table 3-1.

Table 3-1: Experimentally Determined NETD Values

Noise Sources	NETD [mK]
NETD_{TOTAL} (MEMS Total Noise)	216
NETD_{OPT} (Optical Readout Noise)	166
NETD_{MEMS} (MEMS Noise)	140

Using a low-noise laser and photodetector will allow for approaching to the measured NETD limit of 140 mK, which is associated with MEMS, for our system. Additionally, theoretical calculations lead to an NETD level of 35 mK for the MEMS sensor, assuming thermo-mechanical sensitivity of 47.8 nm/K based on finite element simulations, 0.43 fill factor, 30Hz detection bandwidth, and 0.86 f#, calculated thermal conductance of 12×10^{-8} W/K and 80% IR transmittance. The discrepancy between theoretical and experimental NETD values associated with MEMS is attributed to the imperfections in the fabrication process possibly resulting in an increase for thermal conductance and a decrease in thermo-mechanical deflection. Furthermore, low frequency vibrations in our setup due to the vacuum pump also appear within 0-30 Hz bandwidth of the MEMS noise spectrum.

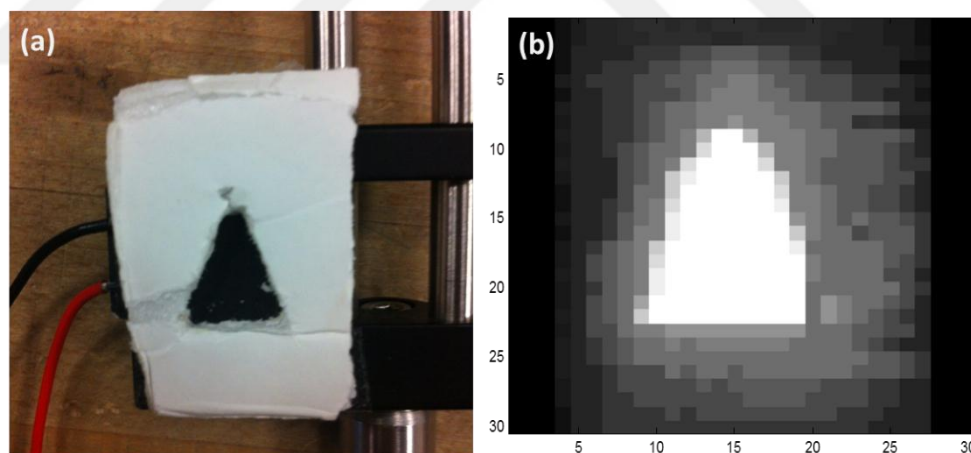


Figure 3-6: (a) Visible image of the target (b) Thermal image of the target.

In addition, thermal imaging was performed by using the selected pixel. A triangular mask, covering a TEC module was used as an IR target (Figure 3-6a). The temperature of the TEC was adjusted as $\Delta T = 15$ °C above room temperature. The TEC was placed before the chopper and mounted on an XY stage to scan the whole target with

100 μm step size at 30 steps in both x and y directions. The target was placed 500 mm in front of the IR lens, providing a demagnification of $\sim 10\times$ on the array. The response of the single pixel readout was recorded as a peak to peak voltage value. Then the data was processed and registered as a thermal image as shown in Figure 3-6b. The temperature levels lie between 30 – 45 $^{\circ}\text{C}$ for the lowest and highest observed temperatures respectively.

3.4 Fabry-Perot Interferometric Readout

Previously, diffraction grating based interferometry was used for the optical readout of the MEMS cantilevers. In this subsection, another interferometric approach is proposed to facilitate the optical readout, which is called the Fabry-Perot readout. Figure 3-7a displays the side view of the single IR pixel with the Fabry-Perot readout. In order to form the cavity a thick Al layer was used as a top reflective mirror, where as another thin layer of Al was used as a half reflector. The laser light was sent from the backside of the pixel through the glass substrate. The mechanical structure of the pixel, which was shown in Figure 2-15 (Design # 4), was designed to allow piston like out-of-plane motion to avoid the tilt errors.

The optical output of the cavity structure, namely the reflectance, was simulated in MATLAB using the transfer-matrix approach in a multi-layered medium [108]. A uniform plane wave illumination was assumed. The MEMS single pixel was considered as a multilayer medium including the glass substrate, half mirror, air gap, SiNx membrane and the top reflector. The thickness and the refractive index of the quartz substrate was assumed as $t_{\text{glass}}=525\ \mu\text{m}$ and $n_{\text{glass}}=1.51$ respectively. The initial air gap was assumed as 2.5 μm . The thickness and the refractive index of the SiNx membrane was assumed as $t_{\text{SiNx}}=200\ \text{nm}$ and $n_{\text{SiNx}}=1.51$. The reflectance of the top mirror was 0.9 and the half mirror was 0.5, which were extracted from the reflectance measurements of Al layers with different thicknesses. The transmittance of the half mirror was measured as 0.25.

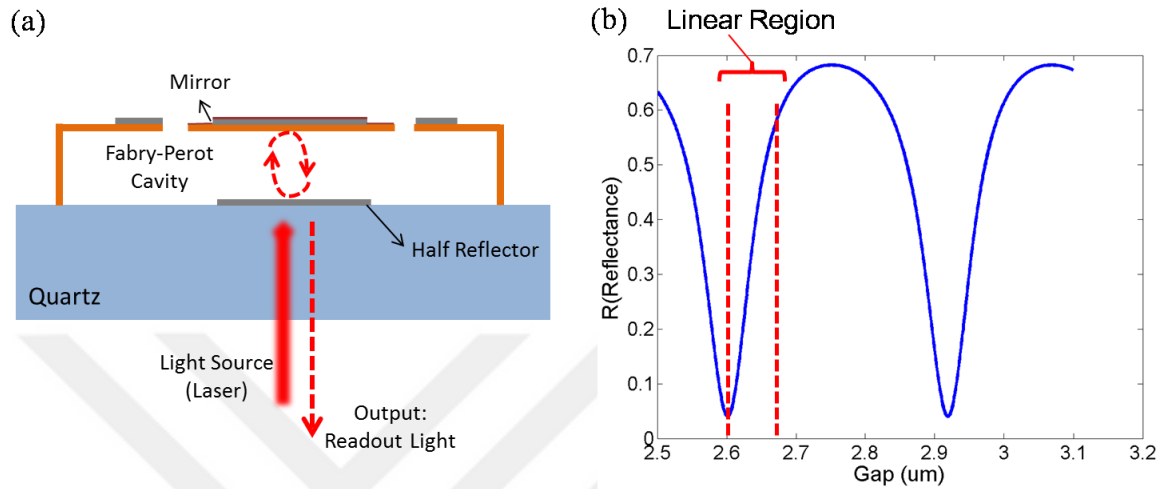


Figure 3-7: (a) Side-view of an IR pixel illustrating the Fabry-Perot readout (b) The reflectance of the Fabry-Perot cavity Intensity of light going to diffraction orders as a function of the distance from the top mirror to the bottom half reflector.

Figure 3-7b was obtained from the MATLAB simulations by varying the length of the air gap using the given thickness, reflectance and refractive index parameters. The linear region displayed in Figure 3-7b is the desired operation interval due to the linearity with a high slope. The MEMS chip is placed on top of a TEC in vacuum chamber. Therefore, one can change the temperature of the TEC to adjust gap of the pixel in order to operate in the linear region.

For the characterization tests, a similar variation of the experimental setup in Figure 3-4 was used. A black painted TEC was used as an IR object, which was heated up to 50 °C. The background temperature was 30 °C. The response of the single Fabry-Perot MEMS pixel to the IR object, which was chopped at 4 Hz, is given in Figure 3-8a. The peak-to-peak signal level was around 200 mV for the temperature difference of $\Delta T = 20$ °C. The noise measurement was performed during the “OFF state” of the IR target to use in the calculations of the NETD. Figure 3-8b depicts the noise levels of the MEMS pixel with Fabry-Perot cavity. The NETD was calculated as 178 mK using the AC coupled photodetector.

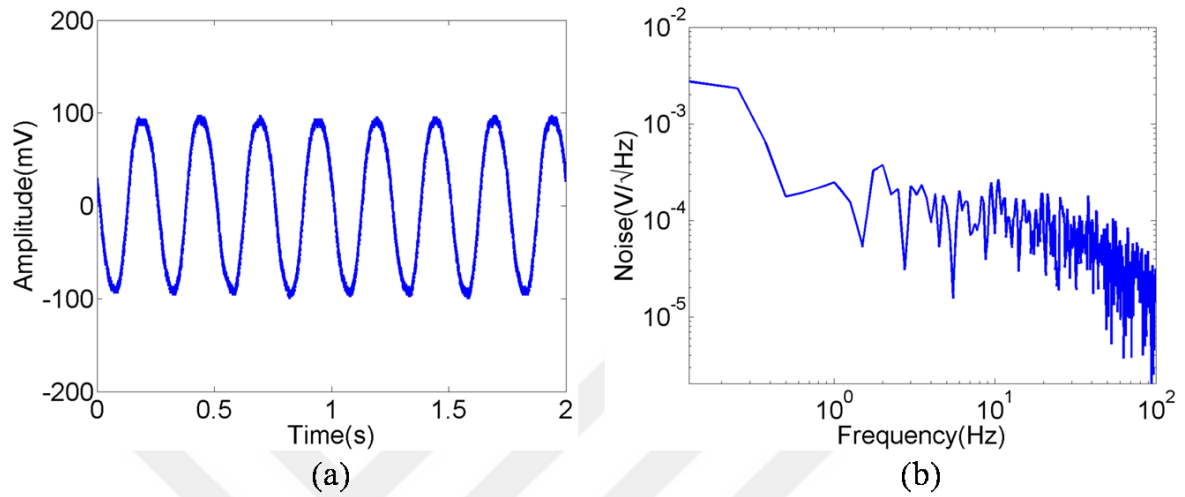


Figure 3-8: (a) AC coupled photodetector signal obtained using a chopper blade (at 30°C) rotating at 4 Hz placed in front of an IR target (at 50°C) for the Fabry-Perot optical readout system (b) Noise levels of the Fabry-Perot optical readout system.

The AC-coupled implementation of the Fabry-Perot readout provided an improved sensitivity for the detection of IR radiation. The performance of the CCD readout was also carried out with the same MEMS pixel. The black painted TEC providing the same temperature difference of $\Delta T = 20^\circ\text{C}$, was used for the CCD experiments. The CCD, used in the experiments, is an 8 bit camera. The CCD image of the single pixel was given in Figure 3-9a with the zoomed in beam profile. Figure 3-9b shows the signal obtained from the single pixel for OFF-ON-OFF states of the black painted TEC ($\Delta T = 20^\circ\text{C}$) with the CCD readout. NETD was calculated as 600 mK for the CCD readout using the binning of 29x29 CCD pixel, which formed the “zoomed in” image. The Fabry-Perot MEMS pixel offers high sensitivity even with 5x5 and 3x3 binning ($\text{NETD} < 1.5\text{K}$) as it is illustrated in Figure 3-9c,d .

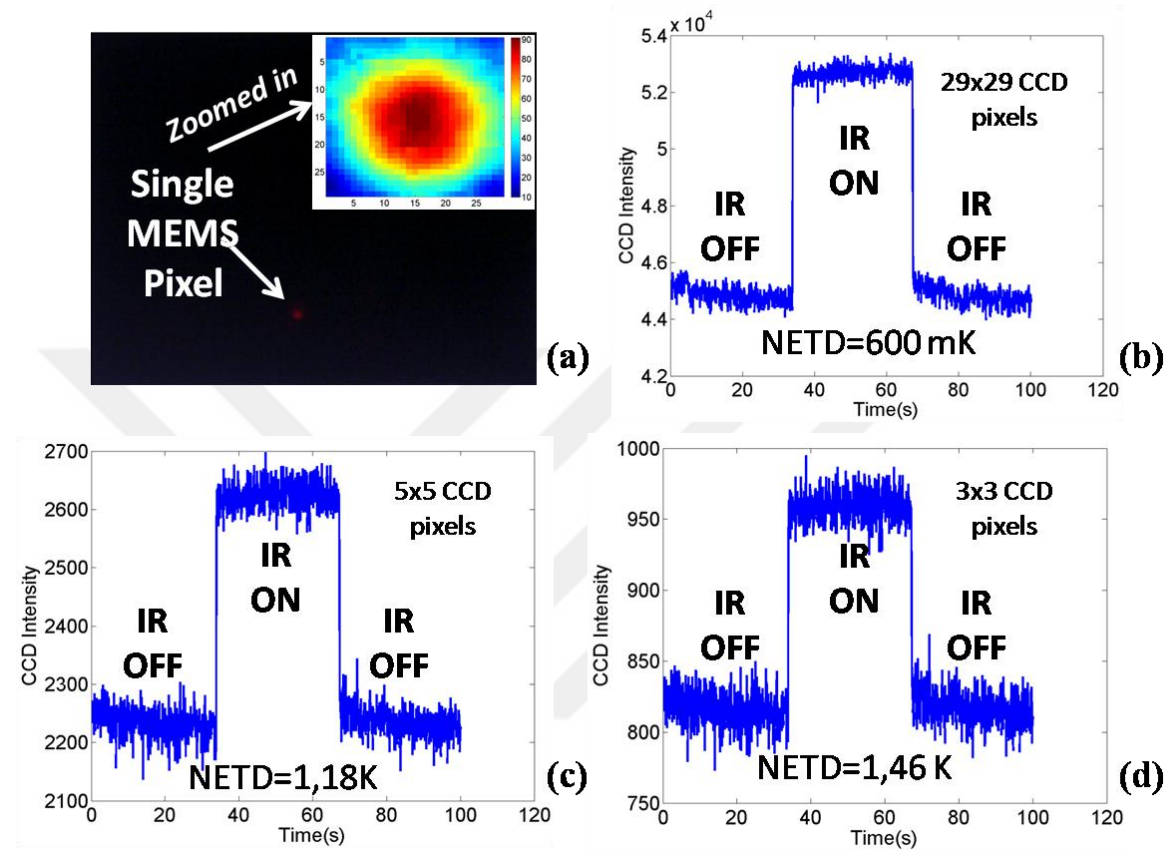


Figure 3-9: (a) Single MEMS pixel on the CCD image with the zoomed in version showing the beam reflected light profile. (b) Signal obtained from the single pixel from a temperature difference of $\Delta T = 20\text{ }^{\circ}\text{C}$ for OFF-ON-OFF states with 29x29 CCD pixels. (c) Signal obtained from the single pixel from a temperature difference of $\Delta T = 20\text{ }^{\circ}\text{C}$ for OFF-ON-OFF states with 5x5 CCD pixels. (d) Signal obtained from the single pixel from a temperature difference of $\Delta T = 20\text{ }^{\circ}\text{C}$ for OFF-ON-OFF states with 3x3 CCD pixels.

MEMS structures with Fabry-Perot cavity was fabricated as single test structures. It can simply be implemented to the arrays, which also has a sensitive performance with 8-bit CCD. It has the potential to achieve higher sensitivities (NETD~200 mK) as an array with high bit depth cameras.

3.5 Performance Improvement using electronic approach

Figure 3-10 shows a single MEMS device with embedded diffraction gratings, where the diffraction orders have different reflection angles. The purpose of this scheme is reducing the DC component of the output by collecting 0th and -1st (or +1st order) diffraction orders at different photodetectors.

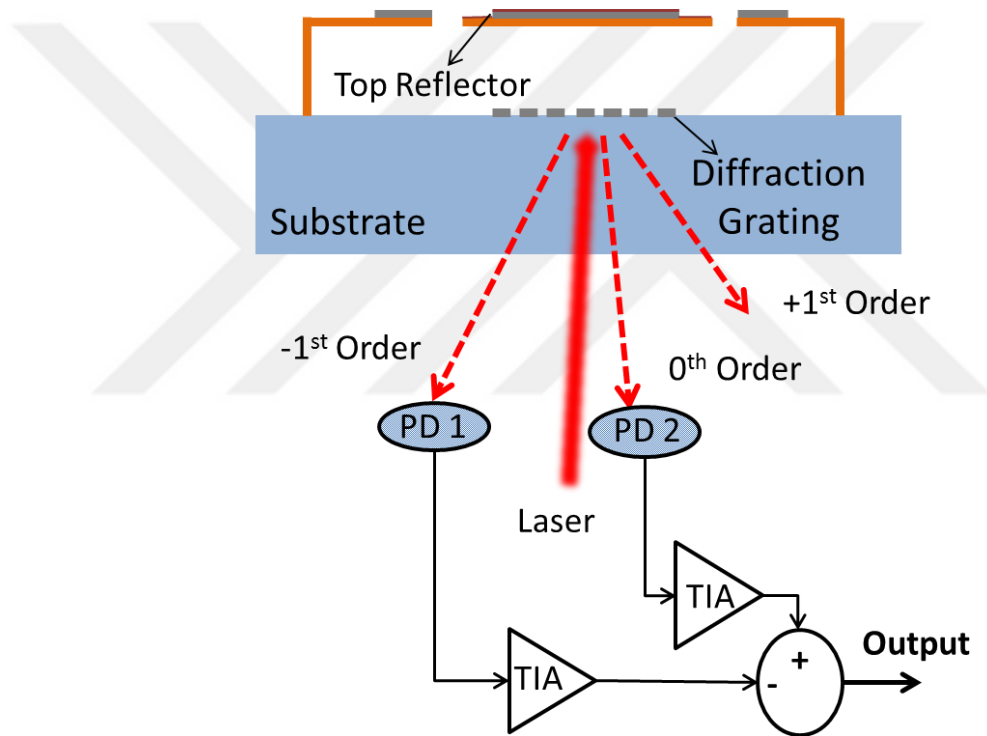


Figure 3-10: DC reduction using electronic approach

Since the 0th and -1st (or +1st order) diffraction orders have a phase difference of 180°, the signal level can be increased and the DC component of the output can be decreased by subtracting these diffraction orders as illustrated in Figure 3-10. Thus, the SBR and SNR of the output can be increased significantly at the same time.

In the experimental setup, Thorlabs PD-036A transimpedance amplified photodetectors were used instead of our custom AC-coupled photodetectors to demonstrate the signal

enhancement effect of our subtraction scheme. Figure 3-11 shows the response of IR target modulated at 10 Hz for the 0th and -1st diffraction orders with the subtracted output as a difference signal.

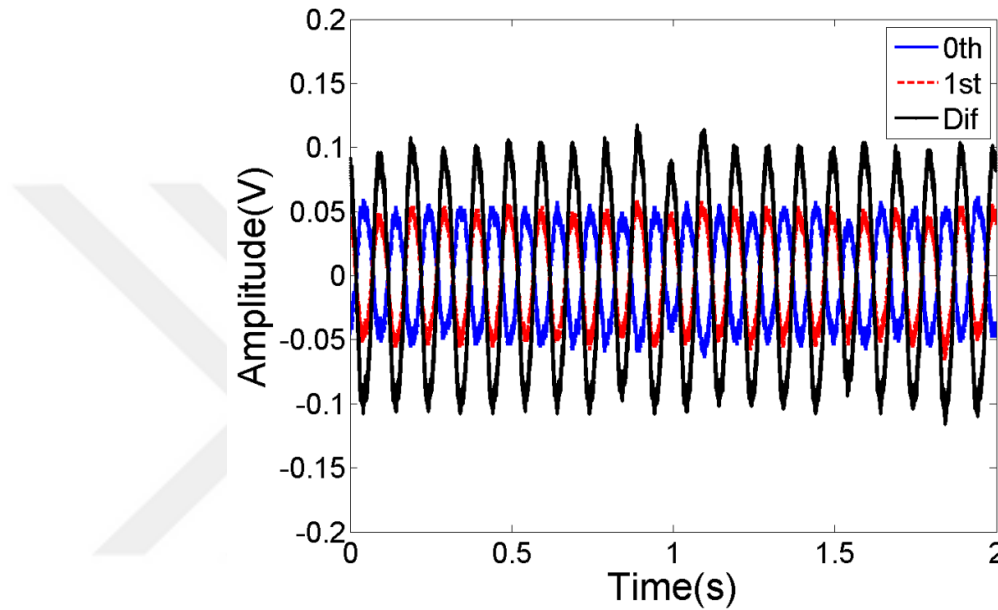


Figure 3-11: The response of the IR target (50 °C) modulated at 10 Hz for the 0th and -1st diffraction orders with the difference signal.

The 0th and -1st diffraction orders were collected at two different photodetectors by using a similar experimental setup that was shown in Figure 3-4. NETD was calculated as 1.3 K and 1.06 K for the 0th and -1st order respectively by using the AC signals. The photodetectors were connected to a low noise preamplifier (*SR-560 Low Noise Preamp*), where the subtraction operation was carried out.

The NETD value for the 0th order signal output of the same MEMS pixel was calculated 1300 mK, which is worse than the others due to having a large DC on the 0th diffraction order. The NETD value for the -1st diffraction order is better than the 0th order. But the difference signal has the best NETD, which was calculated as 700 mK using the DC photodetectors (Table 3-2).

Table 3-2: NETD values for different diffraction orders and the subtracted signal

Output Signal	NETD [mK]
NETD _{0th} (0 th order signal)	1300
NETD _{1st} (-1 st order signal)	1060
NETD _{Dif} (Difference signal)	700

Consequently, the proposed electronic approach improved the NETD of the MEMS based single IR detector by increasing the signal level and decreasing the useless DC component.

3.6 Lever Based Readout

One end fixed cantilever-type IR sensors are used with optical lever readout which has the same working principle with AFMs as previously mentioned. The incident optical beam deflects with a small tilt due to the thermo-mechanical motion. In this subsection, two different methods are analyzed for the intended optical beam deflections. Firstly, a knife-edge optical readout setup will be introduced for single sensor operation. Then, a novel prism-based readout approach will be explained in details [95]. Both methods will be compared theoretically and experimentally.

3.6.1 Knife-edge optical readout setup

Figure 3-12 illustrates the AC coupled optical readout setup for the knife edge method (KEM), utilizing tilting pixel structures and filtering at the knife-edge filter plane [109]. The laser light was focused onto a single sensor, placed in a vacuum chamber ($\sim 1\text{mTorr}$), and the reflected light was captured on a PD with a 4f optical system. The DC bias signal at the photodetector (PD) was eliminated to achieve AC-coupled sensing for a chopped IR target, which improves the noise performance. The PD was connected to a wide band-pass

filter, which was connected to a wide band-pass filter having a bandwidth of 88.5 Hz with the low and high 3 dB cutoff frequencies $f_{\text{LOW}}=1.5$ Hz, $f_{\text{HIGH}}=90$ Hz providing the AC-coupled sensing.

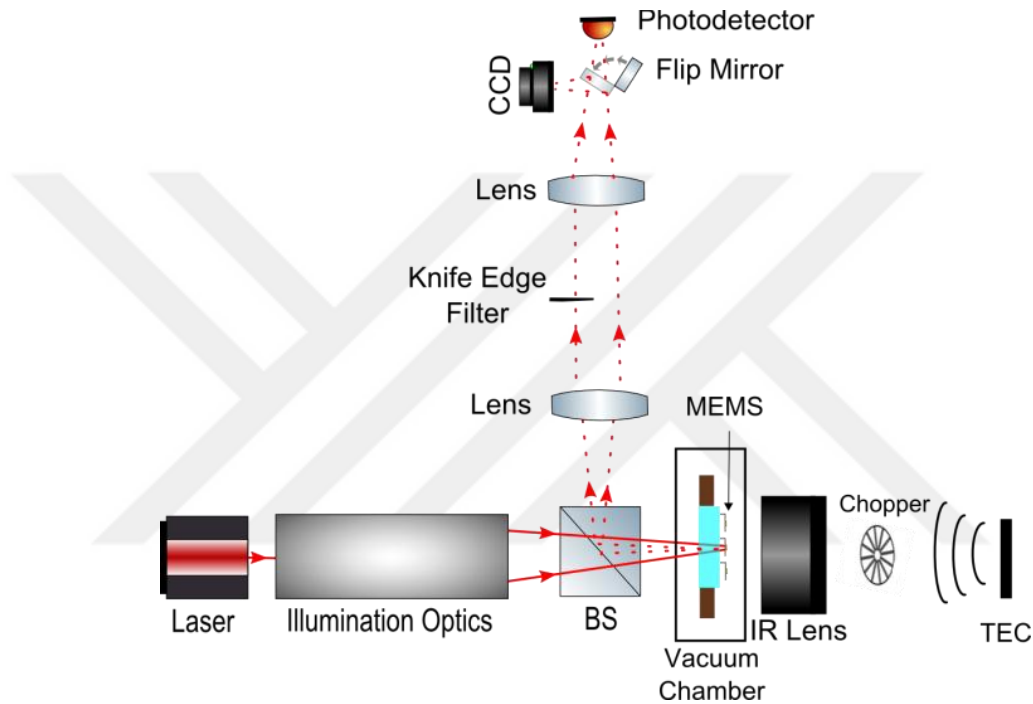


Figure 3-12: Experimental setup for the characterization of single sensor element using Knife-edge method, KEM. The CCD was used to check the alignment of laser with the selected sensor for single MEMS pixel operation.

The CCD camera was used for checking the alignment of the laser beam to the selected MEMS sensor for the single MEMS pixel operation as described in [9] for both methods. The knife-edge filter modulates the optical power and changes the intensity at the image plane with the sensor's tilt motion. The intensity data, in response to the chopped IR target, at the PD output was collected. A low noise preamplifier was exploited to limit the bandwidth by a unity gain low-pass filter with a cutoff frequency of 30 Hz. An oscilloscope and a signal analyzer were used to measure the signal and noise levels.

Finally, for both setups the intensity data, in response to the chopped IR target, is collected at the PD, which is connected to a wide band-pass filter a bandwidth of 88.5 Hz with the low and high 3 dB cutoff frequencies $f_{\text{LOW}}=1.5$ Hz, $f_{\text{HIGH}}=90$ Hz providing the AC-coupled sensing..

3.6.2 Prism-based optical readout setup

With an aim of further improving the response of the sensor, an optical readout method using a glass prism was developed so that the tilt angle of the sensor results in a change in the reflectivity of a glass-air interface, utilizing the critical-angle phenomena. Various prism based methods have been utilized before for angle sensing: (i) Reflection near the critical angle was used for highly sensitive position measurement for a single bulky mirror mounted on a rotational stage [110], (ii) A similar method, which uses non-polarized light in the optical readout, was also used as a readout method for bimaterial IR sensor arrays in order to implement optical background subtraction, however, at the expense of lower responsivity as opposed to polarized light and unilateral readout capability (works only for heating or cooling case) [111].

However, TM polarized wave was used in this framework. Because, it has higher responsivity on the reflectivity curve with respect to the incident angle of the incoming wave, as compared to a TE polarized or non-polarized wave near the critical angle. Furthermore, AC coupled optical detection was implemented for this scheme, too, for sensitivity enhancement and DC subtraction. Although the performance of this method was demonstrated by using a single pixel, prism-based optical readout is also suitable for array imaging. Figure 3-13 shows the proposed optical readout setup, which utilizes a critical angle approach for a TM polarized wave. The illumination optics for the prism-based readout is nearly identical to the knife-edge method (KEM), with the exception of an additional polarizer for polarization control. After being polarized and directed to the MEMS sensor, the laser beam reflects back to the beam splitter.

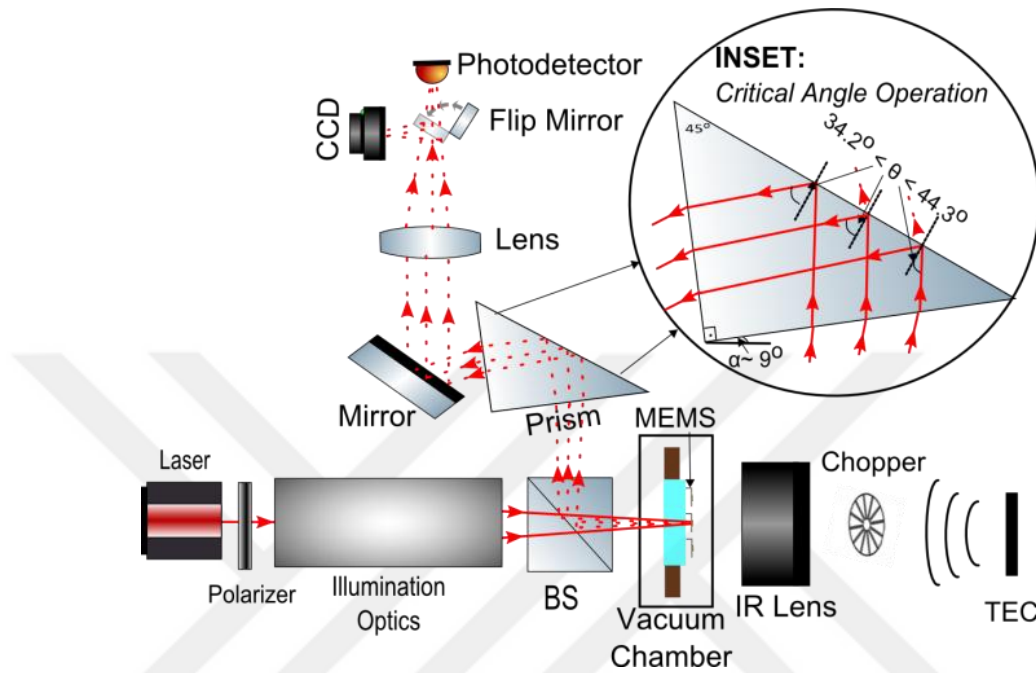


Figure 3-13: Experimental setup for the characterization of single sensor element using Critical Angle Method, CAM. The CCD was used to check the alignment of laser with the selected sensor for single MEMS pixel operation.

The key element of the proposed optical system is the glass prism. One has to provide an initial tilt position to the prism in order to obtain an operation with high responsivity as shown in the inset of Figure 3-13. Since the laser beam was focused onto the reflector of the MEMS pixel, the rays reflected from the MEMS reflector have different reflection angles, whose spread is based on the numerical aperture (NA) of the focusing lens and the size of the MEMS reflector. Therefore, the rays hitting the hypotenuse surface of the prism will have different angles with respect to the normal of the hypotenuse surface. In this case, the prism's hypotenuse plane (the glass–air interface) forms a virtual reflection matrix, which has different reflection coefficients corresponding to different ray angles. The change in the inclination angle of the MEMS sensor results in a change in the experienced reflectivity values. Therefore, there is no need for a Fourier lens or spectral

filtering for light modulation. Laser light that is reflected off the prism is collected via a lens at the PD which is connected to a wide band-pass filter a bandwidth of 88.5 Hz with the low and high 3 dB cutoff frequencies $f_{\text{LOW}}=1.5$ Hz, $f_{\text{HIGH}}=90$ Hz providing the AC-coupled sensing. Finally, the intensity data, in response to the chopped IR target, was collected at this AC-coupled PD for the single sensor operation.

3.6.3 Simulation Results

A simple model based on beam propagation was developed in MATLAB in order to compare the sensitivities of both methods. The numerical simulations of optical beam propagations were carried out by angular spectrum method [112]. In the model, firstly the IR target's temperature was defined and then the related mechanical motion of the single MEMS pixel was calculated. The target temperature from 25 °C to 525 °C was assumed and converted to the temperature change on the single MEMS detector. The calculation was based on 302:1 ratio between target and detector temperature that is determined by the thermal conductivity of the sensor, emissivity of the target, and IR transmittance of the system [58]. Then the temperature change on the single MEMS detector was converted to the corresponding sensor's mechanical tilt angle change based on the FEM findings. According to the calculations, 500 °C temperature difference corresponds to an angular displacement of 0.38° at the prism's entrance plane. The corresponding angle change after refraction through the prism and at the prism's hypotenuse plane was calculated starting from the MEMS top reflector. These angle calculations were used in the optical beam propagation simulations, which were performed for knife-edge and prism-based critical angle method.

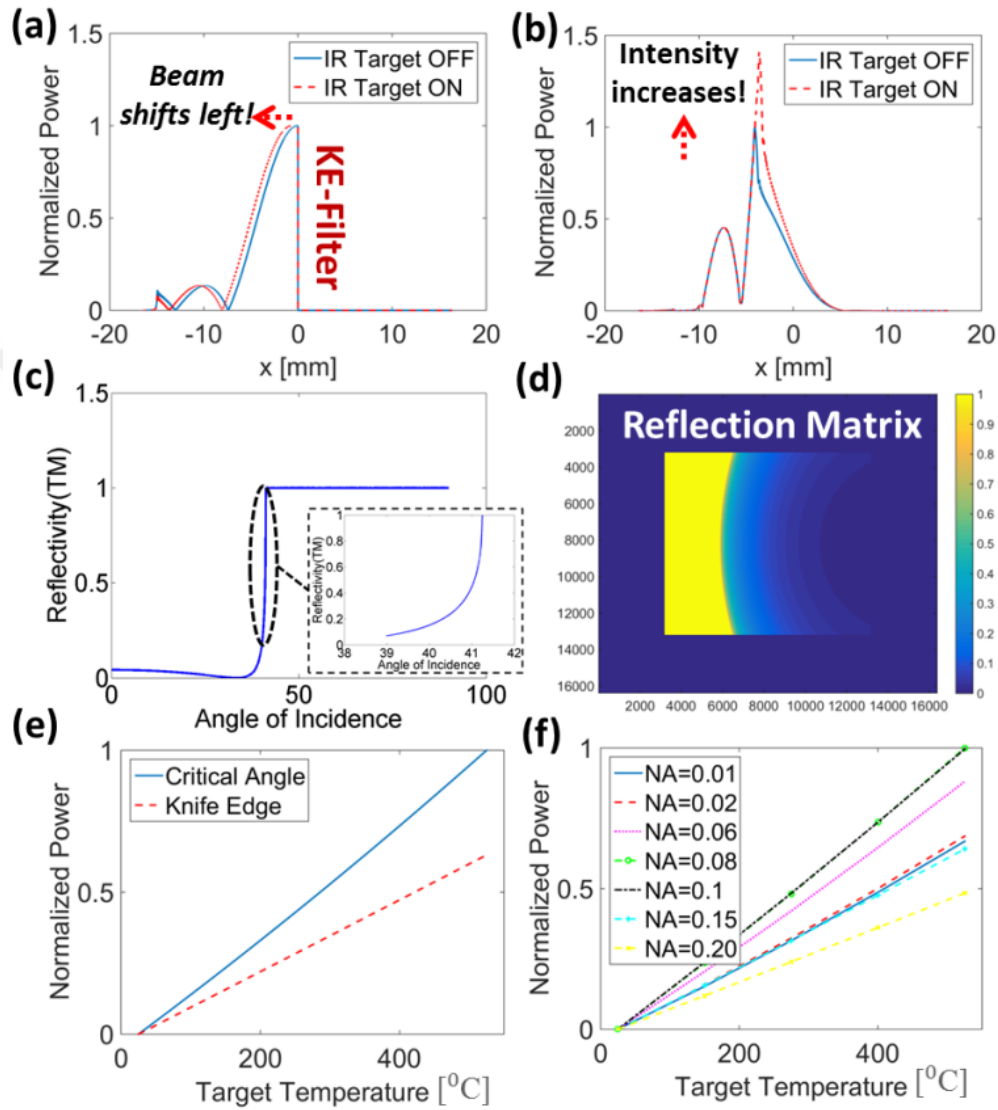


Figure 3-14: Beam propagation simulation results (Sample intervals in space domain are $dx=dy=2 \text{ } \mu\text{m}$.) showing the cross-sections ($y=0$) of the beams according to the two different target temperatures ($25 \text{ } ^\circ\text{C}$ and $525 \text{ } ^\circ\text{C}$) for (a) Knife-edge method, KEM (b) Critical angle method, CAM. (c) Reflectivity of a glass ($n=1.51$) – air interface ($n=1$) for TM polarization. (d) Reflection matrix at the prism (glass-air) interface. (e) Comparison of normalized power changes for both approaches at PD w.r.t. different target temperatures. (f) Results for the normalized power changes at PD w.r.t. different target temperatures using CAM for different illumination angles.

For the KEM propagation simulations, the red laser beam ($\lambda=633$ nm) having 12 mm diameter after magnification, was first focused on the MEMS pixel via a lens ($f=100$ mm). The light reflected from the square MEMS reflector was then back-propagated. Then the beam was collimated with another lens ($f=100$ mm) after propagating a 100 mm distance from the pixel and reaching its initial size. The beam was then knife-edge filtered, blocking half of the beam [66, 85], at room temperature. Figure 3-14a shows the spatially filtered beams demonstrating KEM simulation just after the knife-edge filter. The change of detector temperature causes the MEMS sensor to tilt, which shifts the beam position at the knife-edge plane, resulting in a change of detected optical intensity.

In the CAM, the mechanical tilt motion due to the detector temperature change was directly converted to a change in the incident angle on the prism's glass-air interface, which affects the reflection experienced by the beam. The simulation includes the effects of different angles coming from the MEMS reflector, based on the NA of the focusing lens and the size of the MEMS reflector. These different angles correspond to a reflectivity matrix with different reflection coefficients that is formed on the prism's glass-air interface for a TM polarized wave. The change of the beam position with respect to the reflection matrix leads to an increase for the intensity of the light at the PD plane (Figure 3-14b), owing to the significantly increased reflection coefficients. The secondary lobe of the beam profile in the horizontal direction was significantly enhanced due experiencing a high reflection coefficient.

Figure 3-14c illustrates the reflectivity of a glass ($n_{\text{glass}}=1.51$)-air ($n_{\text{air}}=1$) interface with respect to the angle of incidence. The inset shows the change of the reflectivity around $39^\circ < \theta < 41^\circ$, where the brighter parts of the beam was exposed to a reflection change with a high responsivity. In our model, the initial tilt angle of the prism was optimized as $\alpha=9^\circ$, resulting in maximum responsivity. The reflection angles vary in the range of $34.2^\circ < \theta < 44.3^\circ$ at the prism's glass-air interface for our simulation window that is

limited by the aperture size of the prism. The simulation takes the entire angle spread into account, which forms the 2D reflection matrix at the prism's glass-air interface, as illustrated in Figure 3-14d.

Figure 3-14e compares the change of normalized intensity for both KEM and CAM. Background subtraction was applied to the beams at the room temperature for both methods to focus on the changes in the scene. Therefore, the normalization took place through linear mapping of the power increase obtained for the CAM to values between 0 (25 °C room temperature) and 1 (525 °C target). Since the angle change at the prism's reflector plane is very small ($\Delta\theta = 0.25^\circ$) even for a 525 °C target, the change in the reflectivity and in the power of the optical signal is considerably linear with a maximum deviation of 3% from the linear fit. Assuming an NETD of 150 mK, our method's dynamic range will be 3500 which corresponds to nearly 12 bits. Furthermore, the change in the signal power for a 50 °C target is perfectly linear due to an even smaller angle change. The same linear transformation was applied on the KEM results, revealing a normalized intensity change of 0.63. We conclude that the critical angle approach provided a higher sensitivity than the conventional KEM.

Lastly we analyzed the effect of the angular spread of the beam on the responsivity of the optical readout. The NA of the illumination optics is 0.06 for the previous simulations, which exhibits one of the higher responsivities (Figure 3-14f). For the smaller NA case (NA=0.01-0.02), the diffraction spread related to the MEMS reflector size will be dominant. For the larger NA case (NA=0.15-0.20), the angular spread depends on the NA itself. As a result, NA can be optimized for a better responsivity by considering the size of the MEMS reflector.

3.6.4 Single Pixel Characterization

A black painted TEC was used as a blackbody target for the single pixel characterization and it was calibrated with an IR thermometer (EXTECH / IR201A).

Firstly, the single MEMS pixel was imaged using a CCD (Figure 3-15a). Then, the related image area was determined and processed in MATLAB for the detection characterization (Figure 3-15b). The blackbody target at 75 °C was turned ON after 2.5 seconds from the starting of the record and turned OFF again. The signal was plotted for this OFF-ON-OFF state in Figure 3-15c.

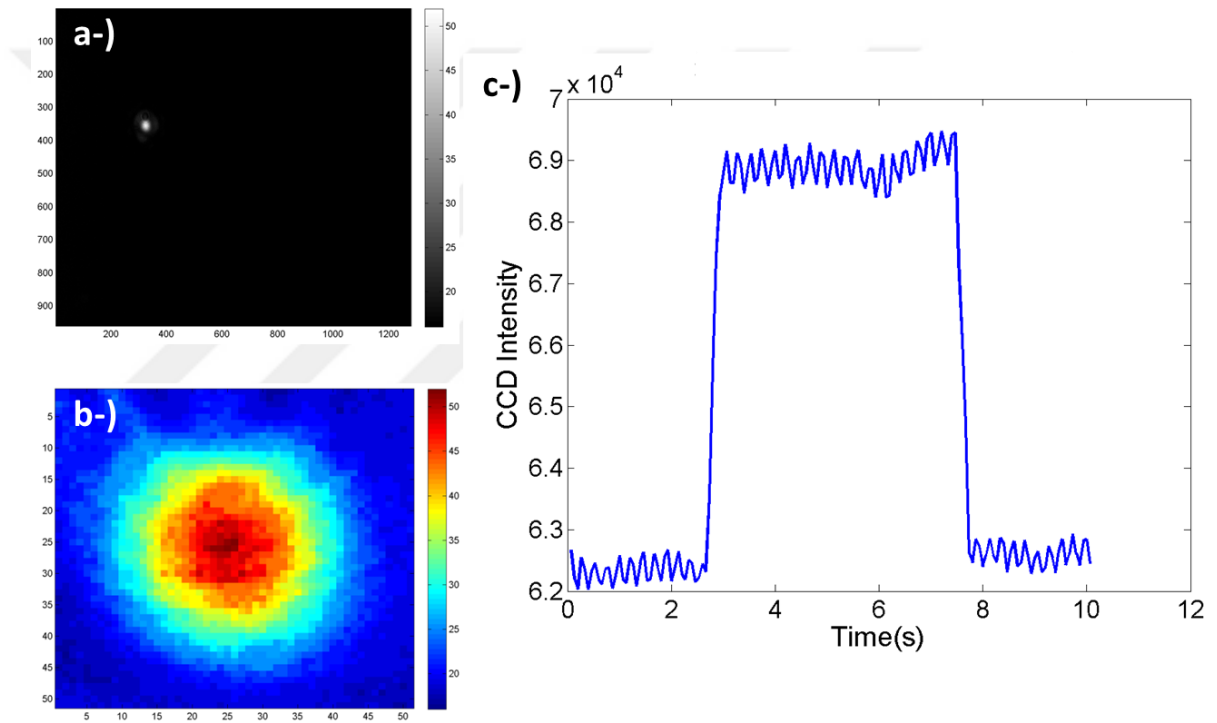


Figure 3-15: (a) Single MEMS pixel on CCD image (b) Zoomed in single pixel image area, which will be used for the IR detection characterization (c) Signal obtained from the single pixel in front of an IR target (at 75°C) for OFF-ON-OFF states.

The NETD of the single MEMS pixel was calculated from this plot. The SNR was determined according to the signal level and the standard deviation of the OFF state signal. The NETD for this single pixel was calculated as 2.1 K with CCD readout.

After that, the single pixel was characterized using the KEM and CAM. In order to do that, the DC light levels of the optical setup were equalized at the PD for both methods by placing neutral density (ND) filters within the “illumination optics” part of the optical setup at room temperature. The target temperature was decreased to 50 °C and the radiation of the 50 °C target was chopped at 10 Hz. The responses of the selected sensor for both KEM and CAM are shown in Figure 3-16a. The location of the knife-edge filter for KEM and the tilt angle of the prism for the CAM were optimized to obtain the maximum signal levels. The peak-to-peak signal level was observed to be 33 mV for the CAM and 22 mV for the KEM, exhibiting a 50% increase in the signal level. The amount of improvement in the signal output, perfectly matches our findings based on beam propagation simulations.

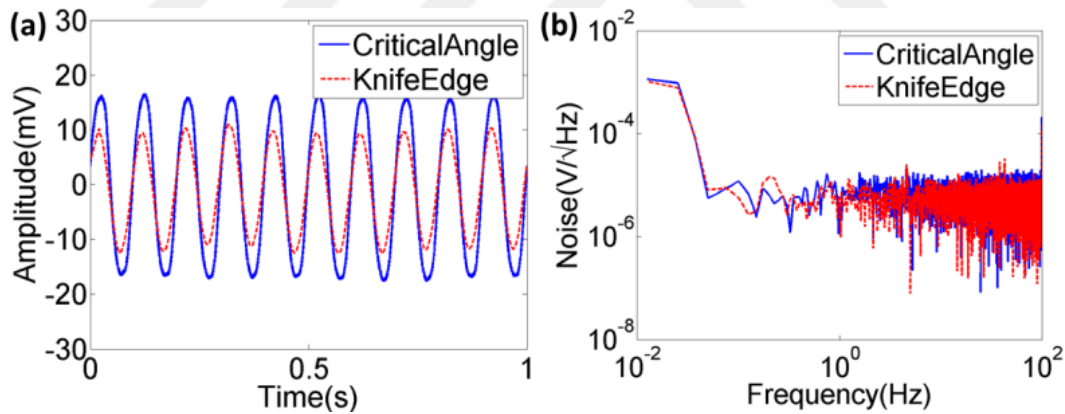


Figure 3-16: (a) AC coupled photodetector signal obtained using a chopper blade (at 25⁰C) rotating at 10 Hz placed in front of an IR target (at 50⁰C) for knife-edge method (KEM) and Critical angle method (CAM). (b) Noise levels of the optical readout system for both methods.

Figure 3-16b shows the noise levels for both methods at room temperature, which exhibit similar characteristics due to the mentioned equalization of the DC light levels at the PD. We integrated the noise between 0-30 Hz for extracting SNR and NETD of the system. The noise spectrum was limited to 0 - 30 Hz as an ideal case to characterize the

system, as capturing 15 Hz video content with Nyquist rate, for real time video applications.

Table 3-3: NETD Values For Different Optical Readout Methods

Optical Readout Method	NETD [mK]
<i>Critical Angle</i>	154
<i>Knife-Edge</i>	200

NETD values were calculated according to a target with a temperature difference of $\Delta T = 25^\circ\text{C}$. The NETD values of the selected sensor for both methods are given in Table 3-3. The experimentally determined NETD values are 154 mK for CAM and 200 mK for KEM using an f/0.86 IR lens. Critical angle approach decreased the NETD of the IR sensor 25%, revealing a significant improvement in the system sensitivity for the indicated target temperatures. The improved NETD value of 154 mK is comparable to the state-of-the-art bimaterial IR sensors that are larger in size [48, 65, 66, 72, 85], owing to the prism-based and AC-coupled readout.

3.7 Conclusion

IR characterization of a $35\text{ }\mu\text{m}$ pixel pitch thermo-mechanical MEMS detectors was presented in this chapter. Firstly, a unique mechanical design employing piston-like out-of-plane motion has been proposed that is compatible with a diffraction grating based optical readout. The low-noise, single pixel AC coupled optical readout significantly isolates the noise associated with the MEMS pixel only. The NETD of the selected MEMS pixel was measured as 216 mK, with which a thermal image was also acquired through scanning the target. The theoretical NETD was calculated for the MEMS as 35 mK without the optical readout noise which implies that the fundamental limit for NETD is below 50 mK using this pixel design with the further development of the implemented method. Further

improvement in spatial and temperature resolution of thermo-mechanical MEMS detectors is possible using this method.

Secondly, a pixel-level Fabry-Perot cavity type optical readout method was facilitated for thermo-mechanical MEMS detectors for the first time. This optical readout method resulted in very high sensitive detection that the measured NETD was around 170 mK with AC-coupled PD and 600 mK with an 8 bit CCD camera.

Lastly, a novel optical readout method using a single prism was developed, employing detection at the glass-air interface of the prism for a TM wave near the critical angle. This approach was compared with the conventional KEM for an IR sensor. Both methods employ AC-coupled sensing that responds only to the changes in the scene to eliminate DC bias signal, and thus DC noise component, at the PD. NETD for a single sensor was measured as 200 mK using the KEM, and 154 mK for the CAM, revealing a 25% improvement of sensor sensitivity accompanied by %50 improvement in the signal amplitude. The difference between the improvements in the sensor sensitivity vs. the signal amplitude is caused by slightly different noise levels, possibly due to random vibrations that are induced in the setup. The proposed CAM offers high sensitivity through precise tuning of the initial angle of incidence by rotating the prism. The CAM approach is also adaptable to array imaging through collimated illumination. For the array operation, the diffraction spread will solely be determined by the aperture (MEMS reflector) size, which will in turn set the initial prism angle for optimal responsivity. Non-uniformity in the arrays may be a problem for both CAM and KEM as each pixel will have different initial angles and sensitivity levels. Non-uniformity can be fixed through the use of look-up tables or a shutter temperature calibration routine.

Despite 35 μm pixel pitch, the measured NETDs with the proposed methods are comparable to the state-of-the-art thermo-mechanical IR sensors that are larger in size [48, 65, 66, 72, 85]. The readout methods have been demonstrated for single MEMS detector

based IR sensing applications. The method is also applicable to other types of sensors, where optical displacement readout is implemented. The AC coupled optical readout method is favorable for single element operation, but for the array structures a custom smart pixel camera should be designed.



4 MEMS Array Readout for Thermo-mechanical IR Sensors

In the single pixel readout configurations, the laser beam is focused onto a single MEMS pixel. However, in the array readout, generally collimated beam with a uniform illumination on the whole array is implemented to acquire signal from each element of the array with an aim of imaging. The optical readout methods for the array readout are similar with the single pixel readout configurations. Diffraction grating interferometer and optical beam deflection based readout methods have been used with thermal sensor arrays for a long time [58, 65, 66, 72, 84]. But the theoretical findings reveal that there is further room for improving the performance of these detectors [58, 64, 91]. For this purpose, interferometric optical readout method for diffraction-grating based thermo-mechanical IR sensors is explained with two different new approaches: Converging Optical System and Two Wavelength Solution using LED.

In the Converging Beam Optical System, it is focused on two different optical setups to improve the performance of the detectors: a 4-f imaging setup and a converging beam optical setup. The setups were evaluated based on performance and system complexity [91]. Secondly, a novel two-wavelength optical readout for grating readout, which uses a two color LEDs butt-coupled to a multi-mode fiber, will be introduced. This system provides spatial auto-registration of two different color images on a single RGB camera. Lastly, the lever based thermo-mechanical IR sensors for the array readout will mainly be discussed.

4.1 4f Optical System

4f optical systems consist of a cascade of two lenses, which are implementing two Fourier Transforms. The spatial filtering at Fourier plane is critical for the array readout in

order to image the array accurately. This system can be used for thermo-mechanical sensor arrays with or without gratings. In the optical system as shown in Figure 4-1, light source beam is collimated to illuminate the FPA of the MEMS pixels with diffraction grating by using a tilted mirror. The angle of the tilted mirror in this configuration might be arranged such that 1st diffraction order of the light beam propagate on axis to the image plane. After meeting this condition, the +1st order diffraction order reflected from FPA goes through a 4f optical system into the CCD. The conventional 4f optical system includes 2 identical spherical lenses, and a pinhole as a spatial filter. The distances between FPA & 1st lens, 1st lens & pinhole, pinhole & 2nd lens, are set as the focal length of the identical spherical lenses (f). Furthermore, image plane is focal length f away from the 2nd lens. Therefore, the transmission function of FPA is Fourier transformed by the 1st lens, the wave function at the pinhole is the Fourier transformation of this transmission function. The pinhole is used at the Fourier plane to filter out the 1st order diffracted light and to block the 0th and other diffraction orders. Likewise, the wave function at the image plane is the inverse Fourier transformation of the wave passed through the pinhole [6].

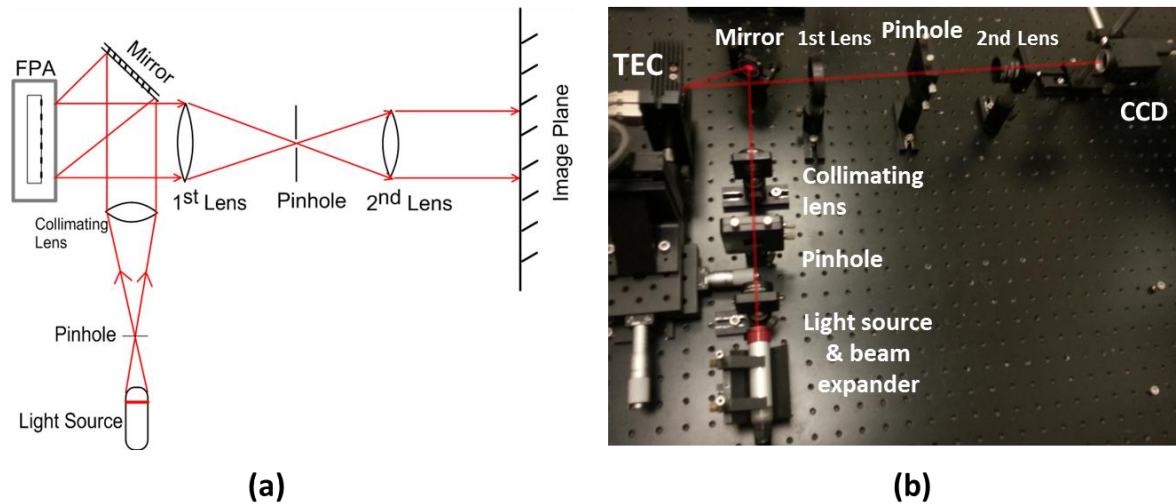


Figure 4-1: 4f Optical System: (a) Schematic (b) Experimental setup

The experiments were performed in ambient to evaluate the performance of the MEMS FPA using a TEC. MEMS device was mounted on the TEC using thermal glue. Figure 4-1b illustrates the experimental setup. A light source with a beam expander passes through the system in Figure 4-1a and captured by a CCD camera at the image plane.

4.2 Converging Beam Optical System

In contrast to plane wave illumination described in 4-f setup, convergent beam illumination was employed in this configuration. As shown in Figure 4-2a, a lens was used after the light source in order to send a converging beam to the FPA. The source was tilted such that -1^{st} diffraction order can propagate on the same axis. Only one lens was used to form the image after FPA and again a pinhole was used as a spatial filter at the Fourier Plane to get the best image.

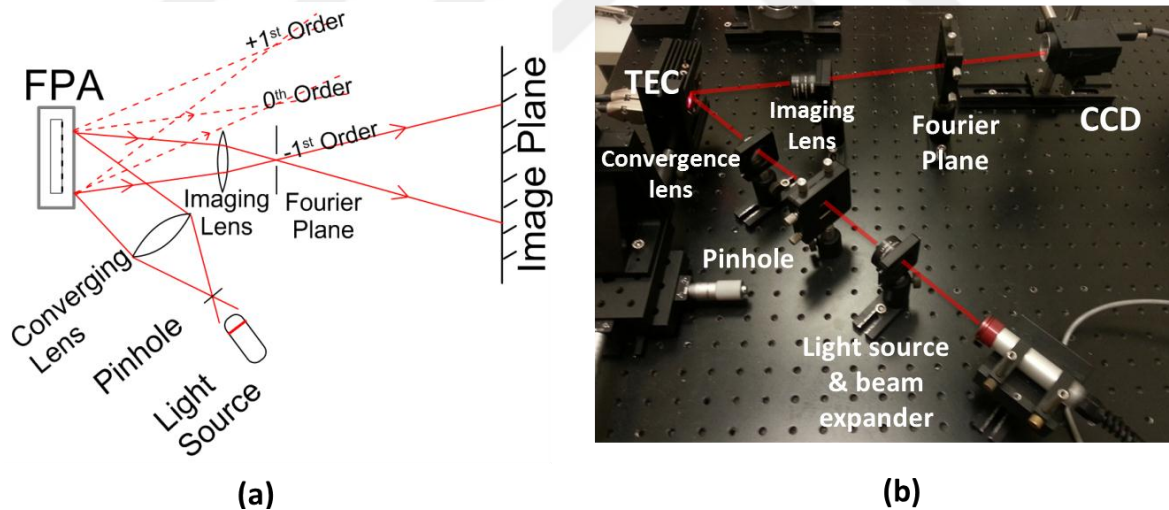


Figure 4-2: Converging Beam Optical System: a. Schematic b. Experimental setup

Converging beam setup was realized by using an off-axis converging laser beam illumination that forms the Fourier plane near the imaging lens. -1^{st} order diffracted light remains on-axis due to off-axis illumination. It was filtered out and it forms the image of

the detector pixels on the CCD. This approach has important advantages such as reducing the number of optical components and minimizing the optical path and offers better image quality due to compact, on-axis imaging optics. The experimental setup is illustrated in Figure 4-2b and the experimental procedure is same with the one discussed in the previous section.

Table 4-1: Converging Beam Optical System Parameters

System Parameters	Value	System Parameters	Value
Wavelength (λ)	633 nm	Imaging lens – CCD distance (d_3)	24 mm
Grating pitch (Λ)	3 μ m	Imaging lens focal length (f)	13.3 mm
Pixel size (P)	35 μ m	Incident beam - -1 st order separation at the Lens Plane (l_1)	6.65 mm
FPA length in horizontal axis	5.6 mm	0 th - 1 st order separation at the Lens Plane (l_2)	6.48 mm
Magnification of the system (M)	0.8	Filtered 1 st order beam size at the Fourier Plane (w_2)	2.1 mm
Converging lens - FPA distance (d_1)	30 mm	Lens aperture size	6.48 mm
Imaging lens - FPA distance (d_2)	30 mm	1 st order beam size filtered at the Fourier Plane	2.1 mm

The system parameters in Table 4-1 were optimized considering parameters such as converging lens location, laser beam size at the MEMS chip, magnification of the imaging system, the distances from chip to light source, lens and CCD. We adjusted the magnification based on the MEMS chip size, and the CCD's chip size to capture the entire detector array on the CCD. Laser convergence angle can be arranged by changing the location or the focal length of the converging lens such that the laser beam size is equal to the 160x120 formatted FPA at the TEC. Meanwhile the location of the Fourier plane can be adjusted near the imaging lens or even on the imaging lens without using any spatial filter. Imaging Lens – CCD Distance (d_3) was calculated by multiplying the magnification

of the system with the Converging Lens - FPA Distance (d_1). The focal length of the imaging lens was chosen according to d_2 and d_3 related to imaging condition.

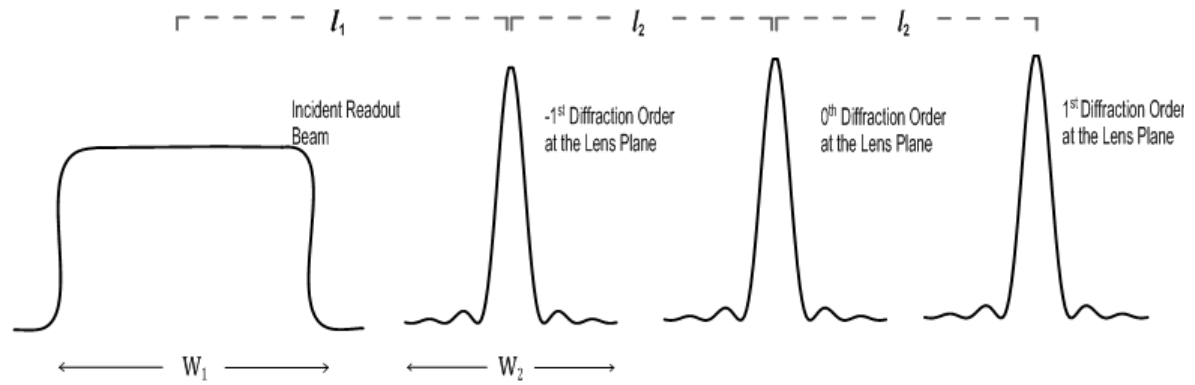


Figure 4-3: Beam width analyses for the converging optical setup at the Fourier Plane

Figure 4-3 shows incident beam – -1^{st} order separation (l_1) and -1^{st} - 0^{th} - 1^{st} order separations at the lens plane (l_2). The incident readout beam width w_1 in one axis is twice the FPA length related to the equally chosen d_1 and d_2 parameters given in Table 4-1. Similarly w_2 was chosen according to the filtered -1^{st} order at the Fourier Plane, where three peaks were chosen in our configuration depending on taking the sharpest image on the CCD. The input parameters were arranged such that the size of the optical system in Figure 4-3 was minimized while diffraction orders were well separated. Equation (15) and (16) show how to calculate these system parameters w_2 , l_1 , l_2 at the lens plane.

$$w_2 \cong 3 \frac{\lambda}{P} d_2 \quad (15)$$

$$l_1 \geq \frac{w_1}{2} + \frac{w_2}{2}, \quad l_2 \cong \frac{\lambda}{\Lambda} d_2 \quad (16)$$

Ray tracing simulations using the system parameters in Table 4-1 were performed using Zemax optical design software as illustrated in Figure 4-4. A slowly converging beam was achieved using the converging lens, which provides illumination beam on the FPA and defines the position of the Fourier plane. The rectangular aperture on the grating structure was used for image analysis. The absorber plate was used to block $m=0^{\text{th}}$ order (shown in green) and $m=+1^{\text{st}}$ order (shown in red) while $m=-1^{\text{st}}$ diffraction order (shown in blue) was used for imaging. The image of the rectangular aperture can be seen in Figure 4-4.b as a detector image.

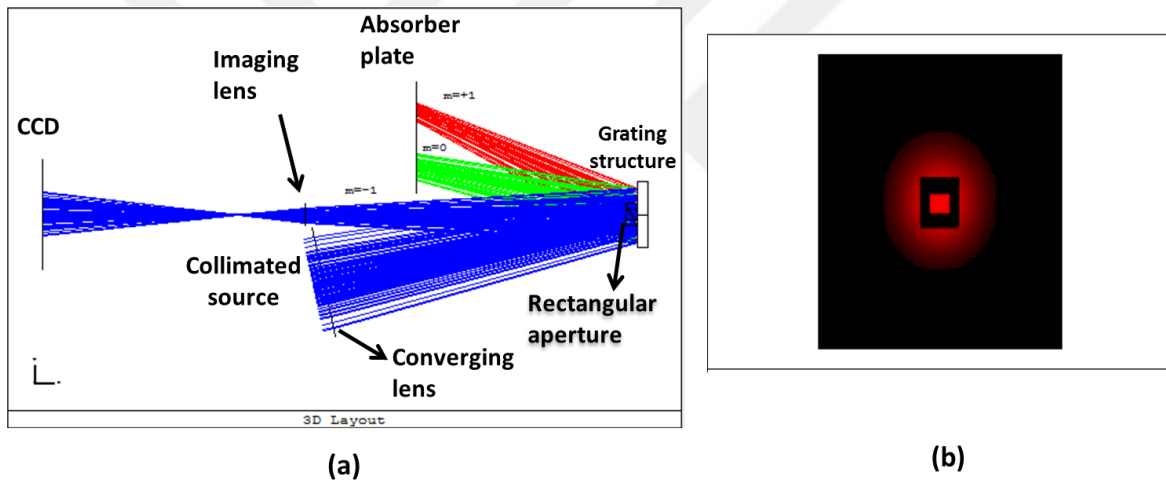


Figure 4-4: a. Ray tracing of Converging Beam Optical System with a rectangular aperture on grating structure using Zemax Optical Software b. Detector Image

The size of the system in Figure 4-4.a is almost 60 mm in horizontal and 30 mm in vertical excluding the size of the laser. It is possible to further decrease the size of the optical system using a fold mirror as illustrated in Figure 4-5 to 40mm x 30mm. The size of the setup scales linearly with the dimensions of the illumination beam and the FPA.

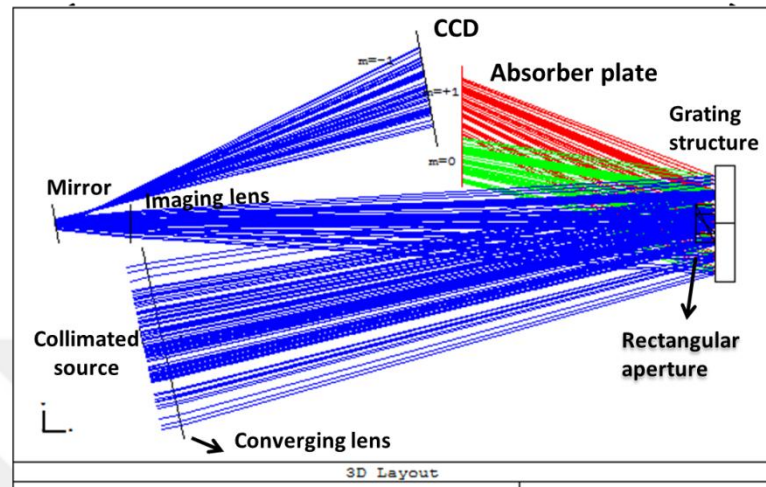


Figure 4-5: More compact form of the converging beam optical setup

As a conclusion, the converging beam optical system provides good imaging, requires fewer components, requires a smaller imaging lens (less aberrations), and can be made more compact compared to the 4f system.

4.3 4f Optical System using Knife-Edge filtering

Knife-edge filtering technique is used in the readout of the lever MEMS structures, which works with optical beam deflection readout. It consists of a cascade of two lenses, which are implementing two Fourier Transforms and a knife-edge filter for the spatial filter at Fourier plane instead of a pinhole.

Figure 4-6 shows the optical setup of the 4f Optical System with the knife-edge filtering technique. The collimated visible light that comes from the light source is expanded through the beam expander. The parallel light was sent to the MEMS FPA by transmitting through a beam splitter. After it was reflected back by the reflectors of the MEMS pixels, the beam was sent to the 4f optical system with the same beam splitter. The reflected diffracting rays forms the spatial spectrum of the FPA at the Fourier Plane after it was transmitted through the first lens. Consequently, the angular change in the MEMS

pixels changes the position of the peaks in the mentioned spectrum. The knife-edge filter at the Fourier plane blocks the half of the 0th diffraction spectrum of each pixel in the spectrum. The second lens after the Fourier Plane images every MEMS pixel of the FPA onto the CCD at a certain intensity level [66].

So if a hot object is focused on the MEMS FPA using an IR lens, each MEMS pixel will tilt regarding the temperature change on each individual pixel of the MEMS FPA. Thus, the optical power of the light will change at the Fourier Plane due to the spatial filtering and so does the visible light intensity of each MEMS pixel on the CCD. As a result, the infrared image of the hot object is transformed into a visible image [113].

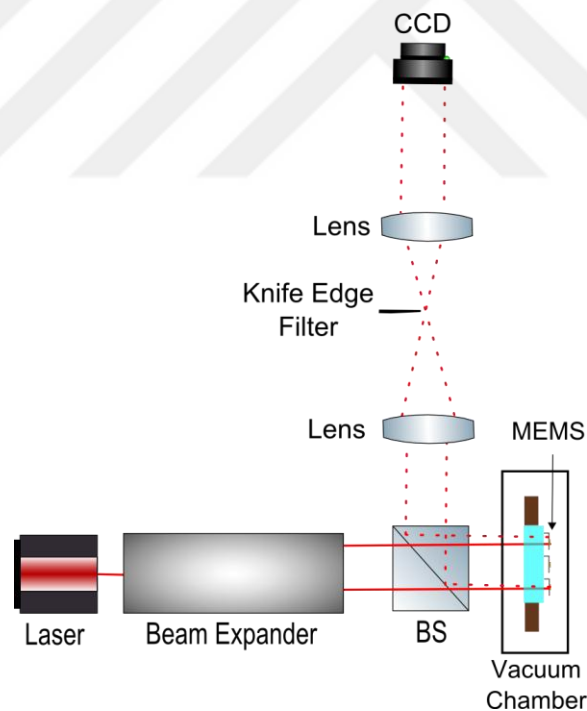


Figure 4-6: 4f Optical Setup using knife-edge filter

4.4 Two-Wavelength Readout using LED and Multi-mode fiber

In this subsection, a novel two-wavelength optical readout for grating based thermo-mechanical MEMS arrays was proposed [114]. The system uses two color LEDs butt-coupled to a multi-mode fiber, which provides spatial auto-registration of two different color images on a single camera. The -1st diffraction orders of the different colors were simultaneously monitored with different channels (R and G) of the RGB camera. The sensitivity of the MEMS array was improved by using the channel data with higher sensitivity for each MEMS detector under a thermal load.

Although the release process of the MEMS fabrication is successful, performance of an array may suffer from non-uniform gap between suspended pixels and the substrate due to fabrication process inaccuracy. Using simultaneous two wavelength interferometer based optical readout can be a solution to this problem.

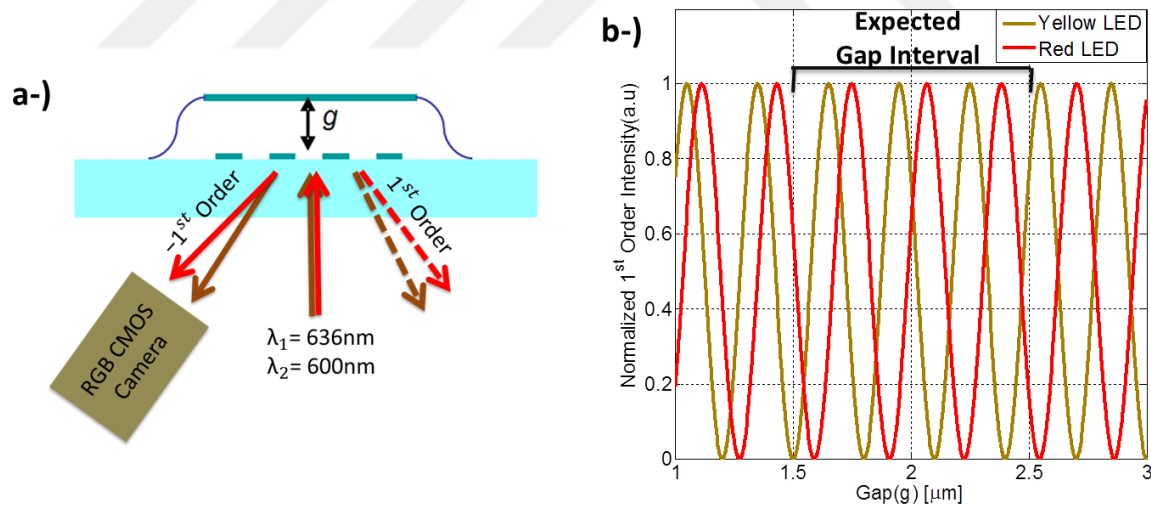


Figure 4-7: (a) Side-view of an IR pixel illustrating grating 2- λ readout (b) Intensity of light going to diffraction orders as a function of the gap (g).

In order to prove this, the MEMS detector with embedded diffraction gratings was used. The gratings were located under each pixel and a reflector was placed on the top of the pixel body. The cross section of the MEMS detector, which is illuminated with two

different wavelengths, is given in Figure 4-7a. In Figure 4-7b, intensity of ± 1 st diffraction orders are plotted according to the possible gap intervals for two different wavelengths that were used in the experiments.

The sensitivity is low at the peaks and the dips of the sinusoidal intensity curve whereas it is higher in between these points. Therefore, for a specific initial gap value one wavelength can be more sensitive than the other. It is better to select the more sensitive wavelength but the selection can be hard. A monochromatic camera can be used sequentially for two different wavelengths and there is a need of post-processing for the registration of the MEMS pixels [64]. In this study, the data for two different wavelengths was collected from two different channels of the RGB camera. Because of the auto-registration of the MEMS pixels, it was easy to select the more sensitive color among two different channels. Moreover, it is applicable to the whole array through the mentioned easy selection process.

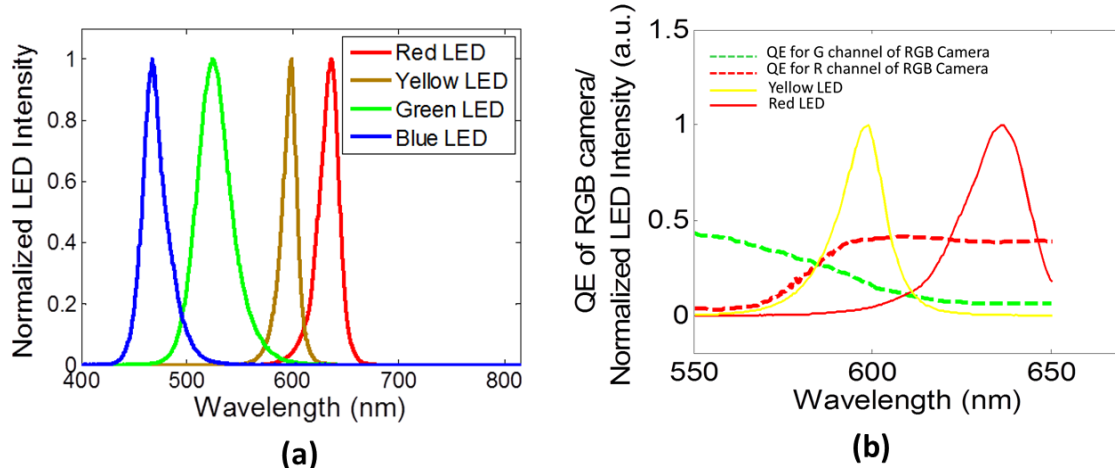


Figure 4-8: (a) Spectrum of different color LED light sources (b) The quantum efficiency (QE) of the R and G channel of the RGB camera and the spectrums of yellow and red LED light sources.

Figure 4-8a shows the spectrum of the different color LED light sources. The coherence lengths of the LED sources were calculated regarding the given plot in order to

select the right wavelengths. Table 4-2 shows the coherence lengths of the different color LEDs, which determines the longitudinal resolution [115].

Table 4-2: LED Color Selection According to the Coherence Length

The Color of the LEDs	Coherence Length [μm]
Blue	4.42
Green	3.42
Yellow	11
Red	8.56

The gap between the top reflector and the diffraction grating is around $2.5 \mu\text{m}$ to enhance the absorption of IR waves ($8\text{-}12 \mu\text{m}$). Therefore, the optical path difference is around $5 \mu\text{m}$. The coherence length of the LED light sources should be greater than the coherence length. Thus, the yellow ($\lambda=600\text{nm}$, $\Delta\lambda=15\text{nm}$) and red light sources ($\lambda=636 \text{ nm}$, $\Delta\lambda=20\text{nm}$) are chosen according to this configuration. Figure 4-8b shows the spectrum of the yellow and red LED light sources with the QE of the red (R) and green (G) channels of the RGB camera. Red light source matches well with the R channel of the camera. However, the yellow LED has a response in both R and G channels. In order to use these channels of the RGB camera for each light source separately, one needs to develop a post-processing algorithm.

The post-processing algorithm for separating each wavelength from the separate R&G channels of the camera is shown in Figure 4-9. Once the RGB video is obtained from the two wavelength setup, the information of R and G channels should be extracted separately. Related individual MEMS pixels can be chosen separately for the characterization of the single MEMS pixel. The locations of the MEMS pixels are same in different channels. Since each channel has different gains, the intensity outputs of the channels should be normalized. The MEMS pixel intensities regarding the yellow light source can be obtained

directly from the G channel. However, in order to obtain the information of the MEMS pixel intensities regarding the red light source, the effect of the yellow LED on the R channel should be eliminated. Thus the G channel is simply subtracted from the R channel. Consequently, the information for the red light source can be obtained.

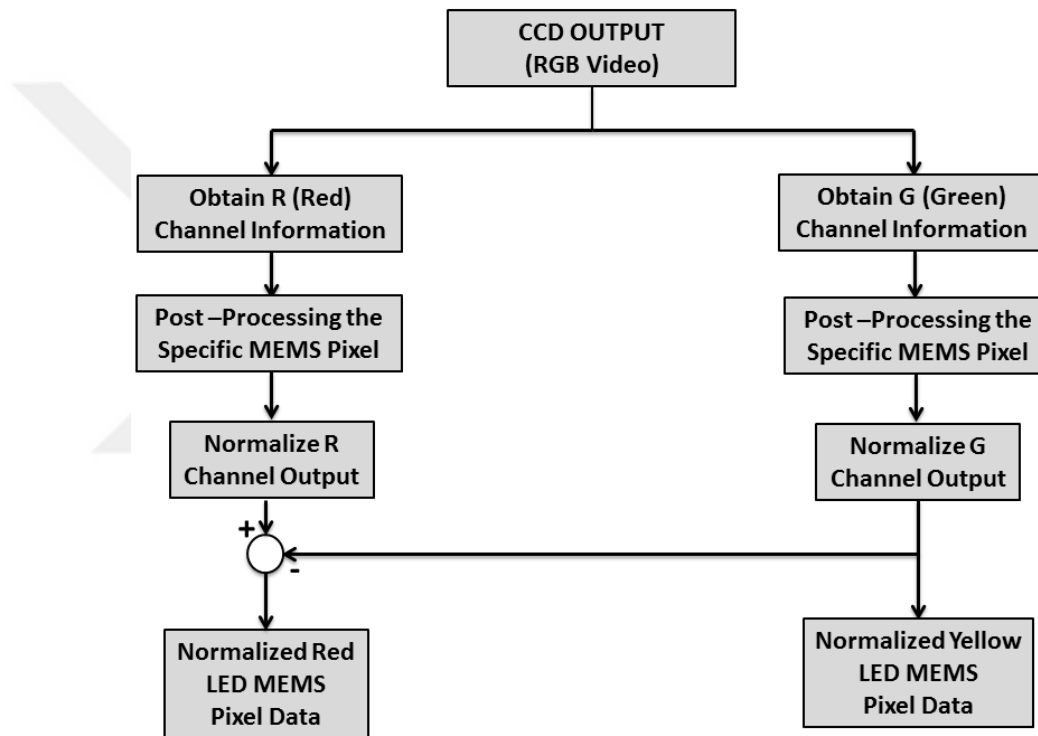


Figure 4-9: Block diagram of the post-processing algorithm for two wavelength setup.

Figure 4-10.a illustrates the schematics of the optical readout system. A yellow ($\lambda=600\text{nm}$, $\Delta\lambda=15\text{nm}$) and a red ($\lambda=636\text{ nm}$, $\Delta\lambda=20\text{nm}$) LED was butt-coupled to a multimode optical fiber. The MEMS device on a TEC was illuminated from this optical fiber through the converging lenses as if there was a single source. Then the -1^{st} diffraction order of the MEMS device was imaged on an RGB CMOS camera. Figure 4-10.b shows the experimental setup.

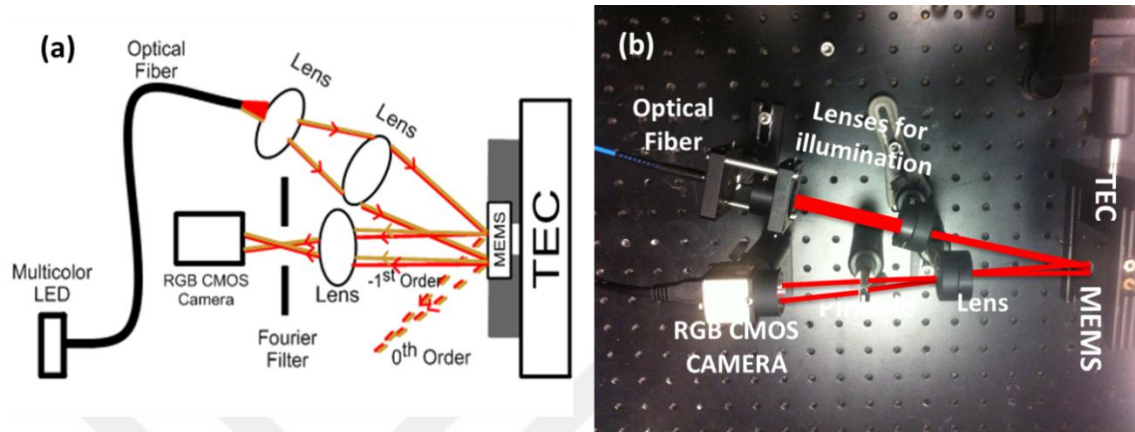


Figure 4-10: Two-wavelength optical readout system: (a) Schematic (b) Experimental setup.

4.5 Experimental Results

In the experiments, SixNy/Al based sensor arrays with diffraction gratings are used. The sensor structure (Design #1) used in the experiments had a piston motion capability. The data was captured at 15 fps using a CCD camera. The TEC was initialized at the room temperature and the temperature was kept constant for the first 100 – 150 frames. Then the temperature of the MEMS device was increased controllably and a video was captured.

Firstly, a comparison was aimed between the conventional optical system and the converging beam optical system. The same experimental conditions were set equally for both setups for a fair comparison. While heating the FPA, $\Delta T = 15^\circ\text{C}$ was adjusted as the temperature difference in the TEC for both cases. Same MEMS device was used in the experiments. The same post processing procedure was applied while processing the image. Figure 4-11a illustrates the -1st order diffraction intensity of an arbitrarily chosen part of the MEMS FPA (160x120) with respect to 1st video frame. It is possible to add all relevant CCD pixels to achieve the total signal that diffracts from a sensor. An image processing algorithm was developed in order to analyze the captured CCD video and suppress the

noise using some binning strategies. The working principle of algorithm can be reduced to 4 steps.

- i. Finding the maximum values by searching the CCD output image by using $N \times N$ blocks
- ii. According to the address of the maximum values, shaping the IR pixel and specifying the number of CCD pixels for binning.
- iii. Summing the addressed image pixel intensity values (binning) for the specific IR pixel and remapping image according to the total intensity values
- iv. Repeating it for the rest of the frames in the CCD output video.

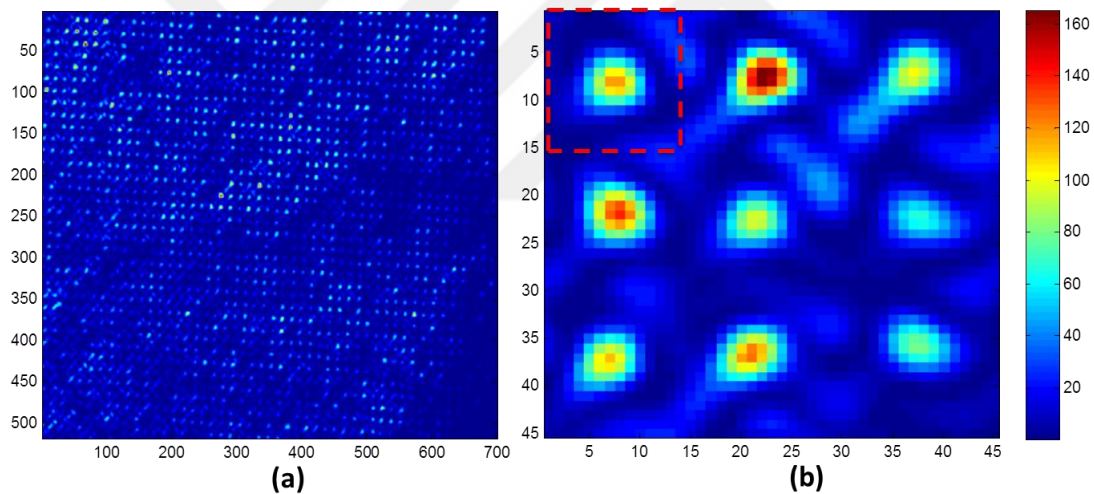


Figure 4-11: (a) A small part of the MEMS FPA (160x120) imaged on the CCD (b) Image of 3x3 IR Pixels.

Figure 4-11b shows the 3x3 MEMS pixels of the FPA as a zoomed version of the whole array image. The block size $N=15$ includes only one MEMS pixel and in order to characterize the single MEMS pixel for both optical setups 9x9 pixels were used, where the maximum of each block is in the center. Choosing the pixels to be used in binning is so important in the defined block, because the coupling between two adjacent IR pixels can

become a significant noise source for each pixel. Red dashed marked pixel in Figure 4-11 is an arbitrary selected pixel according to a reference point in the FPA.

The total intensity value was stable at a certain intensity value with a noise when the TEC is off for the first 120 frames. 120 frames correspond to 8 seconds with a frame rate 15 fps. For the rest of the time TEC is on, which applies a heat that creates a temperature difference $\Delta T = 15^\circ\text{C}$. The intensity starts to change once heating starts, and settles down to certain intensity value, once thermal equilibrium is reached. As shown in the Figure 4-12, for the same IR pixel, signal to noise ratio is about 3 times better in the converging beam optical system. The standard deviation for the first 120 frames is $\sigma_{4f} \approx 25$, which corresponds to the noise of the experimental setup with 4f optical system. Similarly the noise for the convergent beam was extracted as $\sigma_{CBOS} \approx 10$. The SNR of the optical systems are 60.5 and 169.2, which was calculated from the signal and noise levels. Convergent beam optical system provided better noise suppression in our experiments but this needs to be studied further.

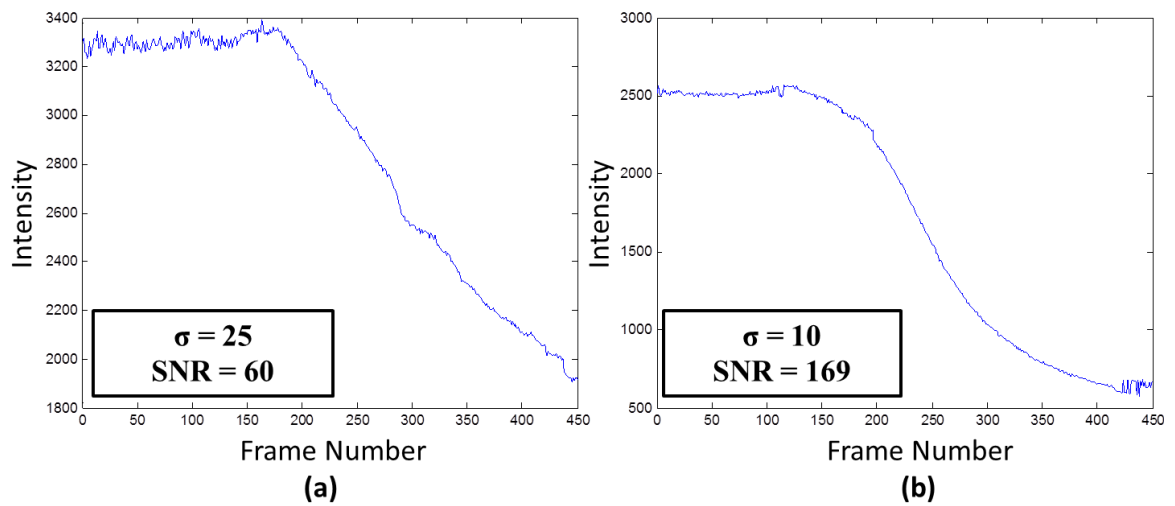


Figure 4-12. Direct heating experiment (15°C heating) results for the marked pixel as a red square: a. using the conventional 4f system b. using converging beam optical system

Furthermore, IR imaging experiments were performed using the same MEMS arrays. A video was captured while moving a hot soldering iron at 300 °C. 2 different frames of a captured video are shown in Figure 4-13. Background subtraction was applied to each frame as a post-processing step to see the hot objects clearly.

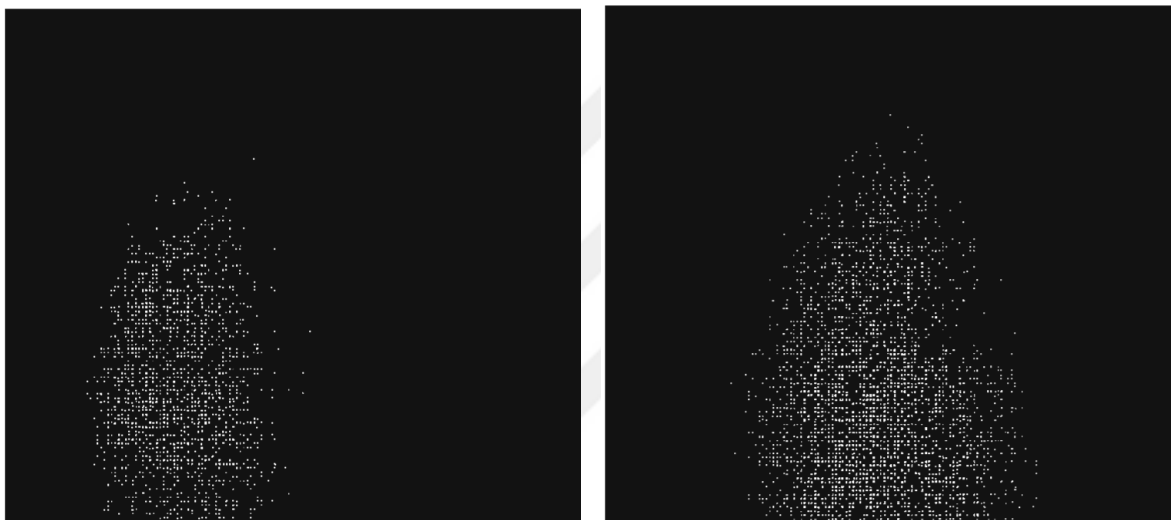


Figure 4-13 A soldering iron was moved from left to right. Background subtraction was applied to both images.

Secondly, IR imaging experiments were performed with the lever based SixNy/Al sensor arrays (64x64 MEMS pixels). In the experiments, SixNy/Al based sensor arrays, which tilt with the induced IR radiation, were used. The sensor structure used in the experiments was shown in Figure 2-15, indicated as Design #2. The data was captured at 15 fps using a CCD camera. Figure 4-14a shows the IR image of a circular target at 1000 °C using the 4f optical system with knife-edge filtering technique. Similarly Figure 4-14b illustrates the IR image of a TEC at 80 °C. Background subtraction was applied to the both captured videos with a simple thresholding algorithm. Although, the array size is small

(64x64), the knife-edge optical system with lever based sensors worked well in the IR imaging experiments.

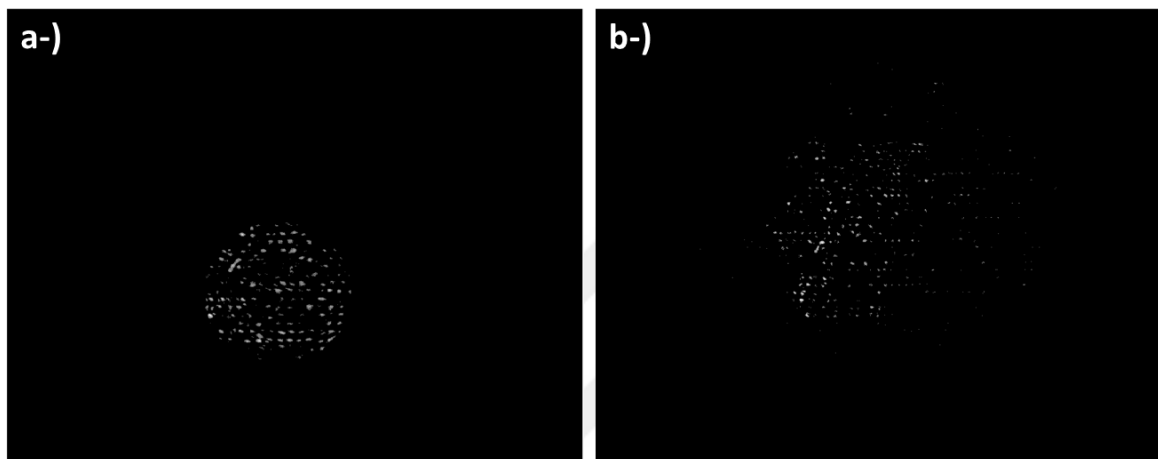


Figure 4-14: (a) Image captured from a CCD output of a circular IR target at 1000 °C (b) Image captured from a CCD output of a black TEC at 80 °C. Background subtraction was applied to both images.

Lastly, the SixNy/Al based sensor arrays with diffraction gratings were used in the experiments of two wavelength setup. The sensor structure has a piston motion capability which operates well with the grating structures (Design #1, Figure 2-8). In the experiments, MEMS array was heated by TEC with a temperature difference $\Delta T=5$ °C. The heating data was received for 70 seconds. The TEC was turned on after 30 seconds and was stabilized in 5 seconds. Figure 4-15a is the image obtained from the RGB camera. The circular spots in the image corresponding to MEMS pixels have different colors for different pixels due to non-uniformity in the array. In addition, it gives some clues on the sensitivity curve of the pixel at first glance. Two arbitrary MEMS pixels (Pixel #1 and #2) were selected from the array in order to compare their responses to heating for two different wavelengths. The response of Pixel #1 for two different wavelengths is given in Figure 4-15b. After the TEC was turned on, the change of the signal level in yellow was more than the change in red.

Therefore, the SNR for yellow was better than SNR for red whereas for Pixel #2 (Figure 4-15.c) it is the opposite case.

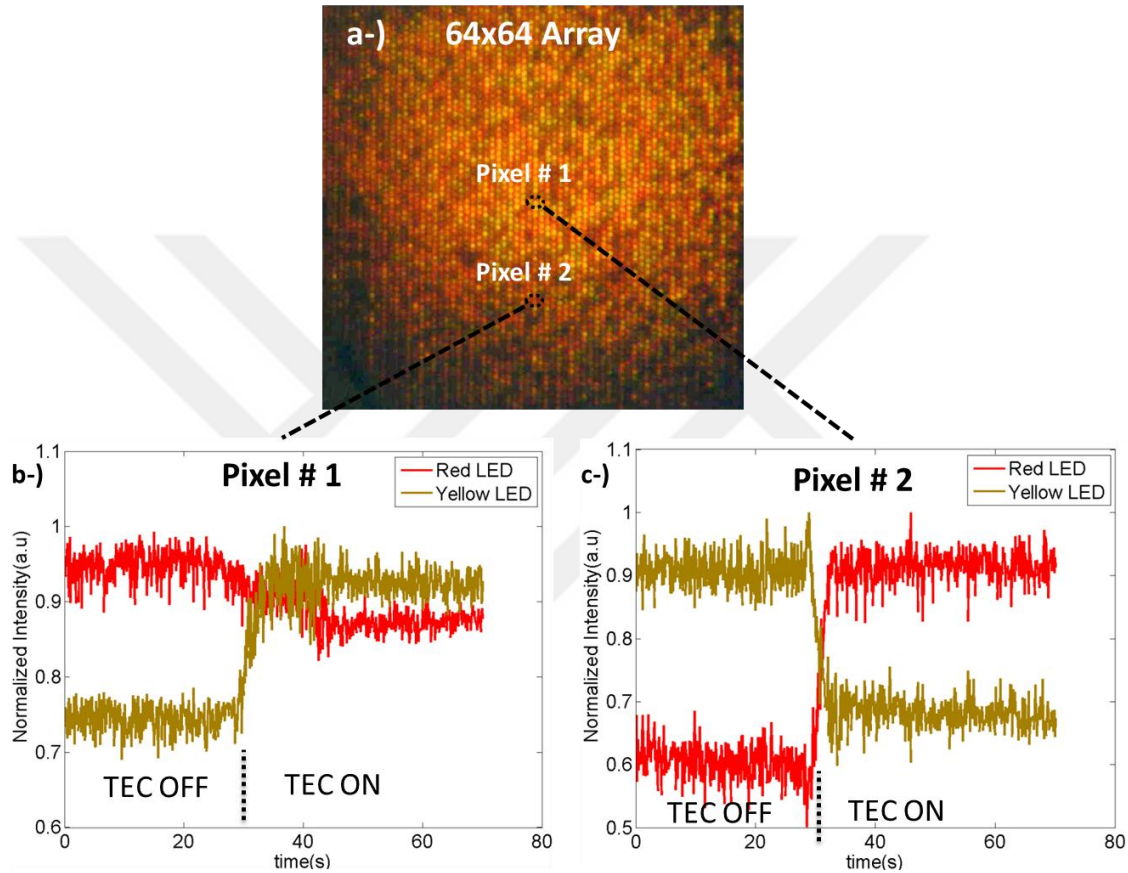


Figure 4-15. (a) Image of the 64x64 array (b) Response of Pixel #1 to $\Delta T = 5^\circ\text{C}$ (c) Response of Pixel #2 to $\Delta T = 5^\circ\text{C}$

4.6 Conclusions

In this section, optical readout methods for thermo-mechanical MEMS FPAs were discussed. Firstly, two different optical systems for diffraction grating based thermal detector arrays were analyzed. Two different schemes were compared for the typical optical readout by using commercial CCD cameras and imaging optics: (i) 4f Optical System (ii) Converging Beam Optical System. The size of the convergent optical system

can be reduced to 30mm x 40mm while also reducing the number of components. This is the most important benefit of the converging optical system over the conventional 4f system. As a result of the experimental tests, the convergent optical system appeared to be more preferable for our thermal detector system due to compactness, potential SNR advantage, and smaller imaging lens compared to the standard 4f optical system [91]. In addition, an IR image of a soldering iron at 300 °C was captured using the converging beam optical system.

Secondly, 4f optical system using knife edge filtering technique was implemented to 64x64 MEMS FPA. Two different IR images of hot objects were obtained using a knife-edge filtering technique. Background subtraction was applied to the both captured videos with a thresholding algorithm in order to better visualize the targets. Despite the small array size (64x64), IR images of hot objects were obtained using the knife-edge optical system.

Lastly, two-wavelength interferometer based optical readout setup was successfully demonstrated with two LEDs butt-coupled to a multimode fiber and an RGB camera. The response of the MEMS to temperature change was simultaneously obtained at the two different channels of an RGB camera. It was shown that for arbitrary pixels the sensitivity of the array can be enhanced by using the most sensitive channel's signal for each individual MEMS pixel.

5 Integrated Optical Readout for MEMS-based Sensor Arrays

Integration of MEMS devices with CMOS electronics in a small package enables many key features such as large array operation, low cost and better control of environment. Integration of optical MEMS devices with customized CMOS has been demonstrated for optical microphones [116] and accelerometers [49]. These are either single devices or a small array of a few devices. Yet, integration of large devices is still challenging and poses a significant bottleneck for current technology. This chapter reports a MEMS-based sensor array integrated with CMOS-based optical readout [50, 117] as shown in Figure 5-1a.

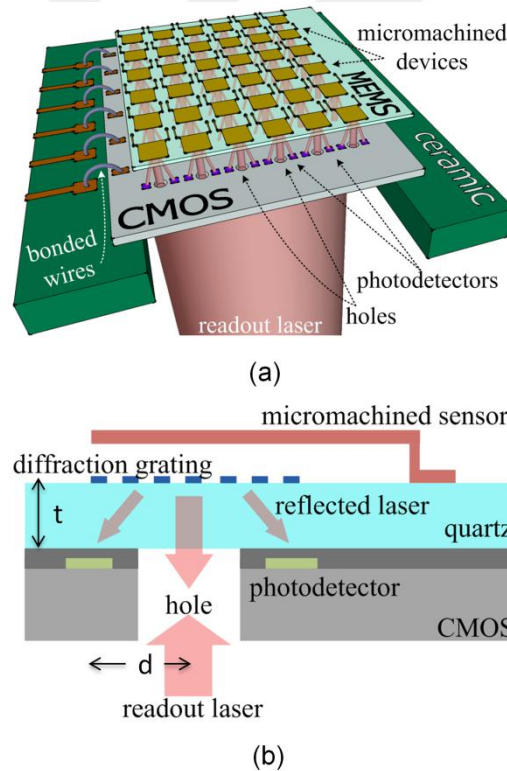


Figure 5-1: (a) Schematic of the integrated device. (b) Side view of one sensor.

The MEMS devices in Figure 5-1 are electrically passive and free of electrical connections. This enables large array formation for parallel measurement applications. Furthermore, different passive MEMS chips can be used with the same CMOS chip that allows configuring MEMS chips as disposable cartridges. Besides, MEMS chip can be operated in ambient, vacuum, or aqueous environments. A customized post-processing flow was developed to integrate the MEMS chip with CMOS-based readout integrated circuit. Via holes were defined on ROIC to enable the integrated optical readout. The chips were aligned with about 1 μm accuracy using self-alignment marks. The CMOS-based optical readout method will be introduced in the first subsection of this chapter. Then the optical simulations required for the integration and the integration process will be explained. After that, the experimental results for the integrated sensor array will be provided. Lastly, the conclusion subsection will summarize the important points.

5.1 CMOS-based Optical Readout Method

It is possible to design sensors with different sensing modalities and sensitivities on the same array for various applications. In this work, the sensor platform is mainly optimized for thermo-mechanical sensing applications. The mechanical deflections of the MEMS devices are detected optically with sub-nm precision using a pixel-level diffraction grating interferometer [64, 91, 118] as illustrated in Figure 5-1b. Light reflects off of the membrane interferes with light reflects off of the diffraction gratings embedded under each device. Since the movable reflector, i.e. the membrane, and the reference reflector, i.e. diffraction grating, lay on the same substrate, the readout beam is immune to environmental vibration. The reflected light goes into diffraction orders determined by the diffraction grating. The intensity of light in diffraction orders is modulated by the gap due to interference. The intensity of 1st diffraction orders are monitored using the detectors located under each MEMS device. Thus, the temperature of the target can be obtained by mapping the intensity to the temperature.

Figure 5-2 shows SEM and optical microscope image of MEMS devices. The pixels are $35\text{ }\mu\text{m}$ in pitch, and the bimaterial legs of the pixels are $25\text{ }\mu\text{m}$ in length for each side of the pixel. The thicknesses of parylene and titanium are 400 nm and 200 nm , respectively. The array format is 64×64 .

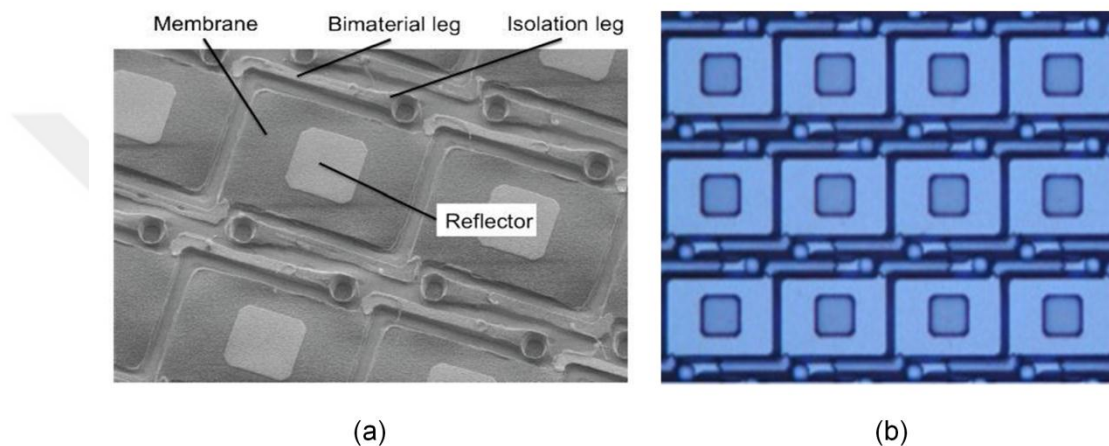


Figure 5-2: (a) SEM pictures of $35\mu\text{m} \times 35\mu\text{m}$ MEMS sensors. (b) Microscope image of a larger array.

CMOS-based optical readout method eliminates the need of electrical interconnects on pixels. So, the devices are free of detrimental effects of joule heating due to electrical bias and thermal crosstalk. Moreover, optical readout improves the sensitivity as it offers sub-nanometer resolution for the detection of the deflection of individual pixels simultaneously. Pixel-level interferometers are formed by blanket illumination of the entire Focal Plane Array (FPA) using a single laser source. Reflected light from the individual devices that propagates in 1st diffraction order is imaged onto a 2D visible detector array.

MEMS chip was integrated with a compatible CMOS ROIC chip to develop a compact and optimized sensing platform. CMOS chip including low power trans-impedance amplifiers, noise cancellation circuits, analog multiplexers and decoders was designed and fabricated using a standard $0.18\text{ }\mu\text{m}$ CMOS process. Figure 5-3 shows ROIC

chip that contains an array of holes and photodiodes to be aligned with MEMS devices. The orange box in Figure 5-3 illustrates single pixel readout part of CMOS ROIC that includes one hole for incident beam and two photodiodes for $\pm 1^{\text{st}}$ diffraction orders. Holes provide optical access to the MEMS chip from backside and the photodiodes are located with respect to the reflectors of the MEMS pixels. Thus, the reflectors on the MEMS pixels should be aligned with the holes on the IC chip.

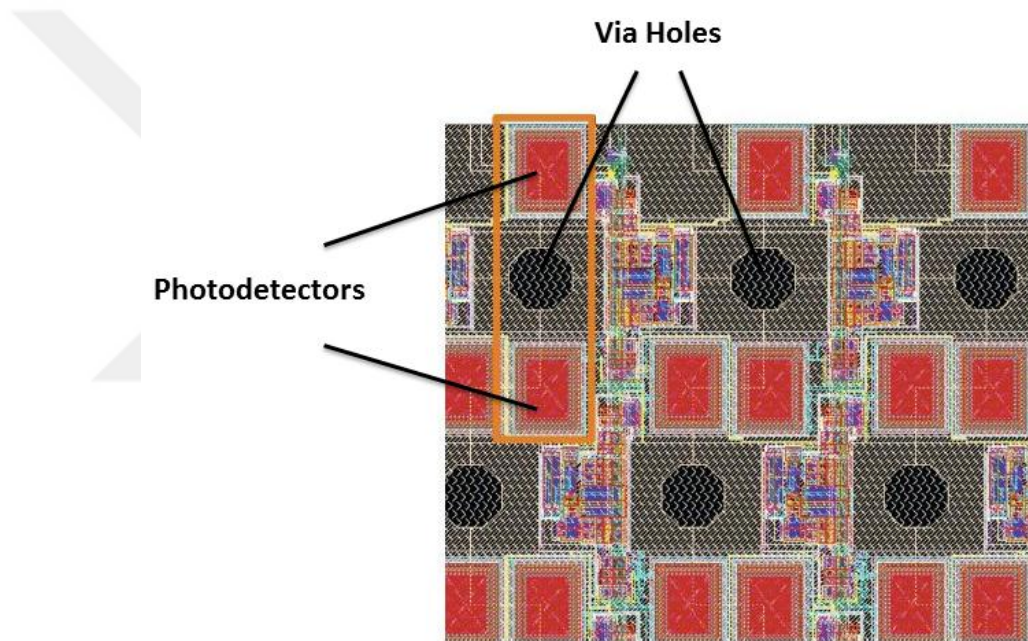


Figure 5-3: CMOS ROIC, Photodetector and hole configuration.

CMOS chip was fabricated with a thickness of $280\ \mu\text{m}$ without the holes. In order to make the MEMS and CMOS compatible for the integration, post-processing is required. Figure 5-4 shows the details of the CMOS chip after post-processing steps. Holes on CMOS chip were defined using a customized post-processing fabrication step. The details of the process are explained in Ref. [119] and [93].

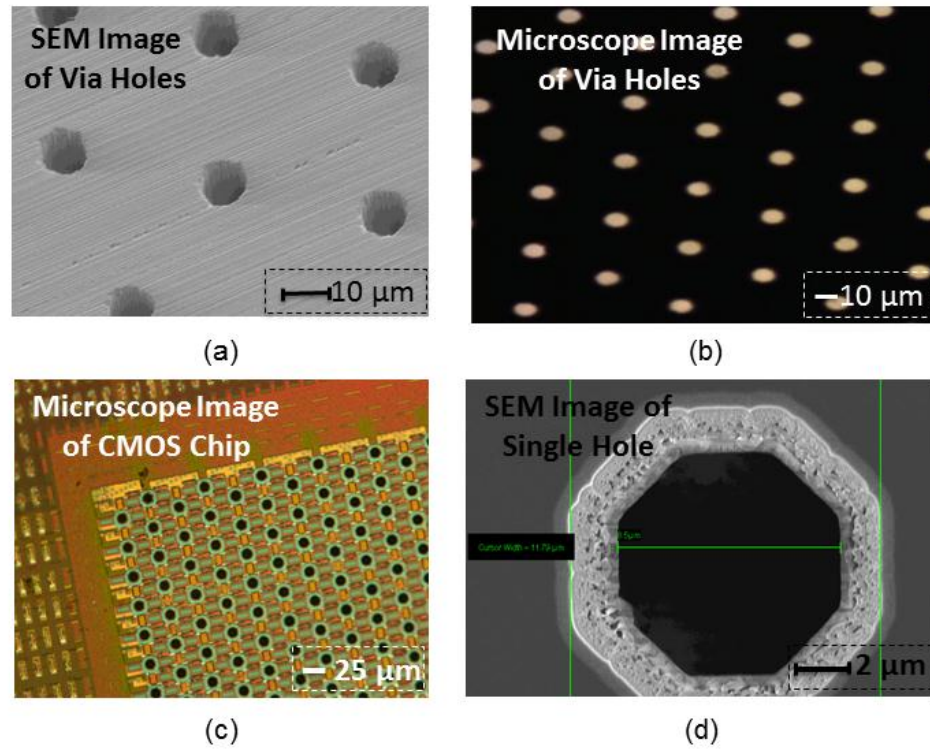


Figure 5-4: (a) SEM image of backside of CMOS. (b) Microscope image showing the light transmission through via holes. (c) Microscope image of post-processed CMOS chip with via holes. (d) SEM image of a single hole from backside of CMOS.

The diameters of via holes are 10 μm that is compatible with the size of the single MEMS pixel. There are two photodetectors next to a hole for one MEMS device in the array to monitor light at +1st and -1st diffraction orders. Photodetectors are individually addressable and the photo-responsivity is measured as 0.163 A/W as shown in Figure 5-5. This figure shows single photodetector current with respect to different incidence laser power. For the characterization, CMOS chip was illuminated using a red laser and a mechanical chopper was used to vary the intensity of incident light.

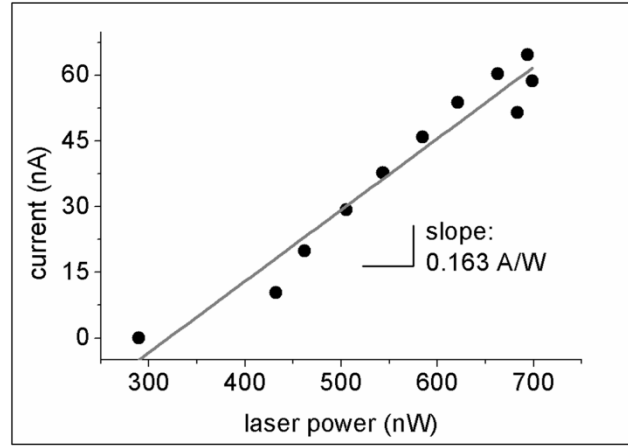


Figure 5-5: CMOS characterization data.

5.2 Optical Simulations

MEMS die post-processing is another important step before the integration. MEMS dies should be grinded to the required thickness before the integration in order to meet the $\pm 1^{\text{st}}$ diffraction orders of the reflected light with the PDs on the CMOS ROIC. Optimal pyrex wafer thickness was computed using ray optics calculations and Fourier optics theory [120]. The MEMS devices were fabricated on a standard pyrex wafer with a thickness of 525 μm . The distance between the photodetectors ($2d$) is determined by the thickness (t) (see Figure 5-1) as shown in Equations (17) and (18).

$$\theta_m = \sin^{-1}\left(\frac{m(\lambda/n_{\text{pyrex}})}{\Lambda} - \sin \theta_i\right) \quad (17)$$

$$t = d \cot(\theta_m) \quad (18)$$

θ_i : The angle of the incident light

m : Diffraction order (Integer)

n_{pyrex} : Refractive index of pyrex.

λ : Wavelength

Λ : Grating period

θ_m : The angle of the diffracted light

d : The distance between the center of the hole and a single photodiode

t : Thickness of the MEMS

The period of diffraction gratings is $\Lambda = 4 \mu\text{m}$. Normal incidence ($\theta_i=0$) and a red laser with $\lambda = 635 \text{ nm}$ was assumed for the calculation. The distance between the center of the hole and the center of the photodiode (d) is $17 \mu\text{m}$. The photodiodes are $14 \mu\text{m} \times 14 \mu\text{m}$, the diameter of the hole is $10 \mu\text{m}$ and the length of guard bands at the same axis is $5 \mu\text{m}$ for both sides. Consequently, the thickness of the MEMS die (t) was calculated as $156 \mu\text{m}$. Therefore, MEMS die should be grinded to $156 \mu\text{m}$ for the given parameters.

A detailed model based on Fourier optics simulations was developed to predict the distribution of intensities at the plane of photodetectors. Beam propagation simulations were performed using the calculated thickness value and the given parameters. Input of the simulator is a uniform circular beam with a diameter of $10 \mu\text{m}$ as defined by the via hole at the backside of the pyrex wafer. The 2D beam profile at the plane of diffraction grating was obtained by propagating the input beam for a thickness of $t = 156 \mu\text{m}$ through grinded pyrex wafer as shown in Figure 5-6a. Then the beam was propagated through the diffraction gratings to the movable reflector and the reflected light was propagated back to the detector plane. The 2D beam profile at the photo-detector (PD) plane was illustrated in Figure 5-6b. The red squares indicate the location of the photo-detectors. The power going into $\pm 1^{\text{st}}$ diffraction orders was captured well with the current design.

The intensity of light at the photodetector plane at $y=0$ is shown in Figure 5-6c. The model verifies that the beams are well separated at the PD plane indicating a better signal quality.

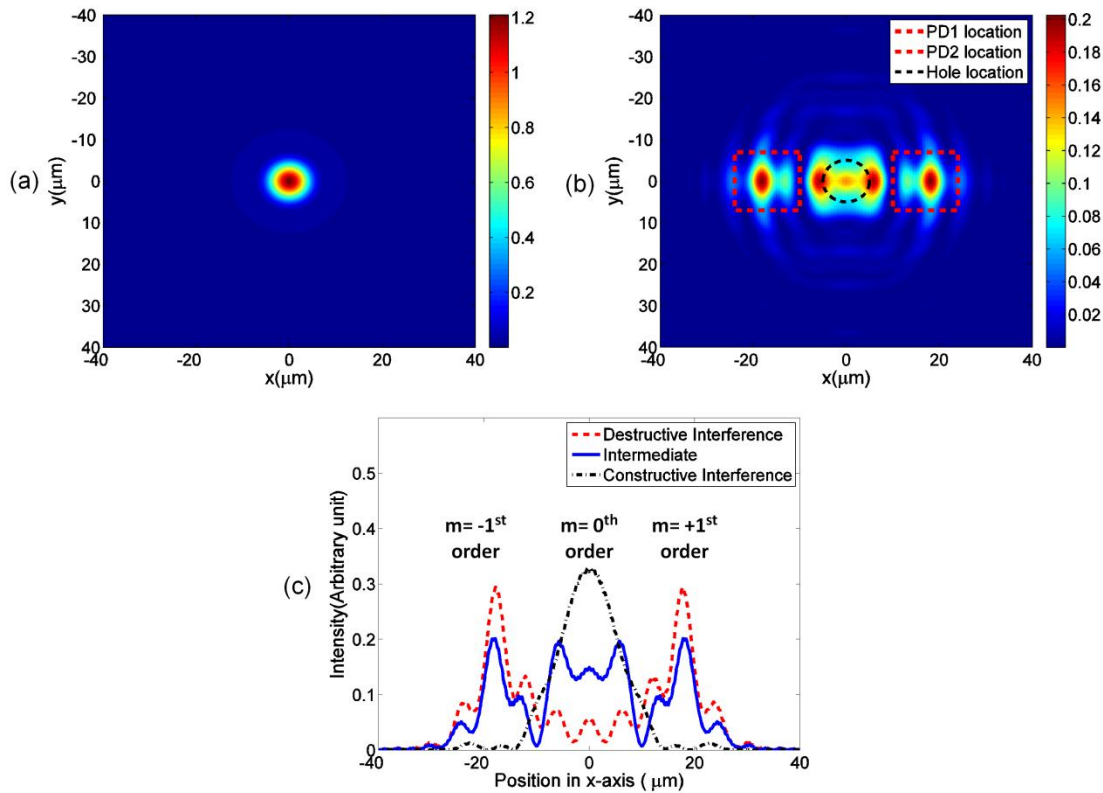


Figure 5-6: (a) The propagated beam at the grating plane. (b) The diffraction orders at the photo-detector (PD) plane for 2 μm gap. (c) The cross section of the beam at the PD plane for three different gap values.

Similar beam propagation simulations were performed for different wavelengths. The thickness of the MEMS die for a green light source ($\lambda = 532 \text{ nm}$) was calculated as 187 μm. Similarly the thickness of the MEMS for a blue light source ($\lambda = 473 \text{ nm}$) was determined as 211 μm.

5.3 MEMS and CMOS Integration

The grinding process of the MEMS devices were performed at EPFL CMI. The grinding process causes a few μm surface roughnesses, which can affect the performance of the CMOS-based optical readout due to the scattering issues.

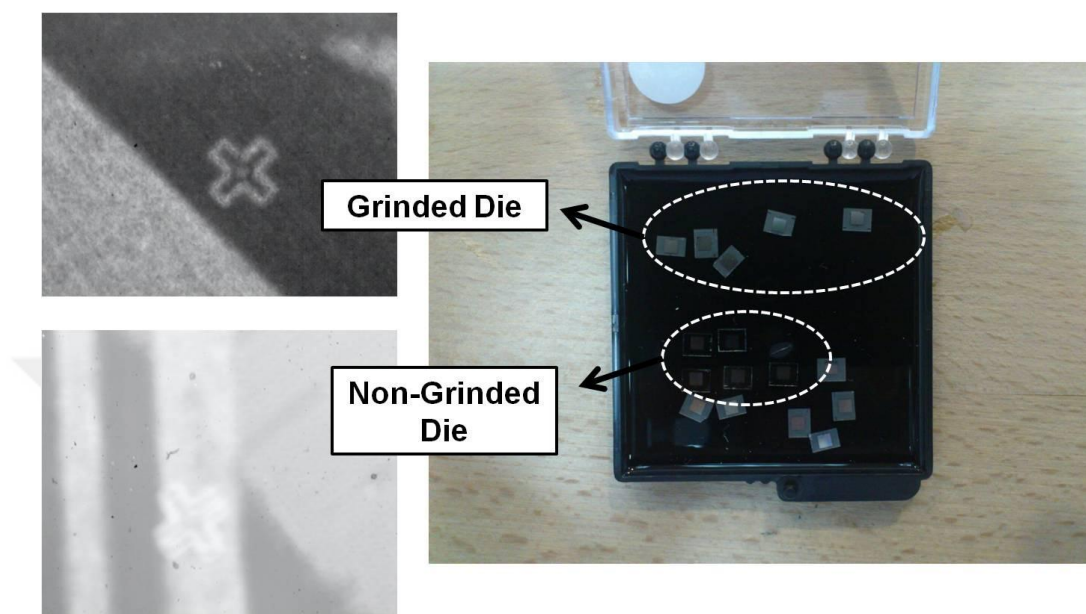


Figure 5-7: The grinded and non-grinded dies

Figure 5-7 shows the grinded and non-grinded MEMS dies. Non-grinded dies seem transparent in the ambient light, but the grinded dies have a transparency problem. Therefore, the grinded chips were polished using Chemical Mechanical Planarization (CMP) process. However, there were some problems on handling the thin MEMS dies and the process couldn't be completed successfully. The problem was solved using epoxy in the integration process, which has a refractive index very close to the pyrex for matching. Figure 5-8 shows a non-grinded die mounted on a silicon wafer using a refractive index matched epoxy. The part with the epoxy seems perfectly transparent. Since a very small amount of epoxy was applied onto the silicon wafer, the thickness of the die changed insignificantly ($\sim 1 \mu\text{m}$). The thickness measurements were done using a caliper and a White Light Interferometer (WLI).

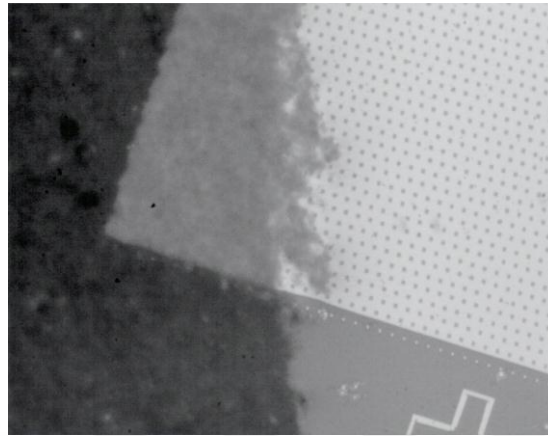


Figure 5-8: Decreasing surface roughness using refractive index matched epoxy

After these post-processing steps, MEMS and CMOS chips were aligned with an accuracy of 1 μm . This alignment accuracy ensures proper operation of relatively small photodiodes.

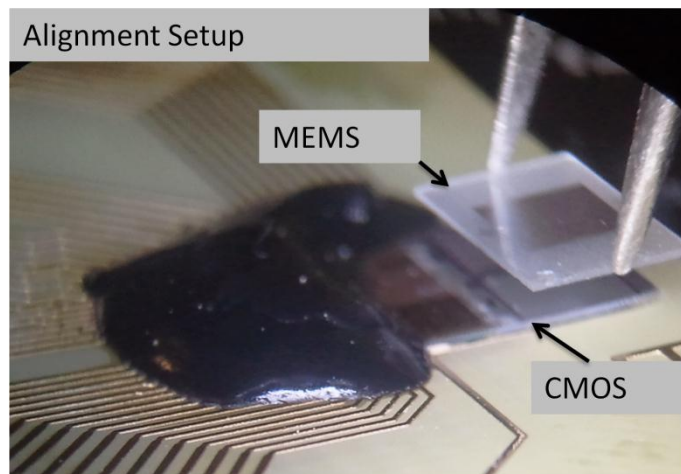


Figure 5-9: Photograph of the alignment setup.

Two alignment marks were added on both MEMS sensor and CMOS chip to facilitate the alignment process. The alignment marks were placed on top and bottom of the arrays in order to avoid rotation errors. A close-up detail of the integrated MEMS and CMOS chip

placement is given in Figure 5-9. A customized setup was built for the alignment. The setup allows four degrees-of-freedom (three translational and one rotational) movement for the chips under a microscope.

5.4 Experimental Results

An experimental setup is presented in Figure 5-10 to characterize the integrated system using different inputs.

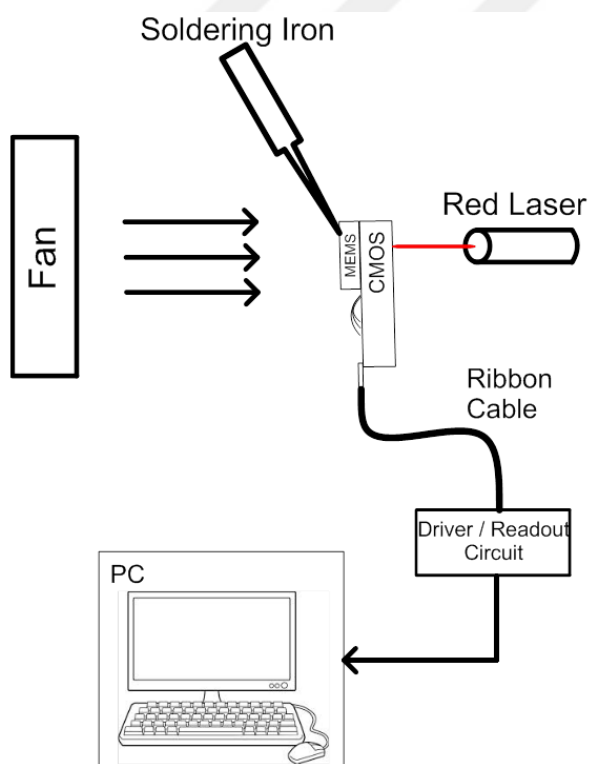


Figure 5-10: Experimental setup to test the integrated system

An integrated device was illuminated using a pulsed laser beam with a wavelength of 635 nm. Response of the device to the pulsed laser beam corresponds to the dynamic range set by the power of the laser. Next, a small fan was placed about 50 cm in front of the MEMS device to test the system for a pressure wave input. The readout laser was ON

continuously while the fan was turned ON and OFF during this experiment. In addition, the response of the integration device was measured for a thermal load. A soldering iron heated at 150 °C was placed within the vicinity of the MEMS chip. The soldering iron was moved towards and away from the device during the experiment.

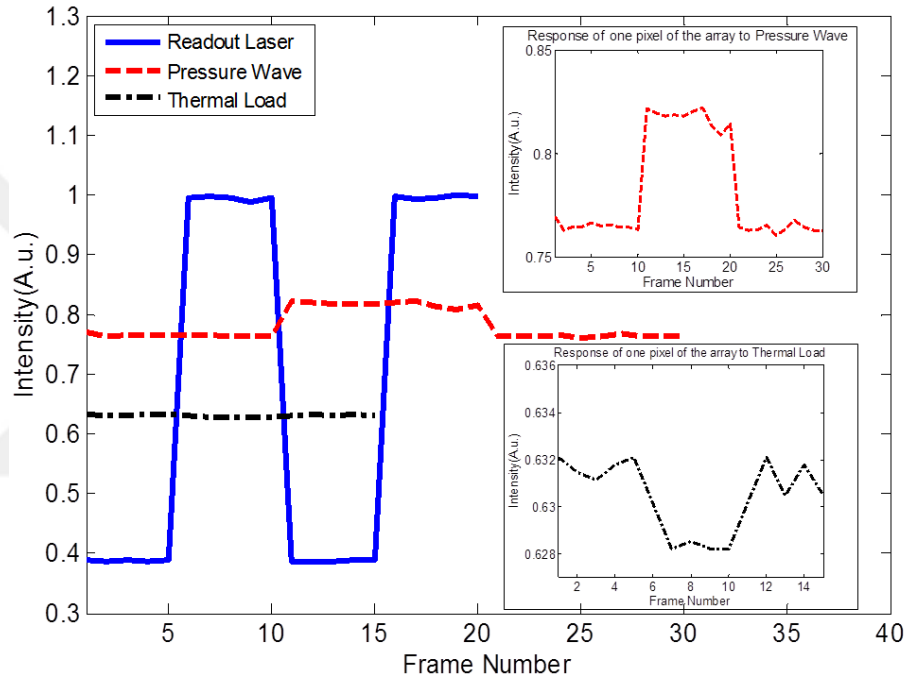


Figure 5-11: Experimental characterization of the integrated system.

Figure 5-11 shows a typical time traces of an exemplary pixel on the array for three different tests mentioned in Figure 5-10. The outputs were normalized according to the response of the modulated laser. Normalized curves show the relative responses of the integrated device to different types of inputs. Nevertheless, the insets in Figure 5-11 show that the system is capable of resolving the changes in the inputs, indicating a successful integration of the CMOS chip with the MEMS. The current performance is limited by the readout electronics and further improvement is possible using higher resolution electronics.

Lastly the integrated sensor array platform, which is mounted on PCB for readout electronics, was placed into a vacuum chamber. The Ge window of the vacuum chamber was extracted to make a proper optical alignment of IR source as it can be seen from Figure 5-12a. After placing the integrated sensor array to the chamber, a modulated IR source at 1000 °C was directed to the sensor array. The response of the sensor array to the modulated IR source can be seen in Figure 5-12b.

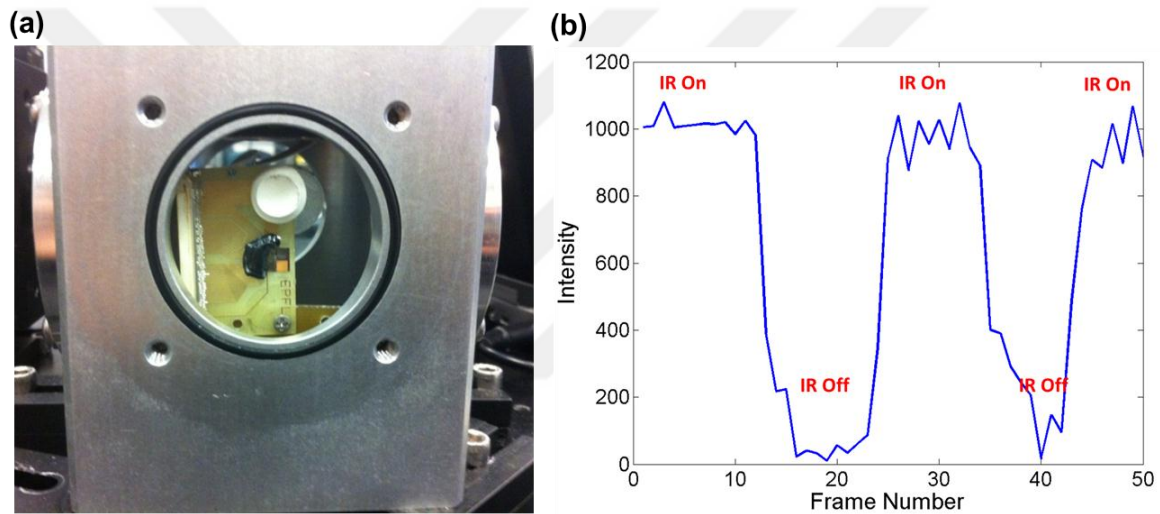


Figure 5-12: (a) Integrated sensor array platform in the vacuum chamber (b) The response of the integrated sensor array to a modulated IR source.

5.5 Conclusion

This section presents a CMOS-based optical readout, which is integrated with MEMS sensor array platform. The presented architecture is proposed as a sensor array for various applications. Optical readout capability without the need for electrical connections to the MEMS chip and simple integration to ROIC enables utilization of disposable and customized MEMS sensor arrays. Currently, the sensor platform is optimized for thermal imaging by designing a proper MEMS chip. Eliminating electrical connections on MEMS

devices eliminate detrimental effects such as Joule heating and cross-talk. Interferometer-based optical readout improves the sensitivity of the integrated system. A successful integration was realized by post-processing the CMOS and the MEMS devices. A model based on Fourier optics simulations was presented. In this process, MEMS and CMOS were optimized and processed separately, improving the yield of the overall process. The system was tested for functionality using pressure load and thermal load, and produced a response that was clearly detectable.

6 Optical Readout for Dynamic Mode MEMS Cantilever Sensor Arrays

Various optical methods have been used for measuring the deflections of the cantilevers in atomic force microscopy (AFM) [32, 105] and cantilever based chemical/biological sensors [15, 96]. Beam deflection [32, 96] and interferometry [121, 122] are the most common forms of optical methods, which are applicable to MEMS and NEMS oscillator arrays for various sensing applications.

Optical methods have the potentiality to offer an important solution to the dense arrays with large number of elements that cannot be interfaced easily to the actuation and read-out electronics. In general, oscillator arrays that share common actuator and common electronics are desirable for multi-channel sensor applications. For this purpose, separate saturation mechanisms, such as optical non-linearities, are required for each cantilever in order to achieve multiple oscillations in a closed-loop system [71, 123].

Two different approaches are discussed in this chapter in order to provide the mentioned optical non-linearities. Firstly, the MEMS cantilevers with embedded diffraction gratings were parallelized for multiple oscillations, which can enable multi-channel sensor applications [104, 123]. However, this system has a drawback. A large diffraction grating at the tip of the cantilever complicates the cantilever design and decreases the quality factor of the MEMS cantilever due to squeezed film damping between the cantilever and the reference surface. Therefore, a prism-based optical readout method based on internal reflection, which provides the required optical non-linearity for rectangular shaped simple cantilever geometry, was proposed as a second approach. In this method, the total-internal reflection at the glass-air interface of a prism acts as a separate

saturation mechanism for each cantilever, which supports the system to limit the diverging oscillations within a single feedback loop.

6.1 Self-sustained oscillations (SSOs) of MEMS cantilever arrays

The concept of self-sustained oscillation (SSO) has been commonly used to maintain oscillations of dynamic MEMS sensors. In resonant mass sensing systems, a MEMS structure is oscillated at its resonant frequency and the shift in the resonant frequency is monitored to detect minute amounts of chemicals that bind on the sensor surface [15, 96]. In atomic force microscopy, SSO has been implemented to perform tapping mode imaging [124, 125]. MEMS cantilevers are commonly used in the above mentioned systems. In an SSO system that uses a cantilever as the mechanical structure, the oscillation frequency locks to the resonant frequency of the cantilever with the help of a feedback loop that contains a saturation mechanism [100]. The feedback loop, which consists of a differentiator and an amplifier, is typically very simple for the fundamental mode oscillation where the system output is delayed, amplified and fed back to the cantilever for the excitation at resonance [102]. Thus, the main advantages of the SSO mode compared to the open loop or phase-locked loop (PLL) driven operations are mainly the simplicity of the electronics used and the possibility to parallelize the system easily due to this introduced simplicity.

The SSO of a single cantilever can be achieved simply by using a nonlinear element (a variable limiter) in the electronics with a single feedback [126, 127]. However, it is not possible to sustain multiple oscillations from an array of cantilevers with a common electrical saturation block [123]. In addition, dense MEMS/NEMS arrays with large number of elements cannot be interfaced easily to the separate actuation and readout electronics for the SSOs from multiple cantilevers. Therefore, oscillator arrays that share common actuator and electronics are desirable for multi-channel sensor applications. Mechanical or optical saturation mechanism can simply provide the required separate

saturation mechanism in order to achieve this multi-channel oscillation operation [123]. Chen et al. presented a mechanical nonlinearity related to the intrinsic nonlinear dynamics of the mechanical oscillator to sustain oscillations [128]. Although mechanical nonlinearity is suitable for sustaining oscillations in an array using a single feedback loop, the designated mechanical nonlinearity was used for a single oscillator [128]. Nevertheless, optical non-linearity offers the required separate saturation mechanisms of each oscillator with a simple architecture to achieve multiple oscillations from multiple cantilevers in a closed-loop system [104, 123].

In the next subsections, it is focused on the analysis of the SSO system and the theoretical limits, in order to maintain multiple oscillations. The theory of the SSO for a single cantilever case was well developed and reported previously [100, 129-131]. However, the theory of the multi-cantilever SSO operation has not been visited until now. The analysis of the multi-cantilever SSO is significant to understand the operation of the system, and it provides better and conscious designs by defining the operation limitations and specifications. Moreover, non-linear optical methods can have a significant effect on enabling the self-sustained oscillation (SSO) operation of MEMS cantilever arrays in a closed-loop system as it will be discussed in detail after analyzing the SSO system and the theoretical limits.

6.1.1 Sensor Array Oscillator Operation

Figure 6-1 shows block diagram overview of a sensor array using multiple cantilevers with SSO. The inputs can be biological, chemical or mechanical and the outputs are the oscillation frequencies of the cantilevers in the array. As it will be discussed in Section 6.1.2, different critical gain for each oscillator would be required for multiple cantilever SSO operation. This can be accomplished using different detector and amplifier for each cantilever. However, if each cantilever has a different saturation mechanism and non-

linearity, only one detector can be sufficient which substantially simplifies the system for array oscillators.

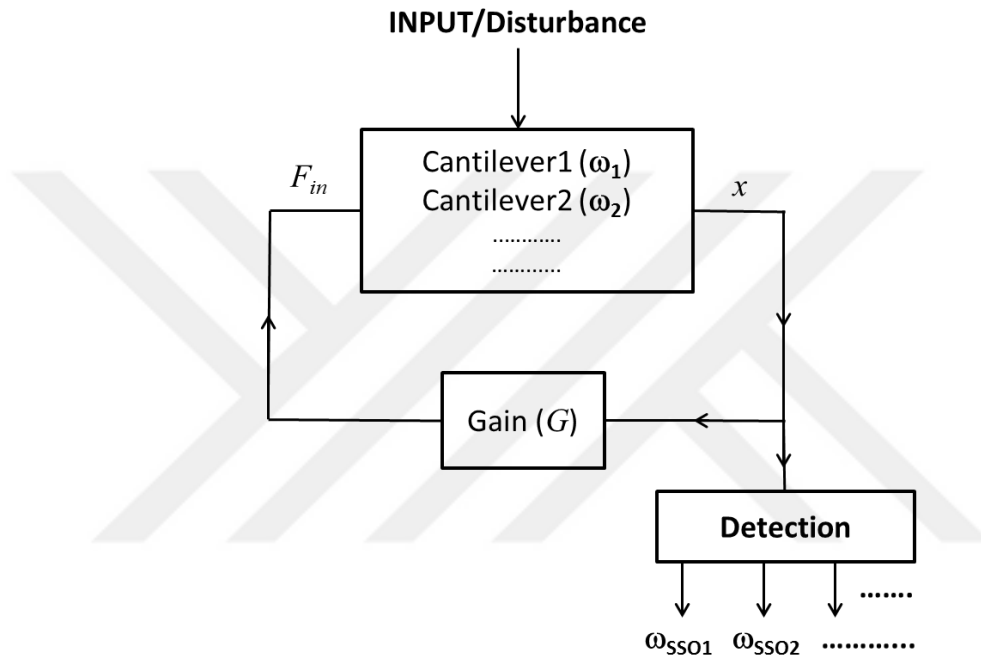


Figure 6-1: The system block diagram of a sensor array operating in self-sustained oscillation mode.

6.1.2 Theory of the Two- Cantilever SSO

In an SSO system the closed-loop oscillation frequency locking is maintained by providing necessary gain and phase shift in the oscillation loop. For the sake of simplicity, “oscillation frequency” term is used for the oscillating closed-loop system whereas “resonant frequency” term is used for the cantilevers throughout the manuscript.

Figure 6-2 shows the block diagram of the closed-loop two-cantilever SSO system which can be built using magnetically actuated nickel cantilevers and a nonlinear optical readout. One such implementation has been described in [122].

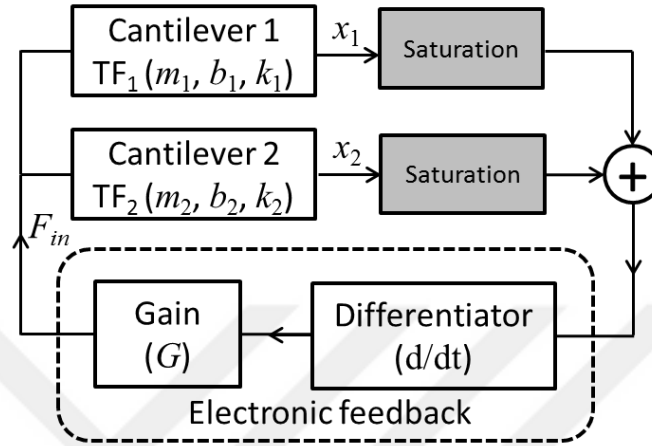


Figure 6-2: Two cantilevers SSO block diagram with separate saturation blocks belonging to the each branch.

The cantilever displacements, x_1 and x_2 , is detected by optical means and the actuation force, F_{in} , is created by an electro coil. The equation of motion of the two-cantilever system can be written starting with the transfer functions of the two cantilevers:

$$m_1\ddot{x}_1 + b_1\dot{x}_1 + k_1x_1 = F_{in} \quad (19)$$

and

$$m_2\ddot{x}_2 + b_2\dot{x}_2 + k_2x_2 = F_{in} \quad (20)$$

where $m_{1,2}$, $b_{1,2}$, $k_{1,2}$, are the effective masses, total damping's, spring constants, respectively. F_{in} depends on both responses of the first and the second cantilevers, i.e. x_1 and x_2 respectively; and also the feedback loop transfer function. F_{in} is:

$$F_{in} = G(\dot{x}_1 + \dot{x}_2) \quad (21)$$

In the Laplace domain, one can combine (19), (20), and (21) to find the characteristic equation:

$$m_1 s^2 + b_1 s + k_1 = G s \left[1 + \frac{m_1 s^2 + b_1 s + k_1}{m_2 s^2 + b_2 s + k_2} \right] \quad (22)$$

Equation (22) results in a 4th order polynomial. In general, there are 2 pairs of complex conjugate roots. If the roots have negative real parts, the system results in exponentially decaying sinusoidal oscillations. For positive real parts, the system exhibits exponentially growing sinusoidal response. One can also plot the locations of the roots on the complex plane. The location of the roots on the complex plane is determined by the gain parameter (G) in the feedback. Therefore the gain parameter determines the nature of the response. In a special case, where G is equal to the total damping of the system, s term in the characteristic equation vanishes and the solution has purely imaginary roots. However, in practice to sustain oscillations, it is not feasible to set the gain such that all the losses in the system are exactly compensated. Thus, by making the gain value a little above the critical value, it is possible to obtain diverging oscillations. These diverging oscillations stabilize at amplitude determined by the non-linearity, i.e. saturation mechanisms in the loop [100]. This non-linearity could be provided electrically, optically or even by mechanical means.

MATLAB was used to find the roots of the characteristic equation in (22). Figure 6-3 shows the location of the roots on the complex plane where only the positive imaginary axis is considered. There are two systems depicted in the graph. The system S1 has two cantilevers with two different resonant frequencies, where one cantilever has a resonance at f1=100 kHz and the second one has a resonance at f2=103 kHz while the second system S2 has two cantilevers with resonant frequencies at f1=100 kHz and at f2=100.5 kHz for the first and second cantilever respectively. The cantilevers in both systems (S1 and S2) are assumed to have the same k=1N/m and Q=100.

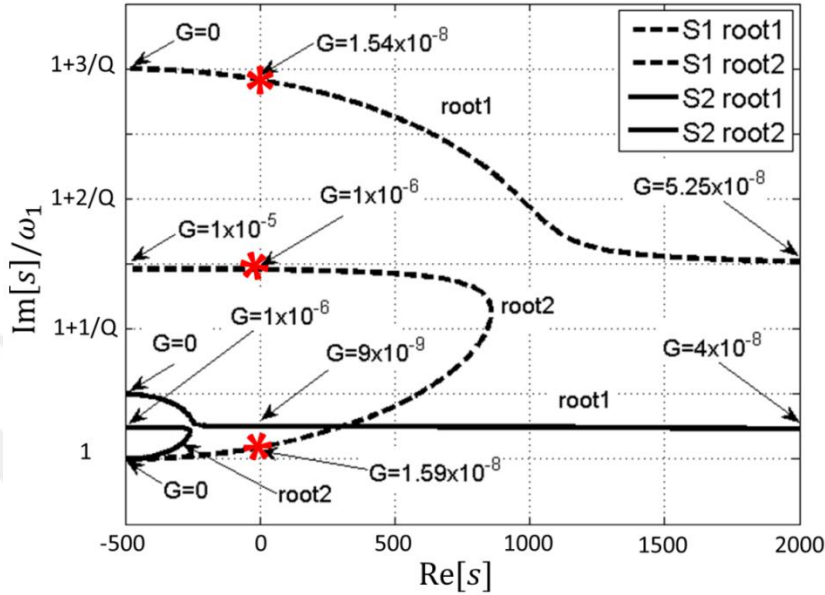


Figure 6-3: The location of the roots of two cantilever SSO system when gain is swept from zero to 1×10^{-5} . S1 has the following properties $f_1=100$ kHz, $f_2=103$ kHz. Red stars indicate the SSO frequencies of S1. S2 has the following properties $f_1=100$ kHz, $f_2=100.5$ kHz. The Q and the spring constants of the cantilevers in both systems are 100 and 1 N/m, respectively.

According to these system definitions, the difference between the resonances of the cantilevers in S1 is adjusted such that both roots intersect the imaginary axis where the real parts are zero, on the other hand only one root of S2 system intersects the imaginary axis. In S2 system, there is very little separation between the individual cantilever resonant frequencies. The roots of the characteristic equation (22) in order to obtain SSO are marked with red star marks. The star in the middle corresponds to the mutual oscillation frequency while the other two stars correspond to separate oscillation frequencies for different gain settings. Therefore, S1 will have potentially two distinct oscillation frequency in a closed-loop system, whereas S2 will have only one oscillation frequency, which is the average of the individual oscillation frequencies of the two cantilevers. Based on Figure 6-3, one can calculate the oscillation frequencies and the required gain in a closed-loop system. The minimum required gain is achieved when the real part is zero (i.e

poles are on the imaginary axis). We ran this calculation for a two-cantilever SSO system where we swept the resonant frequency of one of the cantilevers and calculated the oscillation frequency of the SSO while keeping the resonant frequency of the other cantilever constant. We assumed that the Q s and the spring constants of the cantilevers are the same, which is the case when arrays of cantilevers are fabricated on the same substrate with slightly changing lateral dimensions. Such arrays are used in resonant mass detection systems.

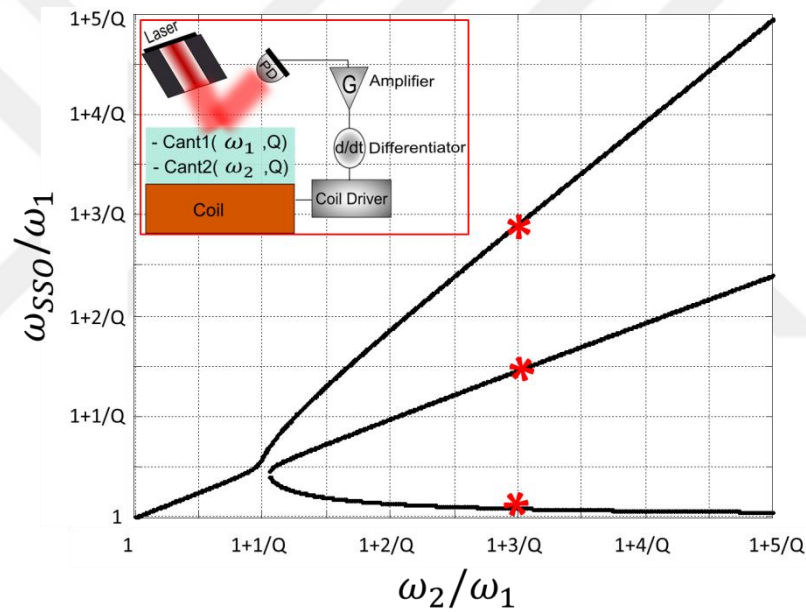


Figure 6-4: The analytical solution of the equation of motion (22) of the two-cantilever SSO system. The cantilevers have two different resonant frequencies (ω_1 , ω_2). Both axes are scaled by the frequency of Low Resonant Cantilever (ω_1). ω_1 is assumed fixed and the High Resonant Frequency is varied (ω_2). Vertical axis shows the solutions of (22) for the two-cantilever SSO system (ω_{SSO}). Spring constants ($=1$ N/m) and the Q -factors ($Q=100$) of cantilevers are assumed equal. Red stars show the SSO frequencies of S1 illustrated in Figure 6-3.

The inset image in Figure 6-4 shows the basic model that is used for the calculation of SSO frequencies (ω_{SSO}) in a two-cantilever system with different resonant frequencies (ω_1 , ω_2). According to the model, obtaining separate oscillations depend both on the resonant

frequencies and the bandwidths of the cantilevers. If the resonant frequencies of the cantilevers are too close to each other (i.e. when the normalized high resonant frequency is in the range 1 and $1+1/Q$), the SSO system collapses into a single joint oscillation frequency. When the normalized high resonant frequency is greater than $1+1/Q$, there are three solutions of (22) as seen in Figure 6-4. The SSO frequencies of the system S1 are indicated with red stars in Figure 6-4, which corresponds to $1+3/Q$ in the x-axis. These three different oscillation frequencies lead to three different critical gain values as expected, which can be called as high, mutual, and low oscillation frequency critical gain values. The critical gain value belonging to the mutual oscillation frequency is always higher than the other two critical gain values (Figure 6-3, 1.54×10^{-8} (corresponds to highest star in Figure 6-4) and 1.59×10^{-8} (corresponds to lowest star in Figure 6-4) for low and high resonances, 1.6×10^{-6} (corresponds to middle star in Figure 6-4) for the mutual oscillation). Therefore, saturation mechanism becomes more of an issue in order to sustain multiple oscillations.

Basically, there can be two different saturation configurations in the SSO closed-loop system: either there is a single common saturation block in the feedback loop, or there are separate saturation mechanisms belonging to each oscillator, i.e. cantilever. When only one common single feedback saturation mechanism is employed, the overall loop gain of the system decreases to the lowest critical gain and sustained oscillations are obtained. Thus, the oscillation frequency with the lowest critical gain can present in the system; whereas the other oscillation frequencies extinguish.

SSO system with separate saturation blocks belonging to each cantilever (shown in Figure 6-2) can have different loop gains, and therefore it is possible to sustain two separate oscillation frequencies having different critical gains. Since the low and the high oscillation frequencies have lower critical gain values compared to the mutual oscillation frequency, two oscillation frequencies, which are sustained in the SSO system will be the

low and the high oscillation frequencies. When the low (high) oscillation frequency sustain in its own branch, its effect on the other saturation block is degraded by the band-pass filtering effect of the high (low) resonance frequency oscillator. Thus, each saturation block is effectively saturated by the oscillation frequency supported by the cantilever in its branch.

Two main criteria are determined so far in order to have separate oscillation frequencies:

- i. Two resonant frequencies of the cantilevers should be separated by more than their 3 dB bandwidth $BW=f/Q$ (i.e., the frequency spacing $\Delta f > BW$ or more precisely $\Delta f > 0.5(BW_1 + BW_2)$).
- ii. Separate saturation mechanisms are needed for each cantilever.

Cantilevers are also used for biosensor applications in liquid environments. The resonant frequency differences between the cantilevers must be relatively large to make them operational, because the resonant frequencies and the damping can change considerably in liquid. For example, if 100 kHz resonant frequency cantilevers with Q of 100 are to be operated in liquid, the resonant frequency will drop to 30 kHz due to fluid damping (based on unpublished experimental data). The 3dB bandwidth will also increase 10 times reducing the Q to 10. In this case, to sustain separate oscillations in an SSO system, one needs to design cantilevers to operate at 30 kHz and 33 kHz. Moreover, the other effects such as cross-coupling between the oscillators should be considered for biosensor applications.

6.1.3 Cross-Coupling Effect

The coupling between the oscillators has first come into consideration to describe the frequency effects of one oscillator on the second one operating at a close by frequency when electronic oscillators were built for microwave systems [132, 133], and continues attracting attention, especially in radio frequency (RF) field [134, 135]. Although it is

mostly investigated for RF systems, the phenomenon can be observed in any system that involves coupled oscillators, such as the cantilever systems considered here. Therefore, the changes in the resonance of one cantilever will affect the oscillation frequency of the other cantilever as shown in Figure 6-4.

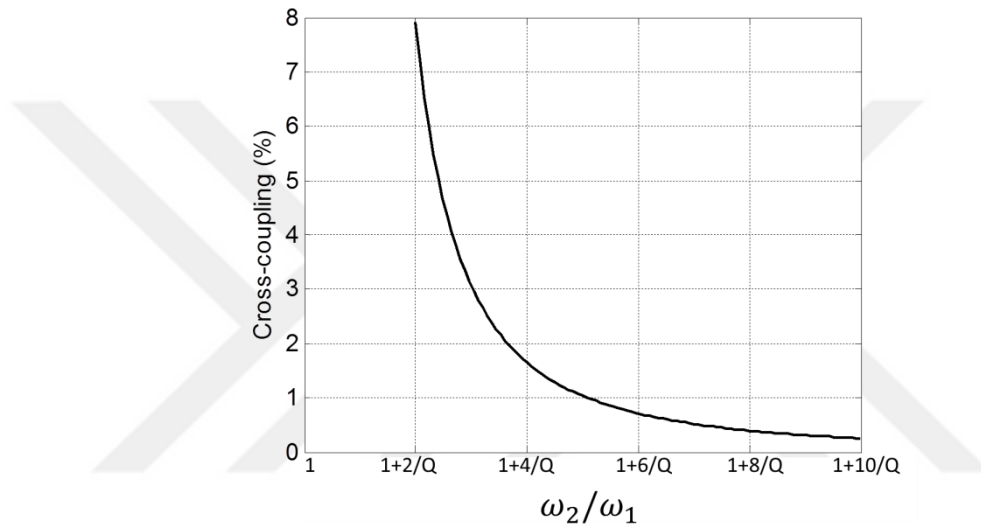


Figure 6-5: Cross-coupling between the SSO frequencies of two cantilevers oscillating in an SSO system. This figure shows the change in the oscillation frequency of the cantilever with low SSO frequency due to a change for the cantilever with high resonant frequency.

Figure 6-5 shows the amount of cross-coupling between two cantilevers as one of the resonances (ω_2) increased while ω_1 is kept constant. As expected, as the frequency separation increases cross coupling decreases. If the separation between the normalized resonant frequencies is higher than 5BW the cross coupling drops less than 1% i.e. if one of the resonances shifts 1 Hz, the other resonance will shift less than 0.01Hz. This cross-coupling leads to another phenomenon called as *frequency pulling* effect. When the two cantilevers are oscillated at the same time, there will be slight changes in the frequencies of the oscillators. This frequency pulling can be investigated by considering the open-loop

frequency response of the system shown in Figure 6-2, from F_{in} to the input of the differentiator stage.

In the closed-loop system, the cantilevers will oscillate at the frequencies determined by the combined phase curve. When the resonant frequencies of oscillators are too close to each other, both oscillators oscillate at a mutual frequency through which is called *injection locking*. If the resonant frequencies are well separated then they affect each other slightly. This is called *injection pulling*. According to the derived solution, cross-coupling between two cantilevers can be calculated, and the sensor output can be corrected in view of the above.

6.2 Non-linear optical readout with integrated diffraction gratings

It's been already mentioned that saturation mechanism is vital for oscillators. In addition to this, we already discussed that separate saturation mechanisms are needed in an effort to sustain multiple oscillations. The electrical non-linearity can be an example of common single saturation whereas both the mechanical and optical non-linearities can be the examples of separate saturation mechanisms for the MEMS cantilever based sensor array system. Consequently, one can use either mechanical or optical non-linearities for the purpose of having separate saturation mechanisms with a single feedback loop. The mechanical saturation depends only on the deflection amplitude and the mechanical properties of the cantilever, and it can be observed when the deflection values are high enough to create non-linearity. But in this work, the operating points of the cantilevers are far away from the mechanical saturation, which makes it unfeasible to use mechanical saturation to sustain multiple oscillations in the SSO system.

In view of the above, the desired saturation mechanism can be generated using a diffraction grating based optical readout as shown in Figure 6-6. Figure 6-6a shows the cross-section of a single cantilever with diffraction gratings. In Figure 6-6b, the system overview with a detailed illustration of the optical readout setup is given. The actuation of

the cantilevers was achieved by using an electro coil, which provides an alternating magnetic field that will drive the cantilevers at their resonant frequencies. The coil was placed underneath the cantilevers along with a set of magnets.

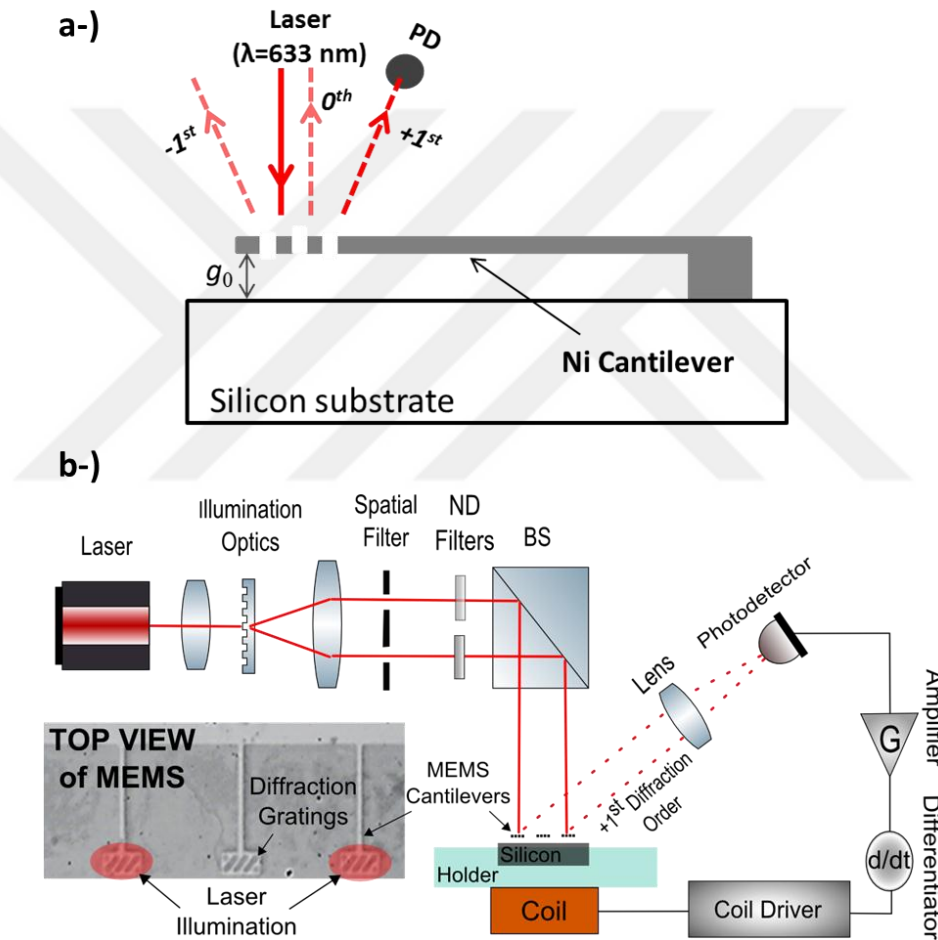


Figure 6-6: a-) Cross-section of a cantilever with an integrated diffraction grating. 0^{th} and $\pm 1^{\text{st}}$ diffraction orders are shown. A photodiode (PD) is used to monitor the $+1^{\text{st}}$ diffraction order. b-) The system overview of the nonlinear optical readout of the two-cantilever SSO system. Neutral density (ND) filter to attenuate and equalize outputs of channels; Spatial filter: two square openings to select the desired cantilevers. Inset shows top view of a cantilever array overlaid with laser illumination area.

The interferometric readout is based on the OPD between the reflected light from the diffraction grating integrated MEMS cantilever surface and from the substrate underneath the cantilever array [56, 122]. The OPD of the incident beam is twice the sum of the initial gap underneath the cantilever and the deflection amplitude of the cantilever. The non-linear characteristic of the interferometric readout is explained as:

$$I = B \sin^2\left(\frac{2\pi}{\lambda}d\right) = \frac{B}{2} - \frac{B}{2} \cos\left(\frac{4\pi}{\lambda}d\right) \quad (23)$$

where I is the intensity, B is the constant amplitude depending on the gain of the photodetector and laser power, λ is the wavelength of the readout laser beam, and d is the varying gap with respect to time, which can be written as:

$$d = g_0 + A \sin(\omega_0 t) \quad (24)$$

where g_0 is the initial gap underneath the MEMS cantilever when there is no deflection, A is the deflection amplitude, and ω_0 is the deflection oscillation frequency.

Figure 6-7 shows the calculated and experimental interferometric response curve based on the intensity of the +1st diffraction order with respect to gap for the grating readout. In the experiment, a magnet was placed under the MEMS cantilevers and the magnetic field deflected the cantilever towards the substrate and the initial gap changed. The selected cantilever was illuminated with a red laser ($\lambda=633$ nm). The amplitude of the +1st diffracted order from the grating was measured while moving the magnet using a precision translation stage. The magnetic field was also measured using a Tesla-meter. We calibrated these measurements by measuring the actual displacement of the cantilever under white light interferometer for a given magnetic field. Then the measured intensity values are plotted with respect to the gap distance which is transformed from the recorded magnetic

fields. There is a good agreement between the experimental and calculated data. As it can be seen from this, the interferometric response curve is the saturation mechanism which limits the oscillation amplitude due to the optical nonlinearity. This sinusoidal nonlinearity provides the separate saturation mechanisms from the diffraction gratings needed for each cantilever. Thereby, each oscillator has its own loop gain and oscillation frequency independent from the other oscillators in the array.

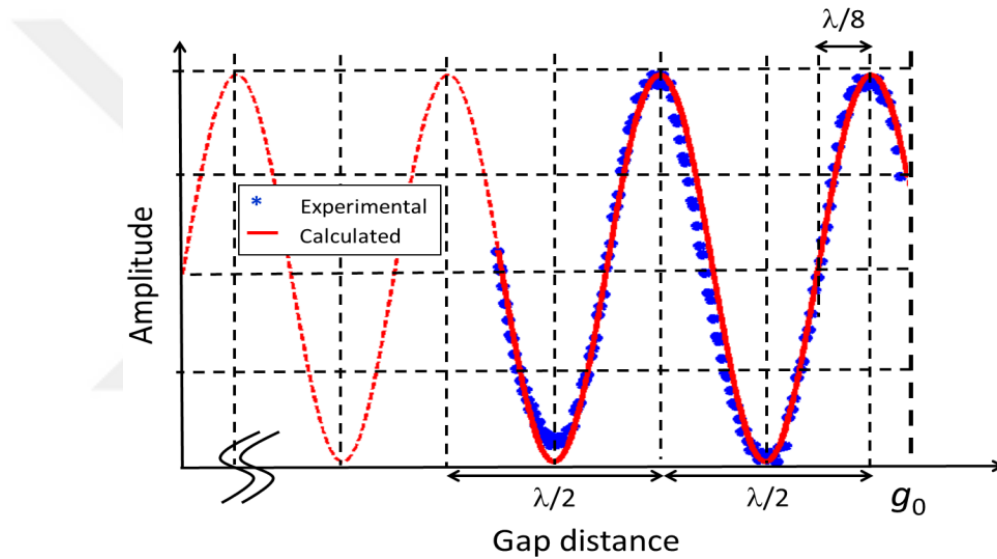


Figure 6-7: Interferometric response curve according to the calculated and the experimental data. Experimental data is obtained by moving a super strong magnet from the closest point to the cantilevers to a farther location. g_0 shows the nominal gap between the cantilever and the substrate. Gaps those are different from the nominal value results in reduced sensitivity.

6.2.1 Simulation Results

MEMS based cantilever array SSO system with two cantilevers was modeled using MATLAB Simulink. System analyses were performed firstly using two cantilever sensor model with a common electronics saturation block. Secondly same cantilever model was used with separate saturation blocks by means of nonlinear optical readout.

Table 6-1: Resonance and corresponding oscillation frequencies of the two-cantilever SSO system for changing dominant saturation mechanisms

Case	1 st cant. res. freq. (kHz)	2 nd cant. res. freq. (kHz)	Dominant Sat. Mech.	System Osc. Freq. (kHz)	
1	100	105	<i>Optical & Separate</i>	100.04	104.96
2	100	102	<i>Optical & Separate</i>	100.11	101.87
3	100	101	<i>Optical & Separate</i>	100.36	100.62
4	100	105	<i>Electrical & Common</i>	Single osc. (~100 or ~105)	
5	100	100.5	<i>Optical & Separate</i>	100.25	
6	100	100.5	<i>Electrical & Common</i>	100.25	

Several cases were investigated as shown in Table 6-1. The frequency of 1st cantilever was fixed at 100 kHz while the frequency of 2nd cantilever was varied. We also assumed the 3 dB bandwidth as 1 kHz for both cantilevers. Table 6-1 lists the cantilever resonant frequencies and the resulting simulated oscillation frequencies in the system. The simulation results listed in Table 6-1 lead to the following conclusions, which also support the analytical findings related to the single and multiple SSO frequencies and the cross-coupling effect between the cantilevers:

- *Case 1, 2, 3:* It is possible to sustain multiple SSO, if the resonant frequency difference is greater than the 3 dB BW. This is enabled by having separate saturation mechanism in each branch.
- *Case 4:* The system oscillates at the resonant frequency of the oscillator with the lower critical gain with a slight shift due to frequency pull of the other cantilever.

Thus, two oscillation frequencies cannot be observed even though the two resonances are well separated. This is due to the common saturation mechanism employed.

-- *Case 5, 6:* There is only a single mutual oscillation in the system, as the resonant frequency difference is lower than the 3 dB BW.

6.2.2 Experimental Results

In the experiments, we used nickel cantilevers with integrated diffraction gratings. Figure 6-8 shows optical microscope pictures of the cantilevers. The resonant frequencies of these cantilevers were around 20 kHz in air.

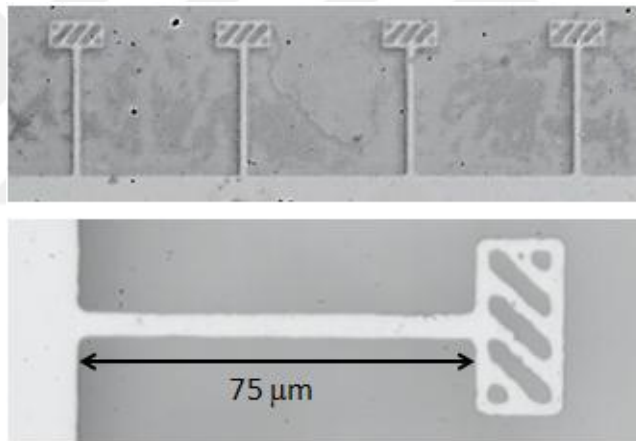


Figure 6-8: Nickel cantilevers were used in the experiments. The thickness is 2 μm . Top picture shows a portion of a cantilever array. Bottom picture is the zoomed view of one of the cantilevers.

In the experiments, the cantilevers were illuminated by a red laser, which has a wavelength of 633 nm. During cantilever fabrication, the gap between the grating and the substrate was set to obtain maximum sensitivity as described in Figure 6-7. If one can set the gap g_0 to $n\lambda/2 + \lambda/8$ where n is an integer number, the grating operates with maximum sensitivity. However, fabrication non-uniformities affected the gap. Therefore, the sensitivity of each cantilever was slightly different depending on where the grating

operates in the non-linear response curve as indicated between $g_0 - \lambda/8$ and $g_0 + \lambda/8$. As shown in Figure 6-6b, we added neutral density filters (attenuator) on the laser beam path to approximately equalize the optical output of the cantilevers, and a spatial filter consisting of two square openings to illuminate the desired cantilevers. The cantilevers were vibrated by an AC magnetic field generated by an electro magnet (coil). While obtaining frequency scans, we kept the drive current for the coil small enough to operate the grating at its linear region. However, we confirmed (using a laser Doppler vibrometer) that the oscillation amplitudes were around 160 nm ($\lambda/4$) peak-to-peak at the tip of the cantilevers for the SSO systems. This confirms that the amplitude is limited by the optical non-linearity, not by the coil drive current.

To demonstrate Case 5 of Table 6-1, we selected two cantilevers with resonant frequencies that were very close to each other. The individual frequency responses of the cantilevers are shown in Figure 6-9. The gain of the feedback electronics were increased until an oscillation was achieved. Cantilever SSOs were observed one at a time by blocking the light diffracted from the other cantilever and subsequently they were observed simultaneously without changing the gain and phase settings.

Resonant frequencies and quality factors are summarized in Table 6-2. The oscillation frequencies for individual cantilevers (f_1 and f_2) are given in the 4th row of the table. The cantilevers do not oscillate exactly at the peak amplitude of the resonance curve due to the additional phase errors that may exist in the electronics. Nevertheless, when both cantilevers are oscillated in the same closed-loop system, rather than two oscillations, there exists only one oscillation at a frequency (f_3) between f_1 and f_2 which is due to the resonant frequency separation which is smaller than $\Delta f < 0.5(BW_1 + BW_2)$. When the two cantilevers are involved in the closed loop system, both SSO frequency (f_3) should be in the middle of f_1 and f_2 according to the theory. Experimentally determined “both SSO” frequency (f_3)

confirms the theory with a small error (due to the phase shift in the electronics) that was outlined theoretically and with the simulation results.

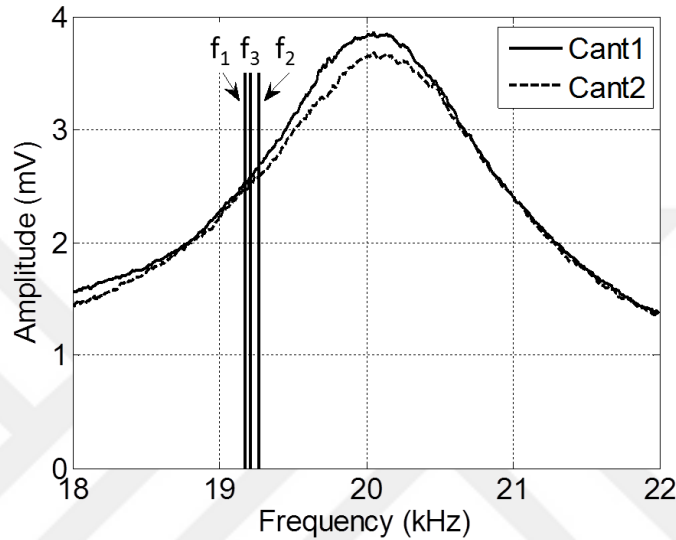


Figure 6-9: Frequency response of two cantilevers that have very similar resonant frequencies. Oscillation frequencies (f_1 , f_2 , f_3) from Table 6-2 are also added to the figure.

Table 6-2: Resonances and corresponding oscillation frequencies of the two-cantilever SSO where individual resonances are very close.

	Cant1	Cant2
Amplitude peak	20.051 kHz	20.055 kHz
BW (Q)	1.5 kHz (13.37)	1.61 kHz (12.38)
Separate SSO	19.176 kHz (f_1)	19.264 kHz (f_2)
Both SSO	19.216 kHz (f_3)	

We also experimented with cantilevers where there was a larger separation in the resonant frequencies. The selection of the cantilevers aligns with Cases 1,2,3 of Table 6-1. We repeated the same procedure to oscillate the cantilevers. We increased the gain until we observed two oscillations. The spectra of the individual cantilever and two cantilevers SSO's are given in Figure 6-10.

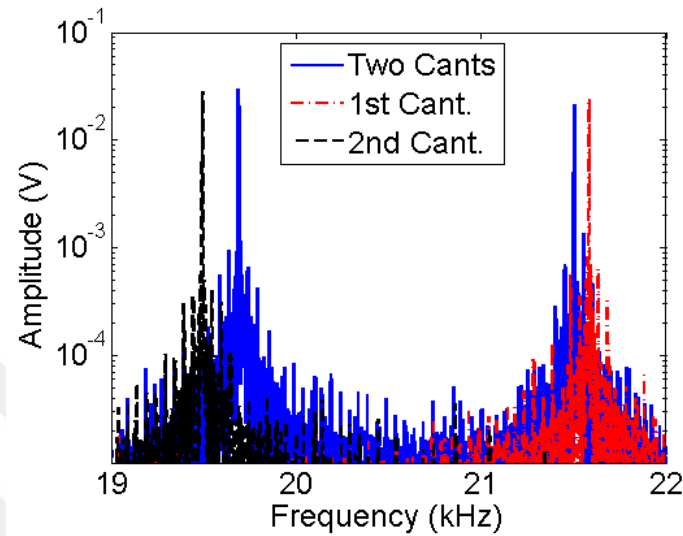


Figure 6-10: Spectra of SSO system when individual cantilevers and both cantilevers are oscillated. The individual oscillations were obtained by selectively blocking the light diffracted from the cantilevers.

The individual frequency sweeps of the cantilevers are given in Figure 6-11 along with the oscillation frequencies of the SSO systems. As before, the cantilevers do not oscillate at the peaks of their resonance curves due to the additional phase errors that may exist in the electronics. Same phase and gain settings were used in all measurements. The resonance properties are summarized in Table 6-3. The individual oscillation frequencies (f_1 and f_2) of the cantilevers in an SSO system are 19.6 kHz and 21.617 kHz. When both cantilevers oscillated in the SSO, the oscillation frequency corresponding to the cantilever with low resonant frequency (f_3) increased by 185 Hz and the oscillation frequency of the other cantilever (f_4) reduced by 90 Hz which is an experimental observation for injection pulling. According to the theory outlined, since the resonant frequencies of the two cantilevers are separated larger than $0.5(BW_1 + BW_2)$, one should observe two separate oscillations in the closed loop system. The separate SSO frequencies (f_1 and f_2) should get closer to each other in a closed loop system, which exhibits the both SSO frequencies (f_3 and f_4). The magnitudes of these shifts are difficult to estimate using the model that we developed

because of the additional phase errors in the electronics but the behavior is consistent with the simulations.

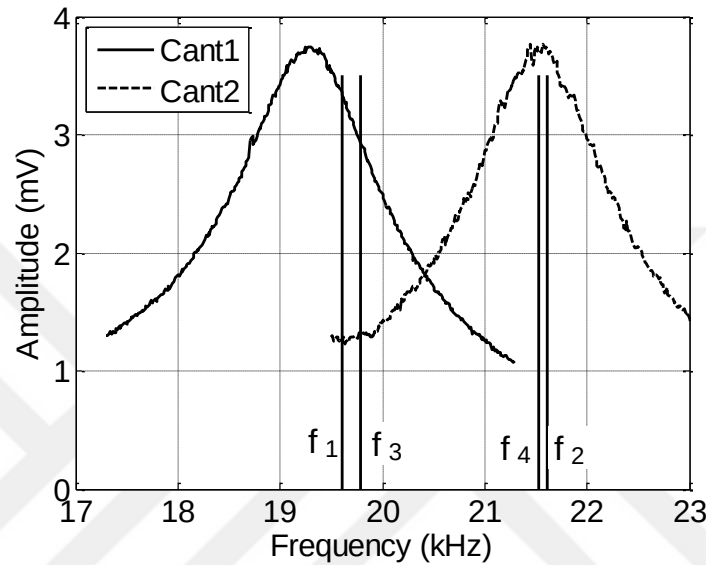


Figure 6-11: Frequency response of two cantilevers that have resonances further away from each other. Oscillation frequencies (f_1 , f_2 , f_3 , f_4) from Table 6-3 are also added to the figure.

Table 6-3: Resonances and corresponding oscillation frequencies of the double cantilever SSO where individual resonances are further away.

	Cant1	Cant2
Amplitude peak	19.325 kHz	21.577 kHz
BW (Q)	1.301 kHz (14.85)	1.234 kHz (17.48)
Separate SSO	19.600 kHz (f_1)	21.617 kHz (f_2)
Both SSO	19.785 kHz (f_3)	21.527 kHz (f_4)

6.3 Prism-based non-linear optical readout for MEMS cantilever arrays

Prism-based approach has been used for angle measurement in the past. The direction of an optical beam reflected from a moving surface can directly be measured by internally reflecting the beam near the critical angle using a single prism [136, 137]. This technique

offers high sensitivity in angle measurements [110]. To our knowledge, prism-based method has not been used for measuring MEMS cantilevers before.

In this section, prism-based optical readout was used for both the open-loop (frequency sweeping) and closed-loop (obtaining SSOs) operation of the MEMS cantilevers. A right-angle prism was used in order to directly convert the change in the tilt angle of the MEMS cantilevers to the change in the optical power at the detector plane. Prism's hypotenuse plane was used for the internal-reflection near the critical angle by means of the refractive index difference between the N-BK7 glass ($n=1.5168$) and air ($n=1$). This hypotenuse plane acts as an optical sensor that transforms the change in the incident angle to a change in the reflectivity for the glass-air interface and thus, optical intensity measured at the detector. The direct measurement of this angular change makes this method simple and convenient for MEMS cantilevers. In order to obtain a better responsivity, a TM polarized wave is used for illumination, for which the reflectivity vs. the incident angle of the incoming wave function has a higher slope. In addition, the prism-based optical readout provides the separate saturation mechanism for enabling the multiple oscillations in a closed-loop system. Furthermore, the prism-based non-linear optical readout method has the potential for being used with smaller size (e.g., nano-cantilevers) cantilevers. This unique optical readout method is explained for open-loop and the closed-loop case in separate subsections.

6.3.1 Open-Loop Operation

In the open-loop operation, an AC signal generator was used in order to sweep the frequency in a pre-defined range to track the resonance of the MEMS cantilevers. Figure 6-12a shows the proposed prism-based optical readout setup for open-loop operation. A TM polarized red laser beam ($\lambda=633$ nm) was focused onto a single cantilever that was placed on top of a coil. The numerical aperture (NA) of the illumination optics, which composed of a magnifier system and a focusing lens, was selected to maximize the

responsivity. The reflected light from the single cantilever was directed to the right angle prism by using a beam splitter. Then the light was refracted through the prism, which has a refractive index of $n=1.5168$, and propagated towards the hypotenuse plane of the prism. The beam was exposed to an internal reflection due to the refractive index difference of the glass-air interface before captured on a PD with a lens.

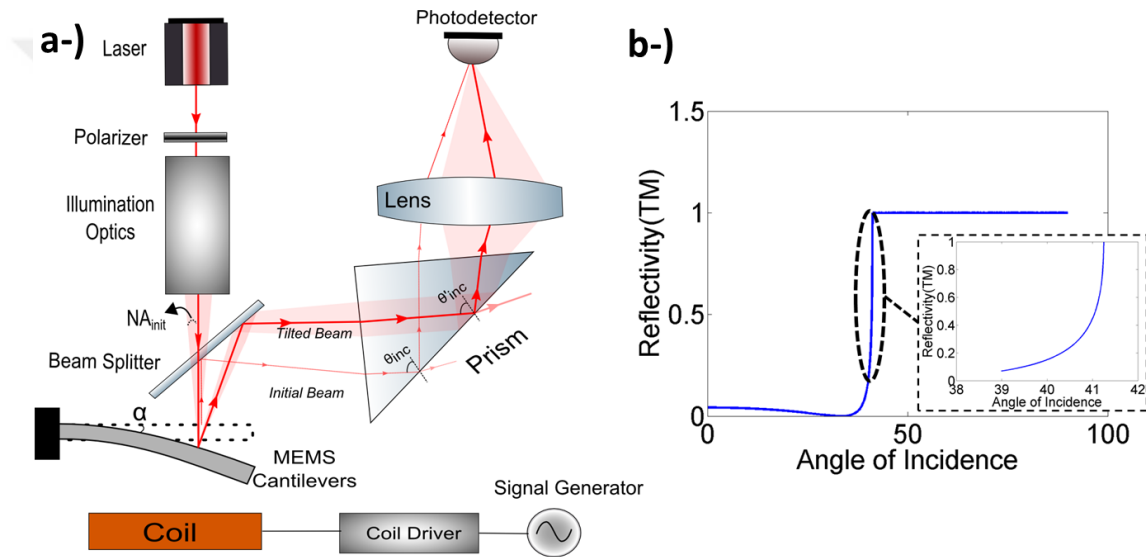


Figure 6-12: (a) The system overview of prism-based optical readout system for open-loop cantilever operation (b) Reflectivity of a glass ($n=1.5168$) – air interface ($n=1$) for TM polarization [136].

Here, α is the cantilever's tilt angle and θ_{inc} is the initial beam's incident angle with respect to the normal of the prism's hypotenuse plane. With an angular tilt of α , the beam's tilt angle changes by 2α at the prism's entrance plane just before it was refracted through the prism. When the tilted beam was exposed to refraction, the angular change in the prism just after the refraction was calculated (assuming that both the initial angle and the tilt angle are small) as $\sin^{-1}((n_{air}/n_{prism})\sin(2\alpha))$ according to the Snell's law. The incident angle of the tilted beam with respect to the normal vector of the prism's hypotenuse plane (θ'_{inc})

can be calculated according to this angle change. Figure 6-12b illustrates the reflectivity of a glass-air interface with respect to the angle of incidence for a TM polarized wave [136]. The inset shows the change of the reflectivity near the critical angle, where the reflectivity curve has the highest slope. One should set an initial tilt angle to the prism in order to operate in this high responsive part.

A model was developed in MATLAB in order to analyze the prism-based non-linear optical readout method. In this model, the laser beam profile was assumed as 1D Gaussian function. The angular intensity distribution of the beam at the prism's hypotenuse plane was calculated using Snell's law. Figure 6-13a shows the Gaussian beam (NA=0.015) with an initial angle of incidence $\theta_{inc} = 41.1^\circ$ and the corresponding reflectivity curve with respect to incident angle. Then, these two functions were convolved with respect to the incident angle. This convolution gives the effective reflected optical intensity from the hypotenuse plane for different incident angles. This optical intensity curve was calculated for different NA's and incident angles, which have significant effects on the system responsivity, as illustrated in Figure 6-13b. It's noteworthy to mention that, the diffraction effects become negligible by choosing the spot size less than or equal to the cantilever width, which is 50 μm . Therefore, we limited NA to 0.015, which produces a spot radius around 25 μm at the focus point.

Since the angular spread is smaller in the smaller NA case, the slope of the optical intensity curve in Figure 6-13b is larger. In order to clearly show these characteristics of the optical intensity change, the derivatives of these curves were calculated. Figure 6-13c shows the effect of the NA on the responsivity, which corresponds to optical intensity change with respect to incident angle change ($dI/d\theta$) for different NA's. For this calculation, the total optical power values of the beams were assumed equal for different NAs at the source side. It is evident that, smaller NA (NA=0.015) exhibits highest responsivity compared to the larger NAs. The optical intensity responsivity will decrease

with the larger NAs ($NA > 0.015$), which the angular spread depends on the NA of the illumination optics. The initial angle of incidence can be arranged as 41.1° for $NA=0.015$ at the prism's glass-air interface to maximize the optical detection sensitivity of the readout system.

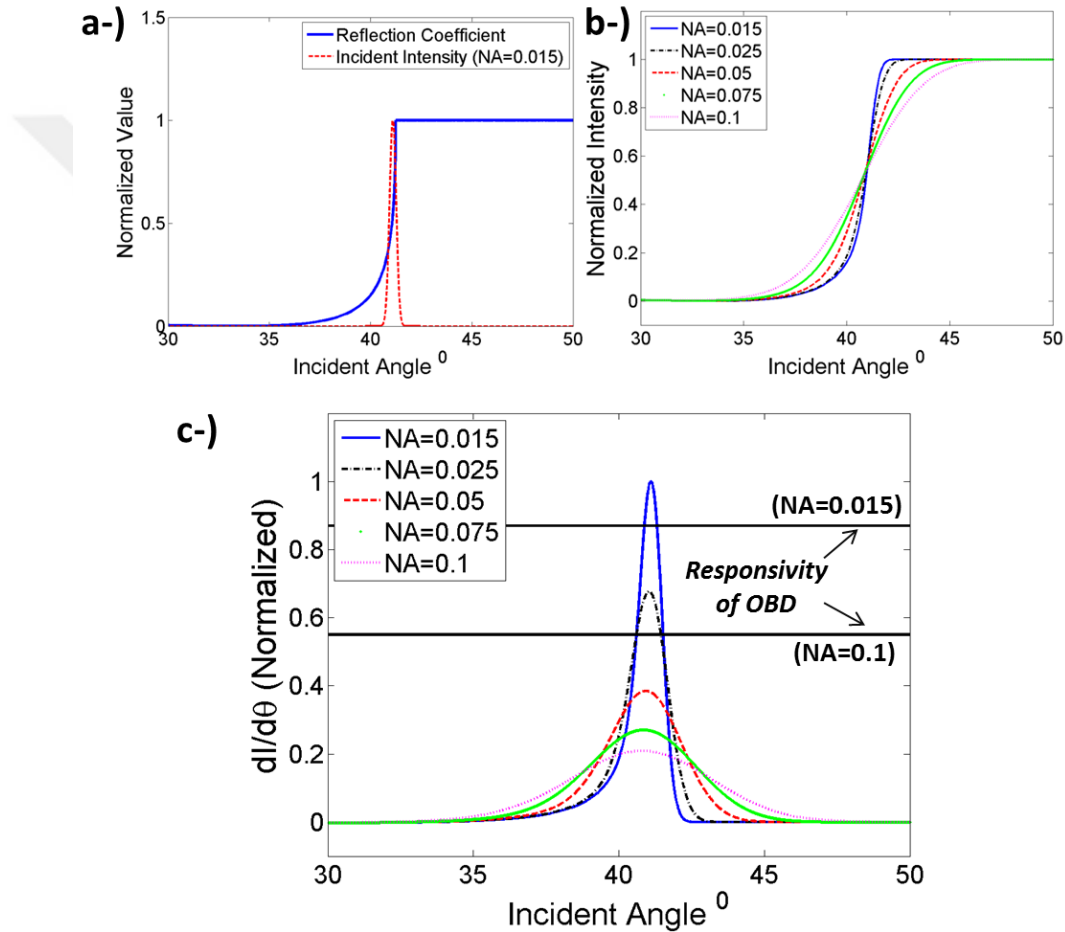


Figure 6-13: Simulations for prism-based optical readout system: (a) Initial Beam Profile ($\theta_{inc} = 41.1^\circ$) at the prism's glass-air interface with respect to incident angle. (b) Normalized intensity (I) with respect to incident angle for different NAs. (c) Optical intensity change (dI) with respect to incident angle change ($d\theta$) for different NAs. The responsivity values of the conventional optical beam deflection (OBD) readout for two different NAs are also provided.

In Figure 6-13c, we also compared the optical beam deflection (OBD) method and the prism based approach. In OBD method, the deflection of the cantilever results in an optical power change due to the imbalance on the two photodetectors of a bi-cell detector. This power change depends on the incident laser power, cantilever length, the displacement of the cantilever and the spot radius at the cantilever plane. On the other hand, it's independent of the cantilever-photodetector distance at the far field [28]. Two different NA values were selected (NA=0.015 and 0.1) for the OBD readout analysis in order to compare this conventional method's responsivity with the prism-based method. Additionally, the laser output power (P) was assumed to be equal for both methods in the analysis. The optical intensity change (dI) with respect to the cantilever angle change (d θ) resulted in $(dI/d\theta)_{bi-cell} = 1.22P\pi/NA$ at the far field for small cantilever angle changes ($\tan \theta \approx \theta$), which was based on the analysis presented in Ref. [28] for a bi-cell detector. The responsivity of the OBD method is constant for different incident angles. The responsivity values for different NAs were normalized according to the largest value in the responsivity curve for NA=0.015. Similarly with the prism-based method, the OBD readout method was also resulted in reduced responsivity for larger NAs as it is illustrated in Figure 6-13c. For the parameters that we used in our experiments, we found that prism based approach resulted in slightly better responsivity than that of OBD method when NA is 0.015.

Further analyses were made for the open-loop operation of a single cantilever as illustrated in Figure 6-14. It was assumed that the cantilever is excited at 30 kHz, which creates 1 μm of peak displacement at the tip of the cantilever (Figure 6-14a). Note that, "peak displacement" term refers to the maximum absolute displacement value at the tip. This 1 μm of peak displacement corresponds to an angle change of 0.535° in the initial beam's incident angle for both direction ($\theta'_{inc} = \theta_{inc} \pm 0.535^\circ$). This will change the total optical light intensity according to the change in the experienced reflectivity values. We selected three different incident angles in the optical intensity curve (NA= 0.015) as

illustrated in Figure 6-14b. Each signal with different incident angles covers an angular range of 1.07° due to the $1\ \mu\text{m}$ of peak displacement. Time and frequency domain optical outputs for the given input are displayed in Figure 6-14c and Figure 6-14d.

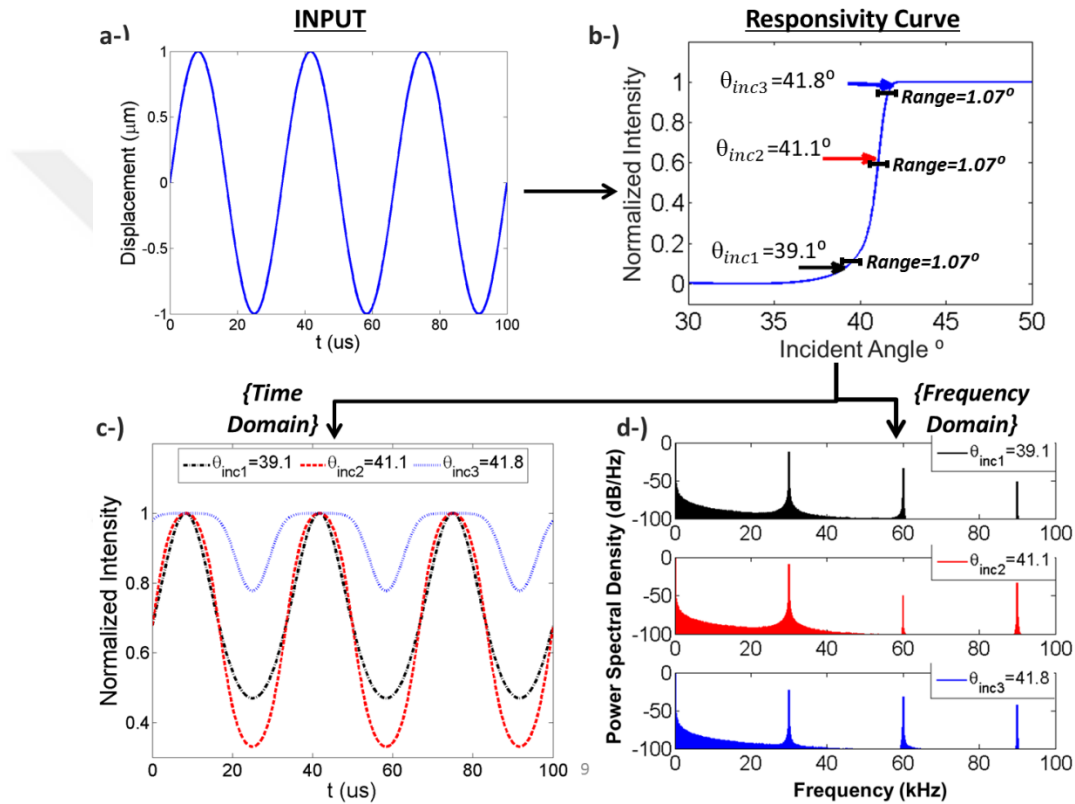


Figure 6-14: Open loop operation of a single cantilever using prism-based optical readout system (a) Input: Cantilever excitation at 30 kHz with a peak cantilever displacement of $1\ \mu\text{m}$. (b) Optical intensity curve with the cantilever displacement range for different incident angles. (c) Time domain output for the given input. (d) Frequency domain output for the given input.

The highest peak to peak signal level was obtained from the signal, which had an incident angle at $\theta_{inc2} = 41.1^\circ$. $\theta_{inc1} = 39.1^\circ$ incident angle gave the second larger signal amplitude. Since $\theta_{inc3} = 41.8^\circ$ is very close to the saturation point of the curve, the peak to peak signal level was smaller with a distortion in the shape. The harmonics of the signal

were more dominant in this case as it can be seen from the frequency domain representation (Figure 6-14d). Consequently, selecting the incident angle around $\theta_{inc2}=41.1^{\circ}$ gives the highest responsivity with less distortion for the cantilever displacement.

In the previous case, the cantilever was excited at 30 kHz. In order to excite the cantilever at resonance, one should determine the resonance frequency of the cantilever using a frequency sweep in a certain range. However, there will be no need for this open-loop operation if the system can have self-sustained oscillations in a closed-loop system.

6.3.2 Closed-Loop Operation

An array of cantilevers can be operated simultaneously at resonance using a single actuator and a single photodetector in the closed-loop operation without the need of frequency sweeping. In other words, SSOs of cantilevers can simply be accomplished in a feedback loop using gain saturation mechanisms in the optics or electronics. As mentioned earlier, array of cantilevers require separate saturation mechanisms and separate sensing electronics for each cantilever. This increases the complexity of the system dramatically [102, 103, 123]. In Section 6.2, optical non-linearity was introduced using diffraction gratings at the tip of each cantilever, which provide separate saturation non-linearity, enabling a very simple system: single detector based oscillator array [123]. To be able to use cantilevers with simple geometry without gratings, a prism was utilized to induce an optical saturation, which is crucial to sustain oscillations for an array of cantilevers by using rectangular shaped simple cantilever geometry.

Figure 6-15a shows an optical microscope image of an array of rectangular shaped nickel cantilevers, which have a length of 200 μm and a width of 50 μm . The thicknesses of the cantilevers are approximately 1.5 μm . The resonant frequencies of the cantilevers are in the range of 25 to 30 kHz. The laser illuminates two cantilevers of the array as it is illustrated in Figure 6-15a. Figure 6-15b shows the experimental setup for the closed-loop

cantilever operation. The laser, polarizer and the illumination optics are the same with the open-loop optical setup. An additional diffractive optical element (grating) was used in order to split the beam into several beams for the operation of multiple cantilevers. The reflected light from the cantilevers was sent to the right angle prism by the beam splitter. After the light beam was refracted through the prism, the internal reflection occurs at the hypotenuse plane of the prism. Lastly, the internally reflected beam was collected at the PD. The output of the PD was connected to a differentiator for 90° phase shifting, which is a critical condition for having the mechanical resonance. Then it was amplified with an adjustable gain and fed into the coil driver, which drives the electro coil and actuates the cantilever. This closed-loop operation generates an AC signal out of the DC power without the need of any external signal.

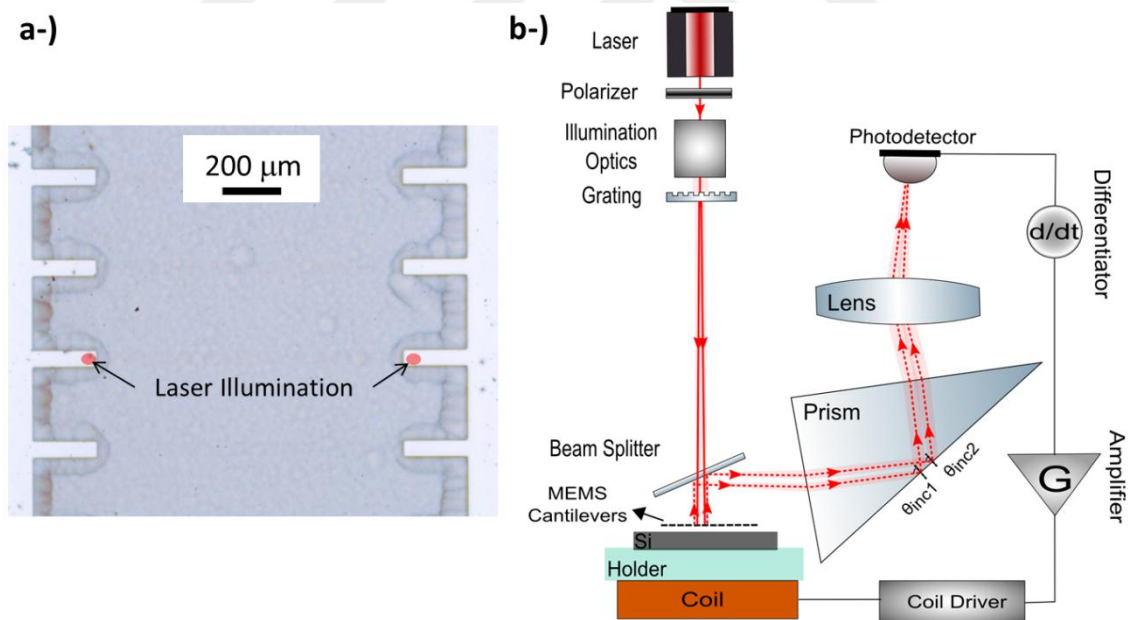


Figure 6-15: (a) Optical microscope image of fabricated array of cantilevers (b) The system overview of prism-based optical readout system for closed-loop cantilever operation.

In order to analyze the non-linearity of the optical readout as the saturation mechanism, a model with a single cantilever (Figure 6-16a) was developed in MATLAB Simulink. The resonance frequency, Q-factor and the spring constant of the cantilever in the model were chosen as 29.62 kHz, 250 and 1 N/m respectively. The actuation force F_{in} , which was created by an electro-coil, causes cantilever displacement x . This displacement was detected by optical means. The electronic feedback that consists of the differentiator and the gain medium is very important for the closed-loop operation at resonance. In addition, one should set the gain to an exact critical value, which can compensate all the losses of the system. However, in practice the loop gain is set slightly above the critical gain. Setting the gain value a little above the critical value causes diverging oscillations. These diverging oscillations stabilize at an amplitude determined by the saturation block, which has the mathematical representation of the optical intensity function for NA of 0.015 (depicted in Figure 6-14b). In order to show that the saturation block limits the system to obtain self-oscillations, the gain of the feedback loop was selected as 20% above the critical gain in the simulations, which is determined by the damping coefficient of the cantilever [123]. The peak displacement, the gain of the feedback loop and the total harmonic distortion (THD) of the closed-loop system were analyzed with reference to the initial angle of incidence according to the determined parameters.

It is clear that the gain of the saturation block changes as the incidence angle changes. Therefore for each incidence angle the gain of the feedback path should be adjusted as shown in Figure 6-16b. The required gain is minimum for the incident angle of 40.8° . In addition, the system requires larger gains in the range of $41.5^\circ < \theta_{inc} < 42^\circ$ as compared to the smaller incident angles. Figure 6-16c shows the peak displacement of the cantilever in the closed-loop system that performs SSO operation with respect to the incident angle. The minimum peak displacement value is 913 nm at $\theta_{inc}=41.2^\circ$. By keeping the incident angle between $41^\circ < \theta_{inc} < 41.3^\circ$, the SSO is achievable with a sub- μ peak displacement. The

operation in this range can easily be implemented by rotating the prism precisely. Nevertheless, it is possible to sustain oscillations out of this range by increasing the gain settings. The gain is slightly larger in the minimum peak displacement point ($\theta_{inc}=41.2^\circ$), which is most likely related with the location of the incident angle in reference to the saturation points of the optical intensity curve (Figure 6-14b).

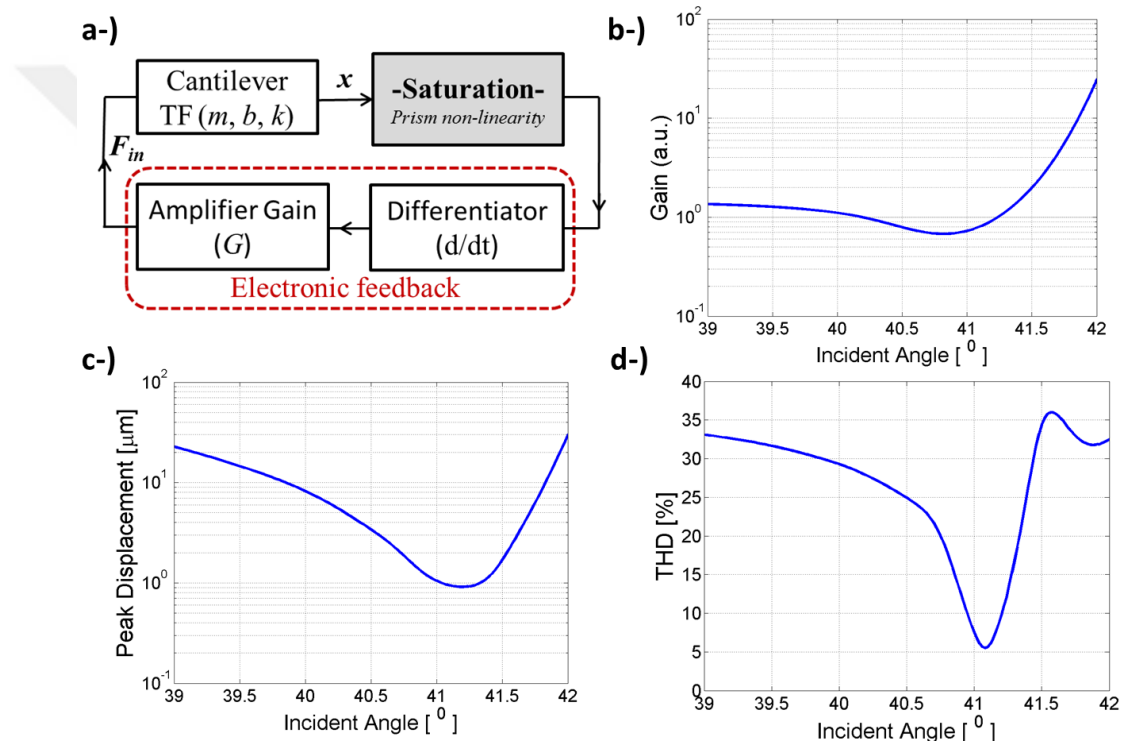


Figure 6-16: Closed-loop operation analysis using a single cantilever for different incidence angles: (a) Block diagram of the single cantilever SSO system that is used in Simulink Model. Simulation results: (b) Gain of the optical readout system for the SSO operation with respect to different incident angles (The gain was selected to be 20% larger than the critical gain value). (c) Peak displacements for the SSO operation with respect to different incident angles. (d) Total harmonic distortion (%) with respect to different incident angles.

As it was discussed previously, the total harmonic distortion, which is arisen from the 2nd and 3rd harmonic, was checked. THD is mostly related with the initial incident angle,

and the displacement range of the cantilever. The THD has its minimum (5.5%) at the incident angle of 41.08° , and the maximum (36%) at the incident angle of 41.68° for the gain values mentioned above. It can be clearly seen that when the initial angle of incidence is closer to the saturation points of the optical intensity curve, THD value remarkably increases. As a result of these analyses, keeping the incident angle around $\theta_{inc}=41.2^\circ$ is desirable due to the smaller peak displacement values, less gain requirements and smaller THD values.

Additionally, optical non-linearity, which is arising from the prism-based optical readout, can provide the separate saturation mechanisms to achieve multiple oscillations from multiple cantilevers. The non-linear nature of the optical intensity curve (Figure 6-14b) can prevent the output of the system to diverge in the gain medium by fine-tuning the incident angle at the prism's hypotenuse plane and setting the gain value. Thus, the tilt angle of the prism and the gain of the feedback loop should be adjusted in order to sustain oscillations from multiple cantilevers. The closed-loop operation with two cantilevers was modeled using MATLAB Simulink in a similar way with the previous simulations. System analyses were performed for two cantilevers model with separate saturation blocks by means of prism-based non-linear optical readout.

Figure 6-17a shows the block diagram of the closed-loop operation on MEMS based cantilever array SSO system for two cantilevers. $m_{1,2}$, $b_{1,2}$, $k_{1,2}$, are the effective masses, total damping's, spring constants of the two cantilevers respectively. Similarly, the actuation force F_{in} causes cantilever displacements, x_1 and x_2 , which are detected by optical readout. The incident angles of both cantilevers at the prism's hypotenuse plane were assumed as 41.2° . The gain of the feedback loop was selected to be 20% larger than the critical gain value at the mentioned incident angle. Two cases for the simulations were investigated.

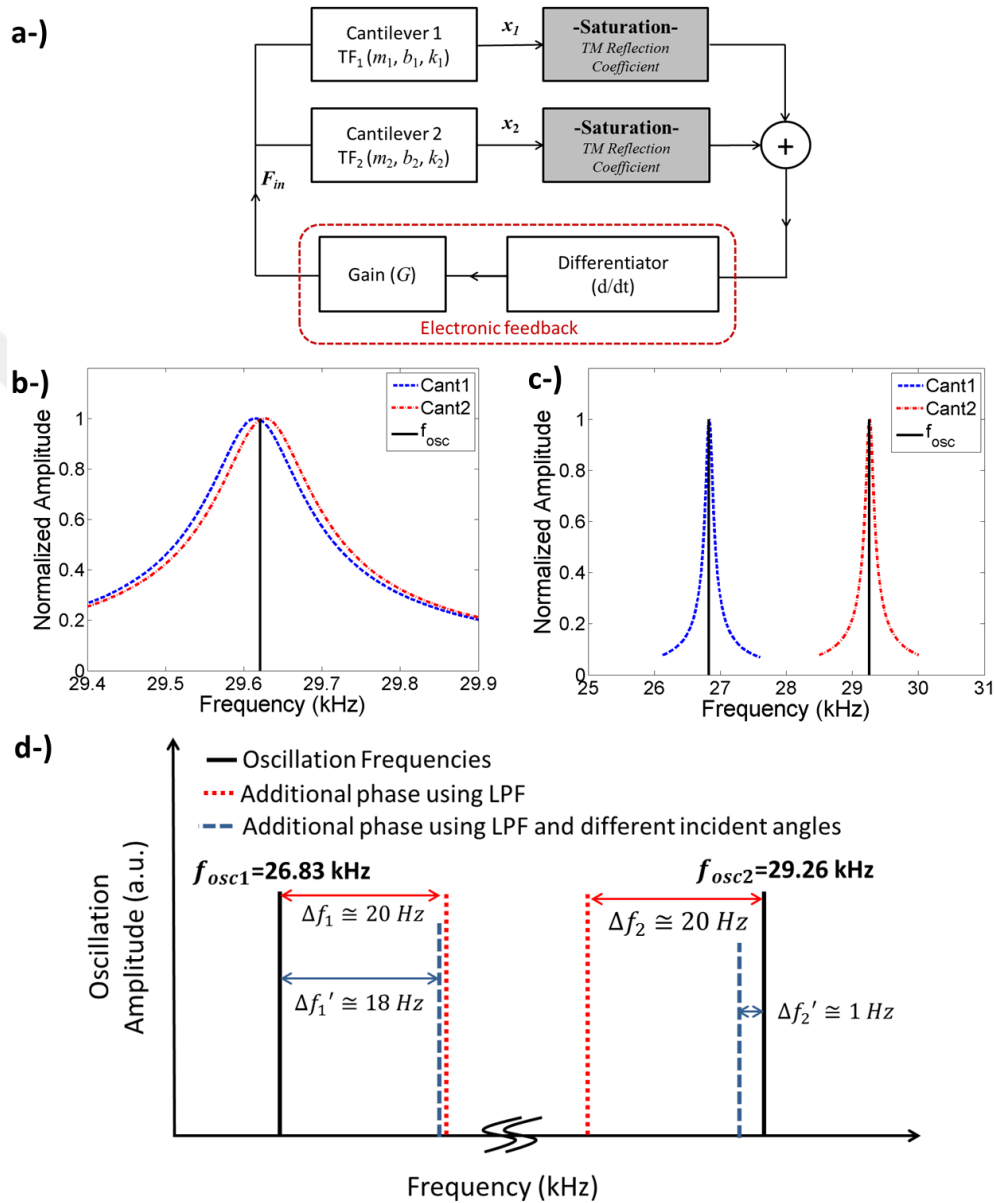


Figure 6-17: (a) Block diagram of the system that is used in Simulink Model. Simulation results: (b) Frequency response of two cantilevers that have closer resonant frequencies (Only one oscillation frequency observed.) (c) Frequency response of two cantilevers that have resonances separated by more than 3dB bandwidth (d) Effect of phase and incident angle on the oscillation frequency. Phase shift in the electronics shift both resonances simultaneously while different incident angles shift each resonance separately.

In the 1st case, the resonant frequencies of each cantilever are very close to each other. For the 2nd case, the resonant frequencies of the cantilevers were selected further away. In the 1st case, the resonant frequencies of the cantilevers are 29.615 kHz and 29.627 kHz. Spring constants ($k_{1,2}=1$ N/m) and the Q-factors ($Q_{1,2}=250$) of the cantilevers were assumed as equal. The frequency sweeps of two cantilevers for the given parameters are displayed in Figure 6-17b as dotted lines. The closed-loop simulation for these two cantilevers resulted in a single oscillation frequency as illustrated in Figure 6-17b as a straight line. The oscillation frequency was determined as 29.621 kHz, which is between the resonant frequencies of two cantilevers.

In the 2nd case, the resonant frequencies of the cantilevers were selected as 26.832 kHz and 29.261 kHz for the two cantilevers, respectively. The spring constants ($k_{1,2}=1$ N/m) and the Q-factors ($Q_{1,2}=250$) of the cantilevers were assumed to be equal to each other. Figure 6-17c displays the frequency sweeps of two cantilevers as dotted lines. Furthermore, closed-loop operation simulations reveal multiple oscillations for the 2nd case, where the resonant frequencies of the cantilevers are placed further away from each other. The oscillation frequencies appear at the same frequency with the resonant frequencies as it is illustrated in Figure 6-17c. In this case, the effect of additional phase and the incident angle difference resulted from the cantilever non-uniformity on the oscillation frequency were also analyzed. Firstly, a phase shift was introduced by using a low-pass filter, which has a cut-off frequency at 60 kHz to represent the bandwidth of the electronics. Consequently, nearly 20 Hz shift was observed at the oscillation frequencies of the cantilevers due to the introduced phase shift as it is shown in Figure 6-17d. Secondly; the effect of the non-uniformity of the cantilevers was analyzed. If the two cantilevers have a small difference in the initial angles due to non-uniformity, the frequency shifts can be different from each other. For instance, the incidence angle of the first cantilever was set to $\theta_{inc1}=39.1^\circ$ and the second cantilever was set to $\theta_{inc2}=41.1^\circ$. These different incident

angles for the two cantilevers change the gain requirements of the cantilever system to larger values. In this case we observed a frequency shift $\Delta f_1' \cong 18 \text{ Hz}$ for the first cantilever and $\Delta f_2' \cong 1 \text{ Hz}$ for the second cantilever. Consequently, an additional phase with different gain requirements changes the magnitude of the oscillation frequency shift differently for each cantilever.

The simulation results match very well with the theoretical findings. If the resonant frequencies of the cantilevers are separated by more than their 3 dB bandwidth $BW=f/Q$ (i.e., the frequency spacing $\Delta f > BW$ or more precisely $\Delta f > 0.5(BW_1 + BW_2)$), multiple oscillations can be obtained [123]. In the 1st case, a single oscillation was observed, because the difference between the resonant frequencies is smaller than the 3 dB bandwidth of the cantilevers. But in the 2nd case, the multiple oscillation requirements were established. As a result, multiple oscillations were observed. The prism-based non-linear optical readout works well for the closed-loop operation due to its natural saturation mechanism. Hence, the prism-based optical readout provides the required separate saturation mechanism for simple cantilever geometries (e.g. rectangular shaped).

6.3.3 Experimental Results

Figure 6-15a shows the rectangular shaped nickel cantilevers, which were used in the experiments. The lengths and the widths of these MEMS cantilevers are 200 μm and 50 μm respectively. The resonant frequencies of the cantilevers in air are in the range of 25-30 kHz. Figure 6-12a and Figure 6-15b show the experimental setups for the open-loop and closed-loop operation respectively. The cantilevers were illuminated with a TM polarized red laser ($\lambda=633 \text{ nm}$). The numerical aperture (NA) of the illumination optics in the experiments was 0.015. An N-BK7 right-angle prism was used in the experimental setup, which has a refractive index of 1.5168. For the feedback electronics in the closed-loop setup, a low noise preamplifier (Stanford Research, SR-560) was used for variable

gain adjustment. Furthermore, a band-pass filter between 10 kHz-100 kHz was implemented using this low noise preamplifier to increase the detection sensitivity.

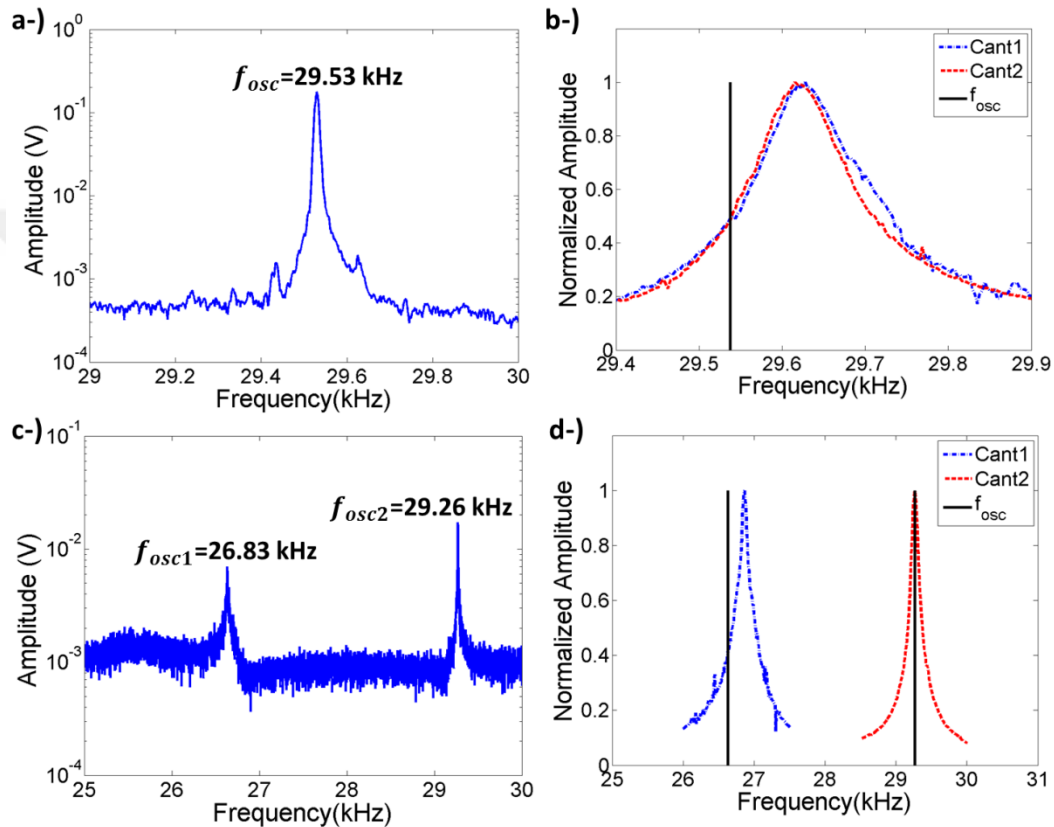


Figure 6-18: Experimental results for two cantilevers that have closer resonant frequencies: (a) Closed-loop SSO operation (b) Open-loop frequency sweeps. Experimental results for two cantilevers that have resonances further away: (c) Closed-loop SSO operation (d) Open-loop frequency sweeps.

For the first experiments, we selected two cantilevers with resonant frequencies that were very close to each other (< 3 dB BW) as the 1st case of the previous simulations. Open-loop experimental setup (Figure 6-12a) was employed for the individual frequency responses of the cantilevers using a frequency sweep. It's noteworthy to mention that the drive current for the coil was kept small enough to operate the prism-based readout at its

linear region in the open-loop operations. Furthermore, a laser Doppler vibrometer (Polytec OFV-2500) was implemented to the open-loop system to find the cantilever displacement values. Consequently, the displacement amplitudes at resonance were obtained around 220 nm at the tip of the cantilevers for the intended coil currents. Figure 6-18a shows the frequency response for the two cantilevers, which have closer resonant frequencies. Since the resonant frequency separation is smaller than the 3 dB BW (Figure 6-18b), the two cantilever system results in a single oscillation. Figure 6-18b illustrates the individual frequency responses (open-loop operation) with the corresponding oscillation frequency. The resonant frequencies of the 1st and the 2nd cantilevers are 29.627 kHz and 29.615 kHz respectively. The SSO frequency of this system is 29.538 kHz. Note that; for the closed-loop SSO operations, the gain of the feedback electronics and the tilt angle of the prism were adjusted until simultaneous oscillations were achieved.

We also made another experiment with the cantilevers, where there was a larger separation in the resonant frequencies ($> 3\text{dB BW}$) as a 2nd case. We repeated the same procedures to obtain the individual frequency responses (open-loop operation) and to maintain SSO from the two cantilever system (closed-loop operation). Since the separation between the resonant frequencies of the two cantilevers are larger than 3dB BW, multiple oscillations for the two cantilever system was obtained (Figure 6-18c). The individual frequency sweeps of the cantilevers are given in Figure 6-18d along with the oscillation frequencies of the SSO systems. The resonant frequencies of the 1st and the 2nd cantilevers are 26.832 kHz and 29.261 kHz respectively. The SSO frequencies of this system are 26.634 kHz and 29.267 kHz, which corresponds to 1st and the 2nd cantilever respectively.

Resonant frequencies (open-loop), oscillation frequencies (closed-loop) and quality factors of the cantilevers for the two cases are summarized in Table 6-4.

Table 6-4: Resonances and corresponding oscillation frequencies of the two cantilever SSO where individual resonant frequencies are very close (1st case) and further away (2nd case).

	Single Oscillation (1st case)		Multiple Oscillation (2nd case)	
	<i>Cant1</i>	<i>Cant2</i>	<i>Cant1</i>	<i>Cant2</i>
Resonant Frequencies [kHz]	29.627	29.615	26.832	29.261
Oscillation Frequencies [kHz]	29.538		26.634	29.267
BW [Hz] (Q)	108 (274)	106 (279)	140 (192)	120 (244)

As it was mentioned previously, because the resonant frequency separation was very small in the 1st case, single oscillation was observed, rather than two oscillations. When the resonant frequency separation was larger than the 3dB BW (2nd case), two oscillations were observed. Simulations match well with the typical behavior of the SSO system for the two cases. In addition, shifts in the oscillation frequencies were observed due to the additional phase errors in the electronics and non-uniformities of the cantilevers, as it was modeled in the simulations. The magnitudes of these shifts are difficult to estimate because the shifts depend on multiple parameters such as phase errors from the electronics, slight differences in the cantilever initial tilts that affect the incidence angles on the prism.

6.4 Conclusion

This work provides an analysis and modeling of two cantilevers oscillated at resonance with common actuator and a single feedback circuitry. To sustain multiple oscillations two main criteria are established: (i) a frequency spacing Δf greater than 3 dB bandwidth (BW) is required between their resonant frequencies. Otherwise the system collapses into a single oscillation; (ii) separate saturation mechanisms are needed for each oscillator, which is achieved using non-linear optical methods such as the diffraction grating based optical readout and prism-based optical readout systems.

In the diffraction grating based optical readout, one needs to use MEMS cantilevers with diffraction gratings at the tip, which provides the required non-linearity. However as a second approach, a single prism was utilized for the optical readout of rectangular shaped MEMS based cantilever arrays with a simpler geometry. The optical readout method was mainly tailored at the glass-air interface of this single prism using a TM wave near the critical angle. This technique makes the optical readout setup simpler for the resonant based MEMS cantilever arrays by directly measuring the angular change of the incoming wave. It was shown that, the non-linear dependence of optical intensity to the incidence angle provides a natural saturation mechanism, which stabilizes the amplitude of diverging oscillations, by tuning the incident angle at the prism's hypotenuse plane and setting the gain value. As a result of the analyses, it is concluded that the incident angle around $\theta_{inc}=41.2^\circ$ is desirable due to the smaller cantilever peak displacement values, less gain requirements in the electronics and smaller THD values. In addition, two different cases were analyzed using two cantilevers, which were oscillated at resonance using a common actuator, a single photodetector and a single feedback circuitry. Furthermore, phase error and non-uniformities was introduced to the two cantilever closed-loop system. These effects create shifts in the oscillation frequencies, which is an explanation of the shifts at the oscillation frequencies observed in the experiments. Lastly, it's envisioned that, this multiple SSO operation can readily be extended to the dense and smaller size cantilever arrays.

For both optical methods, experimental results matched well with the theory and the simulations. The analysis in this chapter can be extended into large number of cantilevers operated in the same loop using common actuator and feedback electronics. However, there are limitations: the change in one oscillator induces a change in the other oscillator. This cross-coupling effect between the cantilevers can be determined and corrected for a sensor application. Finally, to achieve high performance and low cross-coupling sensor

arrays, high Q-factor and large separation between oscillator frequencies are desired (e.g., $\Delta f = 5BW$ results in $<1\%$ cross coupling).



7 Conclusion and Future Work

Optical readout methods enable remote access to the sensor chip without the need of electrical connections and scalable architectures for sensor arrays. Although the optical readout methods offer high sensitivity, the noise arisen from the detector and the light source can become the limiting factor in sensor applications. This thesis aimed to reduce the optical readout noise and improve the detection sensitivity of MEMS sensor cantilevers for IR detection and dynamic mode MEMS cantilever applications. In addition, it was focused on the potentiality of parallelization with optical methods for dynamic mode MEMS cantilevers using simple architectures.

Firstly, the capabilities of grating and lever based optical readout methods for single pixel measurements were analyzed to enhance the detection sensitivity and the noise performance. AC-coupled optical detection methods were developed to reduce the DC term and increase the sensitivity for single pixel measurements. Modulated IR source at a certain frequency (< 10 Hz), with a detection scheme at the modulation frequency enabled an improvement in the sensitivity of the IR detection. Detailed noise characterizations of thermo-mechanical MEMS detectors with $35\text{ }\mu\text{m}$ single pixel were performed, which showed that the optical readout noise was decreased to the levels of the fundamental noise of the MEMS structure. In addition, a pixel-level Fabry-Perot cavity type optical readout method was designed for thermo-mechanical MEMS detectors for the first time. This readout method offers very high sensitive detection that the measured NETD was around 170 mK with AC-coupled PD and 600 mK with an 8 bit CCD camera. Lastly a novel prism-based optical readout was proposed for a lever based single thermo-mechanical detector. This method improved the detection sensitivity significantly compared to the conventional beam deflection methods. The measured NETDs for different sensor designs

were below 200 mK, with the best NETD performance of 150 mK thanks to the AC-coupling. Even though the pixels sizes for the thermo-mechanical detectors are small compared to the state-of-the-art thermo-mechanical detectors, the measured noise levels are comparable or even better [48, 65, 66, 72, 85]. The AC coupled optical readout method is implemented easily for single pixel operation, but for the array readout it may be more complex. A custom smart pixel camera can be designed and fabricated for the array readout, which may increase the complexity and the cost, but obviously, offer high sensitive IR detection.

In addition to the improvements in the single pixel readout, the possibilities for the improvements in the array readout were also analyzed by developing a compact optical system, converging beam optical system, and a $2\text{-}\lambda$ solution for non-uniform arrays. Converging optical system is based on forming the Fourier Plane very close to the imaging lens by using a converging illumination. This system has compactness and SNR advantage over the conventional $4f$ optical system. Secondly, in order to improve the sensitivity of the non-uniform arrays, a novel two-wavelength optical readout was proposed. LED light source unit, which provides different wavelength options, was used for the first time in the grating based readout of thermo-mechanical arrays. The main advantage of this system compared to the previous $2\text{-}\lambda$ schemes is the spatial auto-registration capability using a single RGB camera. Eventually, it was experimentally demonstrated that the sensitivity of the thermo-mechanical IR detector was improved by using the most sensitive channel's signal for each individual MEMS pixel.

Reducing the size of the detector system can be pushed forward by using integrated approaches. In order to achieve this, a MEMS-based sensor array with a large number of elements (64×64) was integrated with a CMOS ROIC for the first time. This small package enables a low cost sensor system with many key features such as large array operation, small size and better control of environment. In this integration process, MEMS and

CMOS were optimized and processed separately, improving the yield of the overall process. A diffraction grating interferometer-based optical readout was realized by pixel-level illumination of the MEMS chip through the post-processed via holes and by capturing the reflected light using a photodetector array on the CMOS chip. The system was tested for functionality using pressure load and thermal load, and produced a response that was clearly detectable.

The parallel measurements of dynamic mode MEMS cantilevers are very challenging. As a last work, the non-linear optical readout methods were analyzed and developed for MEMS cantilever oscillator arrays, which enable the self-sustained oscillations of the cantilevers. The optical non-linearities provide separate saturation mechanisms for each cantilever, which is crucial to achieve multiple oscillations. An interferometric readout for diffraction grating based cantilevers and a prism-based approach, which employs the total internal reflection phenomenon, for lever based cantilevers were utilized for the required saturation mechanisms that parallelized the array for multiple oscillations. It is theoretically and experimentally shown that MEMS cantilevers with different geometries oscillated at resonance using a common actuator, a single photodetector and a single feedback circuitry.

BIBLIOGRAPHY

- [1] C. S. Smith, "Piezoresistance effect in germanium and silicon," *Physical review*, vol. 94, p. 42, 1954.
- [2] J. Bryzek, "Impact of MEMS technology on society," *Sensors and Actuators A: Physical*, vol. 56, pp. 1-9, 1996/08/01 1996.
- [3] K. E. Petersen, "Silicon as a mechanical material," *Proceedings of the IEEE*, vol. 70, pp. 420-457, 1982.
- [4] S. D. Senturia, *Microsystem design*: Springer Science & Business Media, 2007.
- [5] F. Khoshnoud and C. W. de Silva, "Recent advances in MEMS sensor technology–biomedical applications," *IEEE Instrumentation & Measurement Magazine*, vol. 15, pp. 8-14, 2012.
- [6] W. P. Eaton and J. H. Smith, "Micromachined pressure sensors: review and recent developments," *Smart Materials and Structures*, vol. 6, p. 530, 1997.
- [7] Q.-A. Huang and N. K. S. Lee, "Analysis and design of polysilicon thermal flexure actuator," *Journal of Micromechanics and Microengineering*, vol. 9, p. 64, 1999.
- [8] L. Löfdahl and M. Gad-el-Hak, "MEMS applications in turbulence and flow control," *Progress in Aerospace Sciences*, vol. 35, pp. 101-203, 1999.
- [9] L. Lin, R. T. Howe, and A. P. Pisano, "Microelectromechanical filters for signal processing," *Journal of Microelectromechanical systems*, vol. 7, pp. 286-294, 1998.
- [10] J. A. Walker, "The future of MEMS in telecommunications networks," *Journal of micromechanics and microengineering*, vol. 10, p. R1, 2000.
- [11] P. Vettiger, J. Brugger, M. Despont, U. Drechsler, U. Dürig, W. Häberle, *et al.*, "Ultrahigh density, high-data-rate NEMS-based AFM data storage system," *Microelectronic Engineering*, vol. 46, pp. 11-17, 1999.
- [12] H. Urey, D. W. Wine, and T. D. Osborn, "Optical performance requirements for MEMS-scanner-based microdisplays," in *Micromachining and Microfabrication*, 2000, pp. 176-185.
- [13] T. Thundat, P. Oden, and R. Warmack, "Microcantilever sensors," *Microscale Thermophysical Engineering*, vol. 1, pp. 185-199, 1997.
- [14] G. Binnig, C. F. Quate, and C. Gerber, "Atomic force microscope," *Physical review letters*, vol. 56, p. 930, 1986.
- [15] N. V. Lavrik, M. J. Sepaniak, and P. G. Datskos, "Cantilever transducers as a platform for chemical and biological sensors," *Review of scientific instruments*, vol. 75, pp. 2229-2253, 2004.
- [16] <http://www.microchem.com/Appl-MEMs-Cantilevers.htm>. (2016, 28.08.2016). *Cantilevers*.

BIBLIOGRAPHY

- [17] H. Sadeghian, F. Van Keulen, and H. Goosen, "Mechanics of nanoelectromechanical systems: bridging the gap between experiment and theory," 2013.
- [18] T. Thundat, G. Chen, R. Warmack, D. Allison, and E. Wachter, "Vapor detection using resonating microcantilevers," *Analytical Chemistry*, vol. 67, pp. 519-521, 1995.
- [19] T. Thundat, E. Wachter, S. Sharp, and R. Warmack, "Detection of mercury vapor using resonating microcantilevers," *Applied Physics Letters*, vol. 66, pp. 1695-1697, 1995.
- [20] P. G. Datskos, M. J. Sepaniak, C. A. Tipple, and N. Lavrik, "Photomechanical chemical microsensors," *Sensors and Actuators B: Chemical*, vol. 76, pp. 393-402, 6/1/ 2001.
- [21] R. Raiteri, M. Grattarola, H.-J. Butt, and P. Skládal, "Micromechanical cantilever-based biosensors," *Sensors and Actuators B: Chemical*, vol. 79, pp. 115-126, 2001.
- [22] C. Ziegler, "Cantilever-based biosensors," *Analytical and bioanalytical chemistry*, vol. 379, pp. 946-959, 2004.
- [23] E. Timurdogan, B. E. Alaca, I. H. Kavakli, and H. Urey, "MEMS biosensor for detection of Hepatitis A and C viruses in serum," *Biosensors and Bioelectronics*, vol. 28, pp. 189-194, 2011.
- [24] O. Cakmak, C. Elbuken, E. Ermek, A. Mostafazadeh, I. Baris, B. E. Alaca, *et al.*, "Microcantilever based disposable viscosity sensor for serum and blood plasma measurements," *Methods*, vol. 63, pp. 225-232, 2013.
- [25] O. Cakmak, E. Ermek, N. Kilinc, G. Yaralioglu, and H. Urey, "Precision density and viscosity measurement using two cantilevers with different widths," *Sensors and Actuators A: Physical*, vol. 232, pp. 141-147, 2015.
- [26] P. Datskos, N. Lavrik, and S. Rajic, "Performance of uncooled microcantilever thermal detectors," *Review of Scientific Instruments*, vol. 75, pp. 1134-1148, 2004.
- [27] M. Steffanson and I. Rangelow, "Microthermomechanical infrared sensors," *Opto-Electronics Review*, vol. 22, pp. 1-15, 2014.
- [28] D. Sarid, *Scanning force microscopy*: Oxford University Press, New York, 1991.
- [29] J. Amírola, A. Rodríguez, L. Castañer, J. Santos, J. Gutiérrez, and M. Horrillo, "Micromachined silicon microcantilevers for gas sensing applications with capacitive read-out," *Sensors and Actuators B: Chemical*, vol. 111, pp. 247-253, 2005.
- [30] P. A. Rasmussen, J. Thaysen, O. Hansen, S. C. Eriksen, and A. Boisen, "Optimised cantilever biosensor with piezoresistive read-out," *Ultramicroscopy*, vol. 97, pp. 371-376, 10// 2003.

BIBLIOGRAPHY

- [31] S. T. Koev, W. E. Bentley, and R. Ghodssi, "Interferometric readout of multiple cantilever sensors in liquid samples," *Sensors and Actuators B: Chemical*, vol. 146, pp. 245-252, 2010.
- [32] G. Meyer and N. M. Amer, "Novel optical approach to atomic force microscopy," *Applied physics letters*, vol. 53, pp. 1045-1047, 1988.
- [33] C. L. Britton Jr, R. L. Jones, P. I. Oden, Z. Hu, R. J. Warmack, S. F. Smith, *et al.*, "Multiple-input microcantilever sensors," *Ultramicroscopy*, vol. 82, pp. 17-21, 2// 2000.
- [34] H. U. Danzebrink, L. Koenders, G. Wilkening, A. Yacoot, and H. Kunzmann, "Advances in Scanning Force Microscopy for Dimensional Metrology," *CIRP Annals - Manufacturing Technology*, vol. 55, pp. 841-878, // 2006.
- [35] S. R. Hunter, R. A. Amantea, L. A. Goodman, D. B. Kharas, S. Gershtein, J. R. Matey, *et al.*, "High-sensitivity uncooled microcantilever infrared imaging arrays," in *AeroSense 2003*, 2003, pp. 469-480.
- [36] R. Amantea, C. Knoedler, F. P. Pantuso, V. Patel, D. J. Sauer, and J. R. Tower, "Uncooled IR imager with 5-mK NEDT," in *AeroSense'97*, 1997, pp. 210-222.
- [37] A. Boisen, S. Dohn, S. S. Keller, S. Schmid, and M. Tenje, "Cantilever-like micromechanical sensors," *Reports on Progress in Physics*, vol. 74, p. 036101, 2011.
- [38] A. Boisen, J. Thaysen, H. Jensenius, and O. Hansen, "Environmental sensors based on micromachined cantilevers with integrated read-out," *Ultramicroscopy*, vol. 82, pp. 11-16, 2// 2000.
- [39] P. Oden, P. Datskos, T. Thundat, and R. Warmack, "Uncooled thermal imaging using a piezoresistive microcantilever," *Applied Physics Letters*, vol. 69, pp. 3277-3279, 1996.
- [40] P. Datskos, P. Oden, T. Thundat, E. Wachter, R. Warmack, and S. Hunter, "Remote infrared radiation detection using piezoresistive microcantilevers," *Applied Physics Letters*, vol. 69, pp. 2986-2988, 1996.
- [41] O. Cakmak, "Microcantilever Based Lab-on-a-Chip Sensor for Real-Time Mass, Viscosity, Density and Coagulation Measurements," PhD, Mechanical Engineering, Koç University, İstanbul, 2015.
- [42] O. Solgaard, A. A. Godil, R. T. Howe, L. P. Lee, Y. A. Peter, and H. Zappe, "Optical MEMS: From Micromirrors to Complex Systems," *Journal of Microelectromechanical Systems*, vol. 23, pp. 517-538, 2014.
- [43] N. A. Hall, B. Bicen, M. K. Jeelani, W. Lee, S. Qureshi, F. L. Degertekin, *et al.*, "Micromachined microphones with diffraction-based optical displacement detection," *The Journal of the Acoustical Society of America*, vol. 118, pp. 3000-3009, 2005.

BIBLIOGRAPHY

- [44] S. Manalis, S. Minne, C. Quate, G. Yaralioglu, and A. Atalar, "Two-dimensional micromechanical bimorph arrays for detection of thermal radiation," *Applied physics letters*, vol. 70, pp. 3311-3313, 1997.
- [45] T. Perazzo, M. Mao, O. Kwon, A. Majumdar, J. Varesi, and P. Norton, "Infrared vision using uncooled micro-optomechanical camera," *Applied Physics Letters*, vol. 74, pp. 3567-3569, 1999.
- [46] T. Uchihashi, N. Kodera, and T. Ando, "Guide to video recording of structure dynamics and dynamic processes of proteins by high-speed atomic force microscopy," *Nat. Protocols*, vol. 7, pp. 1193-1206, 06/print 2012.
- [47] X. Wang, S. Ma, X. Yu, M. Liu, X. Liu, and Y. Zhao, "IR imaging using a cantilever-based focal plane array fabricated by deep reactive ion etching technique," *Applied Physics Letters*, vol. 91, p. 054109, 2007.
- [48] L. Senesac, J. Corbeil, S. Rajic, N. Lavrik, and P. Datskos, "IR imaging using uncooled microcantilever detectors," *Ultramicroscopy*, vol. 97, pp. 451-458, 2003.
- [49] N. A. Hall, M. Okandan, R. Littrell, D. K. Serkland, G. A. Keeler, K. Peterson, *et al.*, "Micromachined accelerometers with optical interferometric read-out and integrated electrostatic actuation," *Microelectromechanical Systems, Journal of*, vol. 17, pp. 37-44, 2008.
- [50] R. B. Erarslan, U. Adiyan, S. Z. Lulec, S. Olcer, Y. Temiz, Y. Leblebici, *et al.*, "Design and characterization of micromachined sensor array integrated with CMOS based optical readout," *Sensors and Actuators A: Physical*, vol. 215, pp. 44-50, 2014.
- [51] R. Howland and L. Benatar, *A Practical Guide: To Scanning Probe Microscopy*: Park scientific instruments, 1996.
- [52] http://Inf-wiki.eecs.umich.edu/wiki/Atomic_force_microscopy. (2016, 29.08.2016). *Atomic force microscopy*.
- [53] T. E. Schäffer and P. K. Hansma, "Characterization and optimization of the detection sensitivity of an atomic force microscope for small cantilevers," *Journal of applied physics*, vol. 84, pp. 4661-4666, 1998.
- [54] C. A. J. Putman, B. G. de Grooth, N. F. van Hulst, and J. Greve, "A theoretical comparison between interferometric and optical beam deflection technique for the measurement of cantilever displacement in AFM," *Ultramicroscopy*, vol. 42, pp. 1509-1513, 1992/07/01 1992.
- [55] H. Torun, J. Sutanto, K. Sarangapani, P. Joseph, F. Degertekin, and C. Zhu, "A micromachined membrane-based active probe for biomolecular mechanics measurement," *Nanotechnology*, vol. 18, p. 165303, 2007.
- [56] G. Yaralioglu, A. Atalar, S. Manalis, and C. Quate, "Analysis and design of an interdigital cantilever as a displacement sensor," *Journal of Applied Physics*, vol. 83, pp. 7405-7415, 1998.

BIBLIOGRAPHY

- [57] D. Iannuzzi, S. Deladi, V. Gadgil, R. Sanders, H. Schreuders, and M. Elwenspoek, "Monolithic fiber-top sensor for critical environments and standard applications," *Applied physics letters*, vol. 88, p. 053501, 2006.
- [58] M. F. Toy, O. Ferhanoglu, H. Torun, and H. Urey, "Uncooled infrared thermo-mechanical detector array: Design, fabrication and testing," *Sensors and Actuators A: Physical*, vol. 156, pp. 88-94, 2009.
- [59] T. Ishizuya, J. Suzuki, K. Akagawa, and T. Kazama, "Optically readable bi-material infrared detector," in *Aerospace/Defense Sensing, Simulation, and Controls*, 2001, pp. 342-349.
- [60] Z. Guo, Q. Zhang, F. Dong, D. Chen, Z. Xiong, Z. Miao, *et al.*, "Performance analysis of microcantilever arrays for optical readout uncooled infrared imaging," *Sensors and Actuators A: Physical*, vol. 137, pp. 13-19, 2007.
- [61] O. Ferhanoglu, "Design, Fabrication and Characterization of a MOEMS based Thermal Imaging System," PhD, Electrical and Electronics Engineering, Koç University, Istanbul, 2010.
- [62] Y. Zhao, "Optomechanical Uncooled Infrared Imaging System," PhD, Mechanical Engineering, UNIVERSITY OF CALIFORNIA, BERKELEY, BERKELEY, 2002.
- [63] Y. Zhao, M. Mao, R. Horowitz, A. Majumdar, J. Varesi, P. Norton, *et al.*, "Optomechanical uncooled infrared imaging system: design, microfabrication, and performance," *Journal of microelectromechanical systems*, vol. 11, pp. 136-146, 2002.
- [64] O. Ferhanoglu and H. Urey, "Sensitivity enhancement of grating interferometer based two-dimensional sensor arrays using two-wavelength readout," *Applied optics*, vol. 50, pp. 3289-3295, 2011.
- [65] M. Erdtmann, L. Zhang, G. Jin, S. Radhakrishnan, G. Simelgor, and J. Salerno, "Optical readout photomechanical imager: from design to implementation," in *SPIE Defense, Security, and Sensing*, 2009, pp. 72980I-72980I-8.
- [66] B. Jiao, C. Li, D. Chen, T. Ye, Y. Ou, L. Dong, *et al.*, "An optical readout method based uncooled infrared imaging system," *International Journal of Infrared and Millimeter Waves*, vol. 29, pp. 261-271, 2008.
- [67] A. Mostafazadeh, G. G. Yaralioglu, and H. Urey, "Optical fiber array based simultaneous parallel monitoring of resonant cantilever sensors in liquid," *Sensors and Actuators A: Physical*, 2016.
- [68] H. P. Lang, M. K. Baller, R. Berger, C. Gerber, J. K. Gimzewski, F. M. Battiston, *et al.*, "An artificial nose based on a micromechanical cantilever array," *Analytica Chimica Acta*, vol. 393, pp. 59-65, 6/30/ 1999.
- [69] S. Kelling, F. Paoloni, J. Huang, V. P. Ostanin, and S. R. Elliott, "Simultaneous readout of multiple microcantilever arrays with phase-shifting interferometric microscopy," *Review of scientific instruments*, vol. 80, p. 093101, 2009.

BIBLIOGRAPHY

- [70] W. Lee, N. Hall, and F. L. Degertekin, "Micromachined acoustic sensor array with diffraction-based optical interferometric detection," 2003, pp. 140-151.
- [71] S. Lulec, C. Sagiroglu, A. Mostafazadeh, E. Ermek, E. Timurdogan, Y. Leblebici, *et al.*, "Simultaneous self-sustained actuation and parallel readout with MEMS cantilever sensor array," in *Micro Electro Mechanical Systems (MEMS), 2012 IEEE 25th International Conference on*, 2012, pp. 644-647.
- [72] D. Grbovic, N. V. Lavrik, P. G. Datskos, D. Forrai, E. Nelson, J. Devitt, *et al.*, "Uncooled infrared imaging using bimaterial microcantilever arrays," *Applied Physics Letters*, vol. 89, p. 073118, 2006.
- [73] M. Steffanson, K. Gorovoy, V. Ramkiattisak, T. Ivanov, J. Król, H. Hartmann, *et al.*, "ARCH-type micro-cantilever FPA for uncooled IR detection," *Microelectronic Engineering*, vol. 98, pp. 614-618, 2012.
- [74] A. Rogalski, "History of infrared detectors," *Opto-Electronics Review*, vol. 20, pp. 279-308, 2012.
- [75] A. Rogalski, "Infrared detectors: an overview," *Infrared Physics & Technology*, vol. 43, pp. 187-210, 2002.
- [76] A. Rogalski, "Novel uncooled infrared detectors," *Opto-Electronics Review*, vol. 18, pp. 478-492, 2010.
- [77] E. Mounier, "Technical and market trends for microbolometers for thermography and night vision," in *SPIE Defense, Security, and Sensing*, 2011, pp. 80121U-80121U-6.
- [78] U. Adıyan, F. Civitçi, O. Ferhanoğlu, H. Torun, and H. Urey, "A 35-Pitch IR Thermo-Mechanical MEMS Sensor With AC-Coupled Optical Readout," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 21, pp. 87-92, 2015.
- [79] E. Wachter, T. Thundat, P. Oden, R. Warmack, P. Datskos, and S. Sharp, "Remote optical detection using microcantilevers," *Review of Scientific Instruments*, vol. 67, pp. 3434-3439, 1996.
- [80] R. Amantea, L. A. Goodman, F. P. Pantuso, D. J. Sauer, M. Varghese, T. S. Villani, *et al.*, "Progress toward an uncooled IR imager with 5-mK NETD," in *SPIE's International Symposium on Optical Science, Engineering, and Instrumentation*, 1998, pp. 647-659.
- [81] Y. Zhao, J. Choi, R. Horowitz, A. Majumdar, J. E. Kitching, and P. R. Norton, "Characterization and performance of optomechanical uncooled infrared imaging system," in *International Symposium on Optical Science and Technology*, 2003, pp. 164-174.
- [82] P. Datskos, S. Rajic, and I. Datskou, "Detection of infrared photons using the electronic stress in metal–semiconductor cantilever interfaces," *Ultramicroscopy*, vol. 82, pp. 49-56, 2000.

BIBLIOGRAPHY

- [83] J. Zhao, "High sensitivity photomechanical MW-LWIR imaging using an uncooled MEMS microcantilever array and optical readout," in *Defense and Security*, 2005, pp. 506-513.
- [84] S. Shi, B. Jiao, D. Chen, C. Li, D. Ding, Y. Ou, *et al.*, "Design, simulation and validation of a novel uncooled infrared focal plane array," *Sensors and Actuators A: Physical*, vol. 133, pp. 64-71, 2007.
- [85] F. Dong, Q. Zhang, D. Chen, L. Pan, Z. Guo, W. Wang, *et al.*, "An uncooled optically readable infrared imaging detector," *Sensors and Actuators A: Physical*, vol. 133, pp. 236-242, 2007.
- [86] F. Dong, Q. Zhang, D. Chen, Z. Miao, Z. Xiong, Z. Guo, *et al.*, "Uncooled infrared imaging device based on optimized optomechanical micro-cantilever array," *Ultramicroscopy*, vol. 108, pp. 579-588, 2008.
- [87] T. Cheng, Q. Zhang, X. Wu, D. Chen, and B. Jiao, "Uncooled infrared imaging using a substrate-free focal-plane array," *IEEE Electron Device Letters*, vol. 29, pp. 1218-1221, 2008.
- [88] M. Steffanson, K. Gorovoy, M. Holz, T. Ivanov, R. Kampmann, R. Kleindienst, *et al.*, "4.4-Low-cost uncooled infrared detector using thermomechanical micro-mirror array with optical readout," *Proceedings IRS² 2013*, pp. 85-88, 2013.
- [89] S. R. Hunter, G. S. Maurer, G. Simelgor, S. Radhakrishnan, J. Gray, K. Bachir, *et al.*, "Development and optimization of microcantilever based IR imaging arrays," in *SPIE Defense and Security Symposium*, 2008, pp. 694013-694013-12.
- [90] H. Torun, "Design and Fabrication of Thermo-Mechanical Thermal Detector Arrays with Optical Readout," MSc, Electrical and Computer Engineering, Koç University, Istanbul, 2005.
- [91] U. Adıyan, R. B. Erarslan, O. Ferhanoglu, H. Torun, and H. Urey, "Diffraction grating-based optical readout for thermal imaging," in *SPIE Optical Systems Design*, 2012, pp. 855026-855026-8.
- [92] A. Parsons and D. Pedder, "Thin-film infrared absorber structures for advanced thermal detectors," *Journal of Vacuum Science & Technology A*, vol. 6, pp. 1686-1689, 1988.
- [93] R. B. Erarslan, "Design, Fabrication and Characterization of a Thermo-Mechanical Infrared Detector Array with Integrated Optical Readout," Master of Science, Electrical and Electronics Engineering, Koç University, 2012.
- [94] O. Ferhanoglu, M. F. Toy, and H. Urey, "Fourier optics analysis of grating sensors with tilt errors," *Optics letters*, vol. 36, pp. 2254-2256, 2011.
- [95] U. Adıyan, F. Civitci, O. Ferhanoglu, H. Torun, and H. Urey, "A Prism-Based Optical Readout Method for MEMS Bimaterial Infrared Sensors," *IEEE Photonics Technology Letters*, vol. 28, pp. 1866-1869, 2016.

BIBLIOGRAPHY

- [96] J. Arlett, E. Myers, and M. Roukes, "Comparative advantages of mechanical biosensors," *Nature nanotechnology*, vol. 6, pp. 203-215, 2011.
- [97] M. Calleja, P. M. Kosaka, Á. San Paulo, and J. Tamayo, "Challenges for nanomechanical sensors in biological detection," *Nanoscale*, vol. 4, pp. 4925-4938, 2012.
- [98] C. A. Van Eysden and J. E. Sader, "Frequency response of cantilever beams immersed in viscous fluids with applications to the atomic force microscope: Arbitrary mode order," *Journal of applied physics*, vol. 101, p. 044908, 2007.
- [99] T. P. Burg, M. Godin, S. M. Knudsen, W. Shen, G. Carlson, J. S. Foster, *et al.*, "Weighing of biomolecules, single cells and single nanoparticles in fluid," *Nature*, vol. 446, pp. 1066-1069, 2007.
- [100] M. Basso, P. Paoletti, B. Tiribilli, and M. Vassalli, "Modelling and analysis of autonomous micro-cantilever oscillations," *Nanotechnology*, vol. 19, p. 475501, 2008.
- [101] T. Albrecht, P. Grütter, D. Horne, and D. Rugar, "Frequency modulation detection using high-Q cantilevers for enhanced force microscope sensitivity," *Journal of Applied Physics*, vol. 69, pp. 668-673, 1991.
- [102] X. Feng, C. White, A. Hajimiri, and M. L. Roukes, "A self-sustaining ultrahigh-frequency nanoelectromechanical oscillator," *Nature nanotechnology*, vol. 3, pp. 342-346, 2008.
- [103] S. Olcum, N. Cermak, S. C. Wasserman, and S. R. Manalis, "High-speed multiple-mode mass-sensing resolves dynamic nanoscale mass distributions," *Nature communications*, vol. 6, 2015.
- [104] S. Z. Lulec, U. Adiyen, G. G. Yaralioglu, Y. Leblebici, and H. Urey, "Cantilever array oscillators with nonlinear optical readout," in *Optical MEMS and Nanophotonics (OMN), 2015 International Conference on*, 2015, pp. 1-2.
- [105] S. Alexander, L. Hellemans, O. Marti, J. Schneir, V. Elings, P. K. Hansma, *et al.*, "An atomic-resolution atomic-force microscope implemented using an optical lever," *Journal of Applied Physics*, vol. 65, pp. 164-167, 1989.
- [106] D. Ogletree, R. W. Carpick, and M. Salmeron, "Calibration of frictional forces in atomic force microscopy," *Review of Scientific Instruments*, vol. 67, pp. 3298-3306, 1996.
- [107] H. Torun, J. Sutanto, K. K. Sarangapani, P. Joseph, F. L. Degertekin, and C. Zhu, "A micromachined membrane-based active probe for biomolecular mechanics measurement," *Nanotechnology*, vol. 18, pp. -, Apr 25 2007.
- [108] B. E. Saleh, M. C. Teich, and B. E. Saleh, *Fundamentals of photonics* vol. 22: Wiley New York, 1991.

BIBLIOGRAPHY

- [109] U. Adiyen, F. Civitci, O. Ferhanoglu, H. Torun, and H. Urey, "MEMS bimaterial IR sensor array with AC-coupled optical readout," in *Optical MEMS and Nanophotonics (OMN), 2015 International Conference on*, 2015, pp. 1-2.
- [110] J. Villatoro and A. García-Valenzuela, "Measuring optical power transmission near the critical angle for sensing beam deflection," *Applied optics*, vol. 37, pp. 6648-6653, 1998.
- [111] C. Gong, Y. Zhao, L. Dong, X. Yu, P. Chen, and W. Liu, "All-optical background subtraction readout method for bimaterial cantilever array sensing," *Optics express*, vol. 23, pp. 20576-20581, 2015.
- [112] J. Goodman, *Introduction to Fourier Optics* 3rd ed. New York: McGraw-Hill, 2005.
- [113] J. Fu, H. Shang, H. Shi, Z. Li, O. Yi, D. Chen, *et al.*, "Design optimization and performance analysis of deformed optical readout focal plane array," *Journal of Micromechanics and Microengineering*, vol. 25, p. 065012, 2015.
- [114] U. Adiyen, F. Civitci, R. B. Erarslan, O. Ferhanoglu, H. Torun, and H. Urey, "Simultaneous two-wavelength readout for thermo-mechanical MEMS detectors," in *Optical MEMS and Nanophotonics (OMN), 2014 International Conference on*, 2014, pp. 169-170.
- [115] C. Akcay, P. Parrein, and J. P. Rolland, "Estimation of longitudinal resolution in optical coherence imaging," *Applied optics*, vol. 41, pp. 5256-5262, 2002.
- [116] M. Okandan, N. Hall, B. Bicen, C. Garcia, and F. L. Degertekin, "Optical microphone structures fabricated for broad bandwidth and low noise," in *Sensors, 2007 IEEE*, 2007, pp. 1472-1475.
- [117] R. B. Erarslan, S. Z. Lulec, U. Adiyen, S. Olcer, Y. Temiz, Y. Leblebici, *et al.*, "MEMS sensor array platform integrated with CMOS based optical readout," in *Micro Electro Mechanical Systems (MEMS), 2013 IEEE 26th International Conference on*, 2013, pp. 181-184.
- [118] O. Ferhanoglu, M. F. Toy, and H. Urey, "Two-wavelength grating interferometry for MEMS sensors," *Photonics Technology Letters, IEEE*, vol. 19, pp. 1895-1897, 2007.
- [119] Y. Temiz, C. Guiducci, and Y. Leblebici, "Post-CMOS processing and 3-D integration based on dry-film lithography," *Components, Packaging and Manufacturing Technology, IEEE Transactions on*, vol. 3, pp. 1458-1466, 2013.
- [120] D. G. Voelz, *Computational fourier optics: a MATLAB tutorial*: Spie Press Bellingham, Wash, USA, 2011.
- [121] D. Rugar, H. Mamin, and P. Guethner, "Improved fiber-optic interferometer for atomic force microscopy," *Applied Physics Letters*, vol. 55, pp. 2588-2590, 1989.

BIBLIOGRAPHY

- [122] A. Ozturk, H. I. Ocakli, N. Ozber, H. Urey, I. H. Kavakli, and B. E. Alaca, "A magnetically actuated resonant mass sensor with integrated optical readout," *IEEE Photonics Technology Letters*, vol. 20, pp. 1905-1907, 2008.
- [123] S. Z. Lulec, U. Adiyen, G. G. Yaralioglu, Y. Leblebici, and H. Urey, "MEMS cantilever sensor array oscillators: Theory and experiments," *Sensors and Actuators A: Physical*, vol. 237, pp. 147-154, 2016.
- [124] M. Basso, P. Paoletti, B. Tiribilli, and M. Vassalli, "Modeling and analysis of auto-tapping AFM," in *Decision and Control, 2008. CDC 2008. 47th IEEE Conference on*, 2008, pp. 5188-5193.
- [125] L. Manning, B. Rogers, M. Jones, J. Adams, J. Fuste, and S. Minne, "Self-oscillating tapping mode atomic force microscopy," *Review of scientific instruments*, vol. 74, pp. 4220-4222, 2003.
- [126] L. G. Villanueva, R. B. Karabalin, M. H. Matheny, E. Kenig, M. C. Cross, and M. L. Roukes, "A nanoscale parametric feedback oscillator," *Nano letters*, vol. 11, pp. 5054-5059, 2011.
- [127] L. Villanueva, E. Kenig, R. Karabalin, M. Matheny, R. Lifshitz, M. Cross, *et al.*, "Surpassing fundamental limits of oscillators using nonlinear resonators," *Physical review letters*, vol. 110, p. 177208, 2013.
- [128] C. Chen, D. H. Zanette, J. R. Guest, D. A. Czaplewski, and D. López, "Self-Sustained Micromechanical Oscillator with Linear Feedback," *Physical Review Letters*, vol. 117, p. 017203, 2016.
- [129] M. G. Muriuki, W. W. Clark, Q.-M. Chen, and Q.-M. Wang, "Design and analysis of a piezoelectric cantilever beam resonator," in *Smart Structures and Materials*, 2003, pp. 36-47.
- [130] J. Adams, G. Parrott, C. Bauer, T. Sant, L. Manning, M. Jones, *et al.*, "Nanowatt chemical vapor detection with a self-sensing, piezoelectric microcantilever array," *Applied physics letters*, vol. 83, pp. 3428-3430, 2003.
- [131] B. Rogers, L. Manning, M. Jones, T. Sulchek, K. Murray, B. Beneschott, *et al.*, "Mercury vapor detection with a self-sensing, resonating piezoelectric cantilever," *Review of Scientific Instruments*, vol. 74, pp. 4899-4901, 2003.
- [132] R. Adler, "A study of locking phenomena in oscillators," *Proceedings of the IEEE*, vol. 61, pp. 1380-1385, 1973.
- [133] H. L. Stover, "Theoretical explanation for the output spectra of unlocked driven oscillators," *Proceedings of the IEEE*, vol. 54, pp. 310-311, 1966.
- [134] B. Razavi, "A study of injection locking and pulling in oscillators," *IEEE Journal of Solid-State Circuits*, vol. 39, pp. 1415-1424, 2004.
- [135] S. Sancho, M. Ponton, A. Suarez, and F. Ramirez, "Analysis of Injection Pulling in Phase-Locked Loops With a New Modeling Technique," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, pp. 1200-1214, 2013.

BIBLIOGRAPHY

- [136] P. S. Huang, S. Kiyono, and O. Kamada, "Angle measurement based on the internal-reflection effect: a new method," *Applied optics*, vol. 31, pp. 6047-6055, 1992.
- [137] P. S. Huang and Y. Li, "Small-angle measurement by use of a single prism," *Applied optics*, vol. 37, pp. 6636-6642, 1998.



VITA

Ulaş Adıyan

Ulaş Adıyan received the B.Sc. degree from Istanbul Technical University (ITU), Turkey, in 2007, in Telecommunication Engineering and M.Sc. degree in Electronics and Communication Engineering from the same university in 2010. He started the Ph.D. study with Prof. Hakan Ürey in the Electrical and Electronics Engineering Department at Koç University, Istanbul, Turkey. He worked in the Optical Microsystems Laboratory (OML) during his Ph.D. studies. His research interests include designing and developing of MEMS cantilever based sensors with optical readout such as thermo-mechanical IR MEMS sensors, dynamic mode MEMS cantilevers, MEMS biosensors and chemical sensors.