DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

# SPECKLE REDUCTION AND IMAGE QUALITY IMPROVEMENT IN DISPLAY TECHNOLOGIES HAVING LASER LIGHT SOURCES

by
İsmail YILMAZLAR

May, 2016
İZMİR

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**by**
**İsmail YILMAZLAR**



**May, 2016**
**İZMİR**

## Ph.D. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled "**SPECKLE REDUCTION AND IMAGE QUALITY IMPROVEMENT IN DISPLAY TECHNOLOGIES HAVING LASER LIGHT**" completed by **İSMAİL YILMAZLAR** under supervision of **ASSOC. PROF. DR. METİN SABUNCU** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.

Assoc. Prof. Dr. Metin SABUNCU

Supervisor

Prof. Dr. Eyüp AKPINAR

Thesis Committee Member

Prof. Dr. Coşkun SARI

Thesis Committee Member

Prof. Dr. M. Salih Dinleyici

Examining Committee Member

Prof. Dr. Gönül Turhan Sayan

Examining Committee Member

Prof. Dr. Ayşe OKUR
Director
Graduate School of Natural and Applied Sciences

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İsmail YILMAZLAR

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## ABSTRACT

Picture quality of a display system is related to its screen quality. There are different display technologies and the qualities of them are related to the used illumination source used inside the device. The popular illumination devices are Cold Cathode Fluorescent Lamp, Ultra High Pressure lamps and Light Emitting Diodes. But due to lasers own special properties if they are used inside the display technologies they come with some advantages, such as more colorful pictures, higher luminance, an improved contrast ratio and also a constant image quality throughout the lasers lifetime, which makes them ideal candidate for display systems.

Because lasers are coherent light sources, the mutual interference of wave fronts create a nonuniform intensity pattern which causes unwanted speckle noise in display and projection systems.

In this thesis, we propose and experimentally demonstrate results of a new laser drive circuit for laser speckle reduction. By modulating the drive current of the laser diode continuously; we manage to generate independent longitudinal modes that arise from mode hopping. Since these modes have no fixed relationship between each other they act as independent sources which results in speckle reduction in the image. For square wave and triangular wave we experimentally demonstrate a speckle reduction factor of 1.32 and 2.16 respectively, which is in excellent agreement with our theoretical expectations. We conclude that mode hopping in laser systems can be used effectively to suppress speckle noise.

**Keywords**: Speckle, speckle reduction, laser current modulation, mode hopping, display systems.

**LAZER IŞIK KAYNAĞI KULLANILAN EKRANLARDA GÖRÜNTÜ KALİTESİNİN YÜKSELTİLMESİ VE LEKELERİN AZALTILMASI**

# ÖZ


Görüntüleme sistemlerindeki resim kalitesi, ekran kalitesi ile ilgilidir. Değişik görüntüleme teknolojileri vardır ve bunların kalitesi cihaz içerisinde kullanılan ışık kaynağı ile ilgilidir. Soğuk katot floresan lamba, yüksek basınçlı lambalar ve ışık yayan diyotlar popüler ışık kaynaklarıdır. Fakat, lazerler kendine özgü özelliklerinden dolayı görüntüleme sistemlerinin içerisinde kulanılırsa daha renkli, daha parlak, zıtlık oranı artmış görüntüler ve lazerin kullanım ömrü boyunca sabit resim kalitesi gibi avantajlar elde edilir, bu lazerleri görüntüleme sistemleri için ideal bir aday yapar.

Lazerler eşevreli ışık kaynağı olduğu için dalga çeperleri birbiri ile girişim yaparak düzgün olmayan parlaklık dağılımı oluşturarak ekran ve projeksiyon sistemlerinde istenmeyen  leke etkilerine neden olurlar.

Bu tezde, leke etkisini azaltmak için yeni bir lazer sürücü devresi önerilmiş ve sonuçları deneysel olarak gösterilmiştir. Lazer diyot akımı sürekli olarak modüle edilerek, mode atlamalarından oluşan bağımsız modlar oluşturulması başarılmıştır. Oluşan bu modlar arasında sabit bir ilişki olmadığı için, bu modlar bağımsız birer kaynak olarak davranarak, resimdeki leke etkisnin azalmasına neden olmuşlardır. Deneysel sonuçlarımızda kare dalga ve üçgen dalga için sırasıyla 1,32 ve 2,16 lık leke azaltım oranları elde edilmiştir, bu bizim teorik beklentilerimiz ile çok iyi bir uyum içerisindedir. Mode atlamaları lazer sistemlerinde etkili bir leke azaltım yöntemi olarak kullanılabilir.



**Anahtar Kelimeler**: Leke, leke azaltma, lazer akım modülasyonu, mod atlaması, görüntüleme sistemleri.

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# CHAPTER ONE
# INTRODUCTION

Laser light can be monochromatic, cover a wide range of color gamut, is bright and reliable. These specific device characteristics make lasers ideal candidates as a light source in display and projection applications (Chellappan, Erden, & Urey, 2010; Fujieda, Kosugi, & Inaba, 2009). Utilization of lasers as a light source in display and projection applications has long been investigated (George & others, 1969). Projection systems and displays that utilize lasers advantage from the extraordinary characteristics of lasers and will make superb pictures that were unachievable by routine sources. Lasers for instance not at all like LED's save their quality all through their lifetime. Normal issues experienced with LED and CCFL lights, for example, fast drops in color saturation and luminance don't happen with laser light sources (Hollemann et al., 2000).

Display systems that utilize lasers empower people to see conceivably 90% of the color gamut range that people can see, while without lasers they can just show around 40% of the color gamut (Morgenstern, 2007). Also having a wide color gamut laser light conserve its output power for a very long time (up to 25000 hours). The laser keeps its quality (such as color saturation and luminance) constant during its lifespan (Hollemann et al., 2000). Moreover it is likewise conceivable to show 3 Dimensional stereoscopic pictures utilizing lasers (Koba, 2004). Every one of these properties make laser a perfect light source for display and projection applications (Chellappan et al., 2010; Fujieda et al., 2009; Zheng et al., 2008).

The fundamental weakness of laser light is the speckle phenomena that creates speckle noise which reduces the picture quality. Because all imaging systems that use lasers suffer from speckle noise is essential to scrap it (Brennesholtz, 2008; Chen et al., 2012; Liren, 2011; Rafiee, Moradi, & Farzaneh, 2004). Until date a lot of techniques have been applied successfully to solve the speckle noise problem (HAO et al., 2006; Li et al., 2008; Xu, Gao, Shi, Wang, & Du, 2014). In this thesis we show the implementation of a current drive modulation circuit for efficient speckle reduction in a laser projection system.

In this thesis firstly in chapter 2 we briefly analyze some features of display systems to explain current display types then look into possible laser based systems. As advantages of laser based display systems comes from laser own properties we explain the laser working principle and features of laser light in chapter 3. In chapter 4 the general principles of laser drive circuits and mode hopping are explained. In the light of the previous chapters advantages and disadvantages of Laser TV are explained in chapter 5. In chapter 6 we explain statistical properties of speckle phenomena and the solutions of the speckle problem. The proposed laser drive circuit is explained in chapter 7 and the speckle measurement setup introduced. In chapter 8 speckle reduction results are given and these results are compared with theoretical calculation and MATLAB analysis. In chapter 9, the thesis is concluded and a short outlook is given.

# CHAPTER TWO
# DISPLAY REVIEW

Human eye reception is very complex and there are many parameters which effect picture quality on display screens. Therefore display technologies are changing and improving their picture quality day by day. But up to now there has been no display system which reaches human eye reception capacity (Seetzen et al., 2004).

There are some famous technologies like as Cathode Ray Tube (CRT), Liquid Crystal Display (LCD) and Plasma. Each technology has different advantages and disadvantages. CRT is bulky, screen size is limited due to its weight so these properties consigning it to history. Due to easy scalable screen size with respect to CRT and PC (Personal Computer) monitor market pressure LCD replaced CRT technology with a big commercial momentum. New technologies are aimed to replace current technologies with slim design trend and picture quality concerns (Choi et al., 2009).

Technology companies and lots of researchers are trying to improve picture quality to get benefits from this trend with the support of content recording and transmission technologies. For resolution improvement High Definition (HD), Ultra High Definition (UHD) technologies announced respectively moreover to use existing bandwidth new video compression technologies likes as H.264 (Wiegand, Sullivan, Bjøntegaard, & Luthra, 2003), high efficiency video coding (HEVC) (Sullivan, Ohm, Han, & Wiegand, 2012) and VP9 (Mukherjee et al., 2013) announced. On the other hand High Dynamic Range (HDR) (Drago, Myszkowski, Annen, & Chiba, 2003; Kang, Uyttendaele, Winder, & Szeliski, 2003) technology help to increase standard camcorder dynamic range capacity. All these improvements increase end user expectations and cause big change in display systems.

## 2.1 Important Features of Display Systems

Human eye has approximately 100 million photoreceptors offers superior reception capability with respect to display systems. Therefore the main objective is to match human eye capacity and display system so it is important to discuss display systems parameters.

### *2.1.1 Brightness*

In display technology, brightness is a white luminance level and measured in candela per square meter ($cd/m^2$) or nits (Lowe, 1997) it can be reflected or emitted from a source in a given direction. It is measured from the center of the screen which is denoted by measurement number 5 in the Figure 2.1.

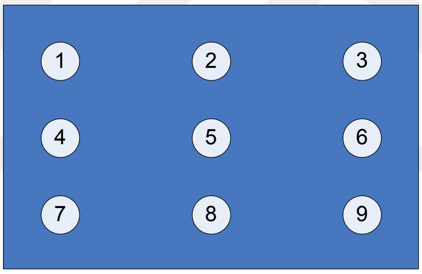


Figure 2.1 Measurement points of the screen

Generally due to the used display technology, luminance may not be uniform and this phenomenon is called as brightness uniformity problem. To define brightness uniformity we measure brightness level of all the 9 measurement points given in Figure 2.1. $B_{max}$ is the maximum brightness level, $B_{min}$ is the minimum brightness between these 9 measurement points. $B_{uni}$ is defined as brightness uniformity and given by the following Equation (2.1). If $B_{uni} = 0$ corresponds totally uniform illumination.

$$B_{uni} = 100 * \frac{B_{max} - B_{min}}{B_{max}} \quad (2.1)$$

Currently different technologies offer different brightness levels. Plasma-based or rear projection based screens can reach 1,200 cd/m$^2$. CRTs typically offer an operational brightness around 150 cd/m$^2$. Standard commercially available mid-range LCD screens can reach 500 cd/m$^2$ (Kranert, Deter, Gessner, & Dotzel, 1998).

Whereas moonlight exhibits around 0.1 cd/m$^2$, indoor lighting is around 100 cd/m$^2$, and sunlight is around 10,000 cd/m$^2$.

### *2.1.2 Contrast and Dynamic Range*

Human eye is more sensitive to difference intensities (Luxenberg & Kuehn, 1968; Wisnieff & Ritsko, 2000). Therefore contrast or sometimes called as contrast ratio $(CR)$ which is a ratio of maximum luminance to minimum luminance as given in Equation (2.2) is another important factor of the display systems.

$$CR = \frac{B_{max}}{B_{min}} \qquad (2.2)$$

Contrast ratio is again measured in the center of the screen as defined by the measurement number 5 in the Figure 2.1. Similar to brightness; during this measurement also we should use different pictures which can provide maximum contrast ratio which are full white and full black respectively (Foley, Van Dam, Feiner, Hughes, & Phillips, 1994).

With higher contrast ratio it is easier to detect smaller objects and this limit of resolution sense is related to contrast and visual acuity which will be explained later (Woods & Wood, 1995). There should be minimum one percent contrast difference for human eye detection. In order to detect an image for the human eye.

Different technologies achieve different black levels for example typical CRT can reach 0.01 cd/m$^2$, again mid-range typical LCD of 0.72 cd/m$^2$ and Plasma of 0.42

cd/m$^2$. Plasma screens can offer better contrast ratio in generally. More black or higher contrast ratio requirement depends on usage. For example movie makers prefer more black levels instead of better contrast ratio.

For better contrast, black level is very important but unfortunately due to light leakage and reflecting ambient light display can't deliver pure black. Moreover this poor performance at the black levels, disturb the color in the darker areas. In LCD technology since the LCD pixels can't block the emitted light from the backlight source the display suffers from black level.

### *2.1.3 Visual Acuity and Resolution*

The resolution of the screen is also another critical performance parameter. It is related to the amount of pixel number, pixel size, size of the display and of course related to our visual acuity (Wisnieff & Ritsko, 2000).

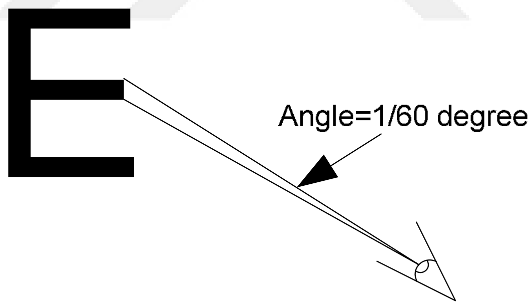


Figure 2.2 Visual Acuity

Acuity is a measure of visual performance. An average human eye can resolve an individual pixel of approximately 1/60 of a degree at the visual content as shown in Figure 2.2. This is a measurement method used by opticians when they are checking your eye performance with the Snellen chart. Again as can be seen from the Figure 2.2 the visual acuity determines the level of detail the human eye can perceive. If you are nearer the object smaller level of details can be determined which means that the distance of the end user from a display screen is an important factor in determining resolution requirements.

Due to general approximation within the display industry pixel density is very important. Key measure is pixels per inch (ppi) and 200 ppi is a good approximation of the human eye visual requirement within a personal screen use like as computer display environment (Alt & Noda, 1998).

Again, like the other parameters different technologies offer different pixel density as an indication, for computer displays, a typical 16 by 9 screen 15-inch display with 1024 ×768 resolution has a pixel density of 90 ppi, and a UHD 40-inch display has a density of 110 ppi. Nowadays pixel density is particularly important factor in small mobile displays such as mobile phones, where they can reach above 400 ppi (Bolster, Giardini, Livingstone, & Bastawrous, 2014).

### *2.1.4 Viewing Angle*

Typically human eye has a 185 degrees horizontally and 155 degrees vertically viewing angle (Rheingold, 1991). Generally displays are positioned in front of the viewer with direct view. But this is not always possible for example in the big living room each person has a different viewing angle. Or think about public displays, in such cases where direct view is not possible,  most of the use case display capacity with wider viewing angle with similar level of screen performance like as contrast, brightness becomes important. The viewing angle is defined as an angle in which the image is seen clearly. Zero degree is direct view 180 degree is right or left hand side of the screen Figure 2.3.

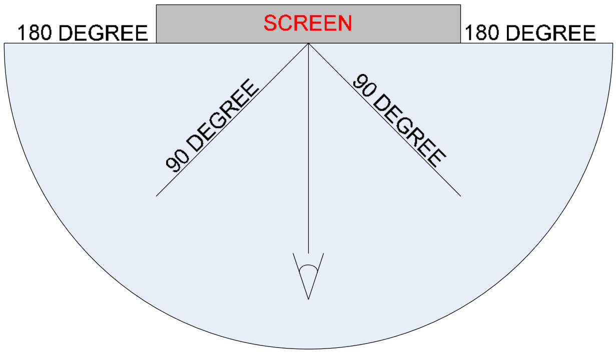


Figure 2.3 Viewing angle

With respect to other display technologies LCD screens have relatively small viewing angle because light passes through many optical materials before reaching the end user (Jin et al., 2006).

Clear image definition is a subjective measure used in the LCD business, defined as the angle at which the brightness level falls down to half of its maximum level. Some display technologies may offer viewing angle at180 degrees theoretically, but in reality as there is no tangential viewing across the surface, this is physically not possible.

### *2.1.5 Perception of Color*

The perception of color is very complex and related to many disciplines such as psychology, physiology, physics and colorimetry (Foley, Dam, Feiner, Hughes, & Phillips, 1990). Color of an object is a function of wavelengths which is emitted or reflected from object surface. Perception of the color has three important parameters;

- Hue: Defined by the dominant wavelength.

- Brightness: Related to the luminosity of the color.

• Saturation: This parameter is related to the relative strength of a color also with simpler term it is related to purity of perceived color. More saturated colors consist of a narrower range of wavelength centered on the hue.

People see different wavelengths as a different color and human eye can differentiate around 3nm. But due to the psychological reasons what a person see is not exactly same as other person can see (Foley et al., 1990). Human eye contains two kinds of receptors rods and cones. Rods are used to perceive shades of gray levels and cones allow the brain to perceive hue. Typical human eye has three types of cones L, M and S types they detects red, green and blue colors respectively. For example if the M type cone is stimulated we see green, if three cones are stimulated at the same time we see white. Sensitivities of cones are given in Figure 2.4 (Besharse & Bok, 2011). Due to various sources people can see between 380 nm to 800 nm, blue color is located between 450 nm to 495 nm, green color is 495 to 570nm and red color is 620 nm to 750 nm (Ohannesian & Streeter, 2001).

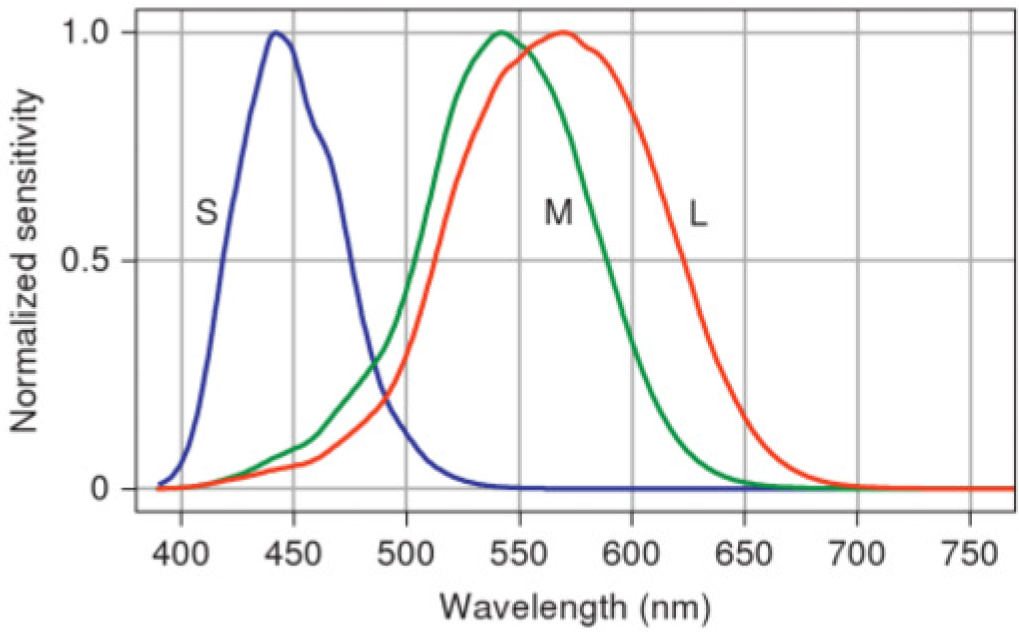


Figure 2.4 Spectral sensitivities of cones (Besharse & Bok, 2011)

### *2.1.6 Color Gamut*

Color can provide a lot of information in an image so display capacity is very important to generate the right color and provide enough information. All the color displays emit or reflect different wavelength of the light to generate the required color. There are three different primary colors (red, green and blue) all of the other colors are a mixture of these primary colors.

The color gamut is a measure the range of colors of a display. And this gamut range is related to the red, green and blue individual performance (Wisnieff & Ritsko, 2000).

In 1931 three dimensional color space was created by the International Commission on Illumination (CIE). CIE used the XYZ coordinate system which is derived from red, green and blue color space. With this three dimensional coordinate system any color can be located on the CIE 1931 XYZ color space.

In 1976 the Uniform Chromatic Space (UCS) created a two dimensional color space which is an alternative to the three dimensional CIE standards. But all different color space coordinates has a relation with the R, G, B domain. The two dimensional color space which is called the color gamut is given in Figure 2.5.

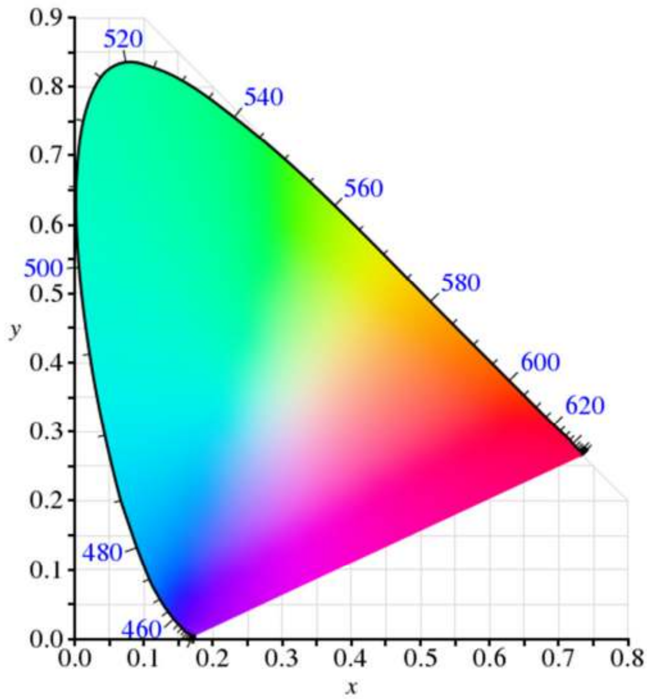


Figure 2.5 Color gamut

Color gamut provided by displays is much smaller than the human eyes visual capacity. This means that real life images are always richer in colors, than images displayed on the screen.

A typical LCD display is either 8 bit or 10 bit. LCD may provide 256 and 1024 different levels respectively and three subpixels for red, green and blue. Recently some manufacturer added a white subpixel as a fourth pixel. This extra pixel provides more brightness and does not enhance color gamut of the display(Elliott, Credelle, Thompson, & Higgins, 2010).

Due to historical reasons most of the display manufacturers gives a percentage comparison with respect to National TV Standards Committee's (NTSC) color space within the standard CIE (Sharma, 2002).

### *2.1.7 Refresh Rate*

The human eye visual system can take about 20 different images per second before they begin to blur together. This effect is used when showing a film or video, as the individual frames blur to form a smooth image.

Refresh rate is a frequency at which a display redraws the image on the screen. This could be raster scan in CRT or pixel control in LCD technology. If the refresh rate is too slow people start to differentiate pictures and this, causes feeling of flicker.

To not see the flicker new term critical fusion frequency (CFF) is introduced at which point eye stops seeing the individual pictures and has a feeling of smooth picture. The CFF is affected by environmental conditions and viewing angle (Levick, 1953). Also it can depend on the person but due to different conditions and feedback from other people a display should be running at least 72Hz for comfortable operation (Dillon, 1992, 2004) moreover at least 95% of a given population to be able to view flicker-free, it should ideally run at 95Hz (Bauer, Bonacker, & Cavonius, 1983).

## 2.2 Display Types

As seen from the previous chapters there are many performance parameters which are related to define display quality. Due to special use case of displays some parameters become more important. For example for outdoor displays brightness and lifetime becomes more important than other parameters, refresh rate is critical for moving scenes, color gamut and contrast ratio is crucial for cinema and consumer electronics devices so there are many specialized screen types. Also due to huge market revenue display companies and researcher are working to develop new screen types and trying to improve current technologies (Chiu, Chen, Tzeng, & Shyu, 2006).

In general, displays can be divided into two groups as shown in Figure 2.6. In direct view technology picture of video occurs on the screen and end user views the composed scene. In the projection type, a small image is enlarged and projected on to the screen by using the lens systems (Bahadur & Tilton, 1992). All the projection displays use a very bright light to project image and provides manual settings interface to correct any scaling artifacts and blurriness and other inconsistencies (Stupp & Brennesholtz, 1999).

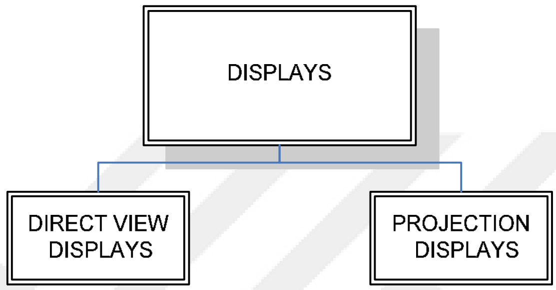


Figure 2.6 Direct view and projection displays

Direct view displays in general can be divided into two groups as shown in Figure 2.7 as an emissive and a non-emissive display. In emissive displays, the image is produced directly on the screen, where phosphors convert electron beams or UV light into visible light. In non-emissive displays light is produced behind the screen and the image is formed by filtering this light (Uchikoga, 2006).

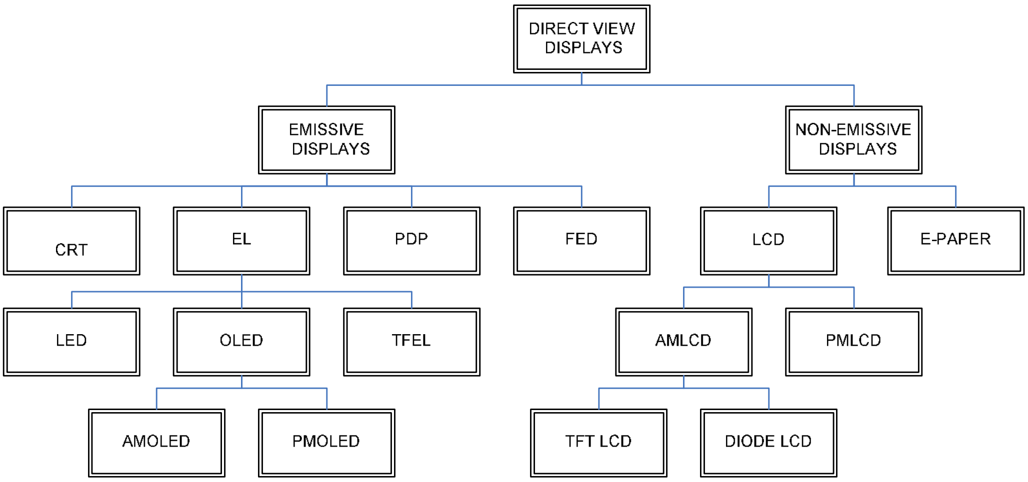


Figure 2.7 Direct view displays

Emissive display can be Cathode Ray Tube (CRT), Field Emission Display (FED), Plasma Display (PDP) and Electroluminescent Display (EL). EL displays can be dived into three groups as Light Emitting Diode Displays, Inorganic Thin Film Electroluminescent Display (TFEL) and Organic Light Emitting Display (OLED). OLEDs can be grouped as an Active Matrix Organic Light Emitting Display (AMOLED) and Passive Matrix Organic Light Emitting Display (PMOLED) (Kelly, 2000).

Non emissive displays analyzable into two groups as a E-paper and Liquid Crystal Display (LCD). Again like as OLEDs, LCDs can have active matrix technology or passive matrix technology. Passive Matrix Liquid Crystal Display can be called as PMLCD and Active Matrix Liquid Crystal Display called as AMLCD and grouped into two category Thin Film Transistor Liquid Crystal Display (TFT-LCD), Diode Liquid Crystal Display (Diode LCD)(Boer, 2011; Kelly, 2000).

Projection displays grouped as a CRT projection and microdisplay as represented in Figure 2.8. At microdisplay technology there are three different technologies which are very popular nowadays. LCD microdisplay, Liquid Crystal on Silicon (LCOS), Digital Light Processing (DLP) (Heynderickx & Langendijk, 2005).

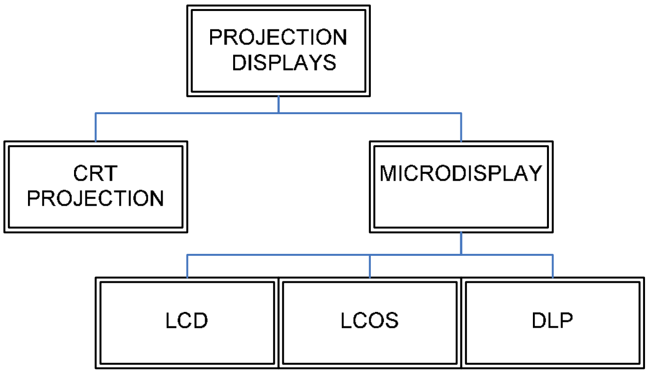


Figure 2.8 Projection displays

With a different perspective with respect to its operation mode displays can be grouped transmissive mode, reflective mode or transreflective mode of operation. In the transmissive mode of operation display has its own backlight source but at reflective mode of operation ambient light reflection is used to produce a picture (Kranert et al., 1998).

Flat panel technologies competing with active matrix LCDs are briefly addressed, including plasma displays, inorganic and organic electroluminescent displays, and front and rear projection.

The final decision to select a certain display technology is usually based on a careful consideration of price and performances which are mentioned at previous section. But even we mentioned many types of display systems rear projection, front projection and LCD technology has better price and performance ratio so they are widely used as display technology. In the next section we will look on display technologies where lasers can be used as a companion light source or standalone light source.

## 2.3 Laser TV Types

There are three types of technology that can be called as laser TV, at this chapter we explain the general structures of these technologies.

### *2.3.1 Laser Projector*

Projectors control how the light is directed onto the screen. The projected light is then reflected back to the viewer eye as shown in Figure 2.9. With this type of setup, the screen is not an active device and reflects all the light inside the medium. So if you have another light source, other than the projector the picture is distributed. So the main question is related to output power of the projector, generally they are in the range of 800-1500 lumens, it is obvious that with a higher lumen output projector you don’t need perfectly dark room so if you can’t control the room lighting it is better to select brighter projector.

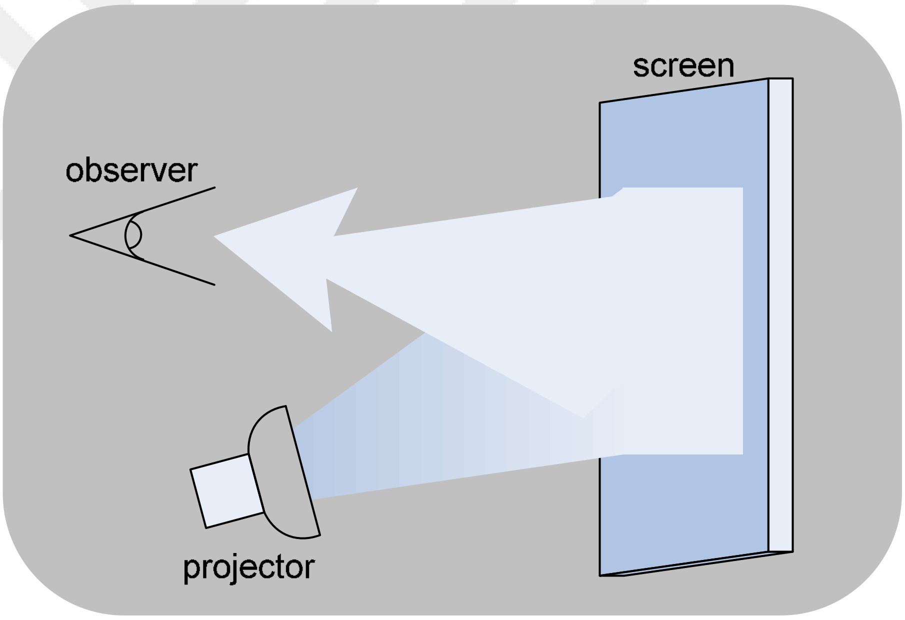


Figure 2.9 Typical front projection

There could be different technologies for the projectors, like as DLP, LCOS and LCD based. General block diagram of traditional lamb based projector shown in Figure 2.10. White light generated by the lamp and separated into red, green and blue light with the help of dichroic filters red, green and blue light separated and modulated then send to combiner, combined light projected to a screen with the help of optical lens systems. For the LCOS structure modulators are replaced with active-matrix liquid-crystal display or microdisplay using a liquid crystal layer on top of a silicon backplane. The structure shown in Figure 2.10, it requires transmissive type AMLCD. But with different configuration it could be reflective type AMLCD. LCD based projectors contains microdisplay called as a LCD screen in Figure 2.11 and the video produced by this small display then projected to a screen with the optical lens system.

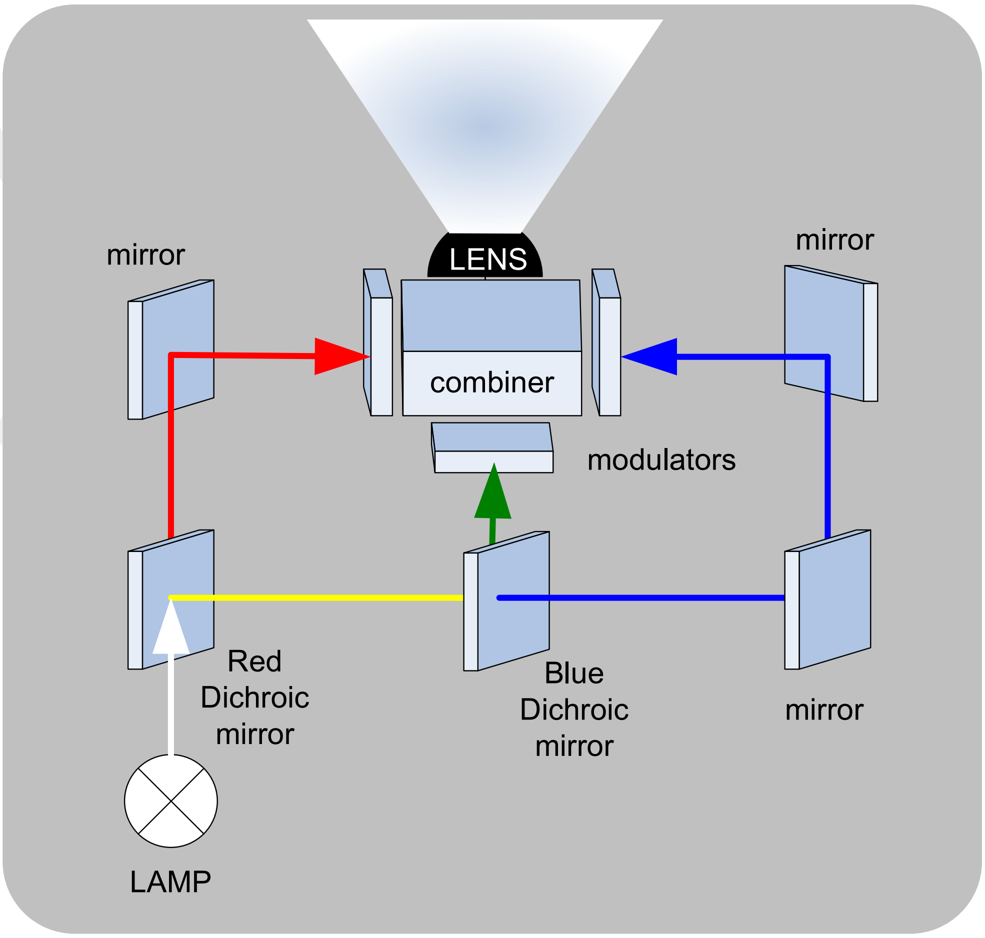


Figure 2.10 General blocks of traditional lamb based projector

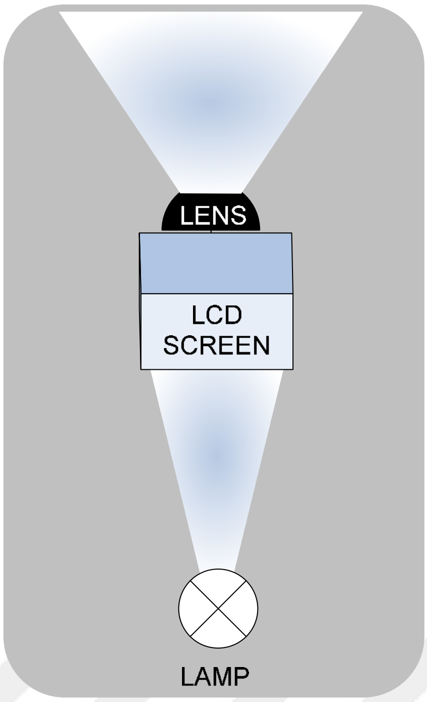


Figure 2.11 General blocks of LCD based projector

DLP is another technology for the projectors. The heart of the DLP chipset consists of an array of highly reflective aluminum micromirrors which is known as the digital micromirror device (DMD). The DMD accepts electrical input signal , and forward optical signal with micro-electrical-mechanical system (MEMS) as shown in Figure 2.12 which allows high speed, efficient, and reliable spatial light modulation (Instruments, 2013).

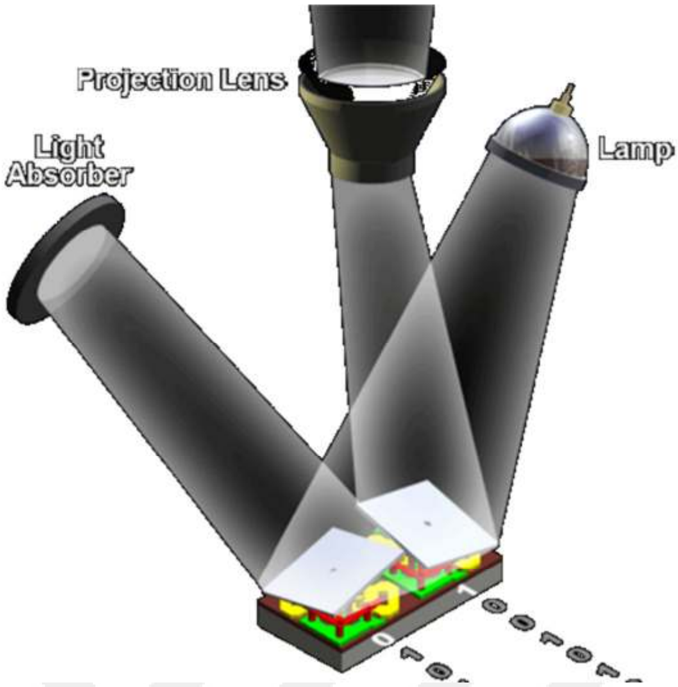


Figure 2.12 DMD pixels(Instruments, 2013)

During operation, the DMD controller loads each underlying memory cell with a '1' or a '0'. Next, a mirror reset pulse is applied, which causes each micromirror to be electrostatically deflected about a hinge to the associated +/-12° state. The deflection angle of these two valid states is very repeatable due to a physical stop against two spring tips. In a projection system, the +12° state corresponds to an 'on' pixel, and the -12° state corresponds to an 'off' pixel. Grayscale patterns are created by programming the on/off duty cycle of each mirror, and multiple light sources can be multiplexed to create full RGB color images. In other applications, the +/-12° states offer two general purpose output ports with a pattern and its inverse.

There could be different technologies for the projectors, such as DLP, LCOS and LCD based. General block diagram of traditional lamp based projector shown in Figure 2.10. White light generated by the lamp and with the help of dichroic filters red, green and blue light separated and modulated then sends to combiner at the end combined light projected to a screen with the help of optical lens systems. For the LCOS structure modulators are replaced with active-matrix liquid-crystal display or microdisplay using a liquid crystal layer on top of a silicon backplane the structure shown in Figure 2.10 requires transmissive type AMLCD but with different configuration it could be reflective type AMLCD. LCD based projectors contains microdisplay called as a LCD screen in Figure 2.11 and the video produced by this small display then projected to a screen with the optical lens system.

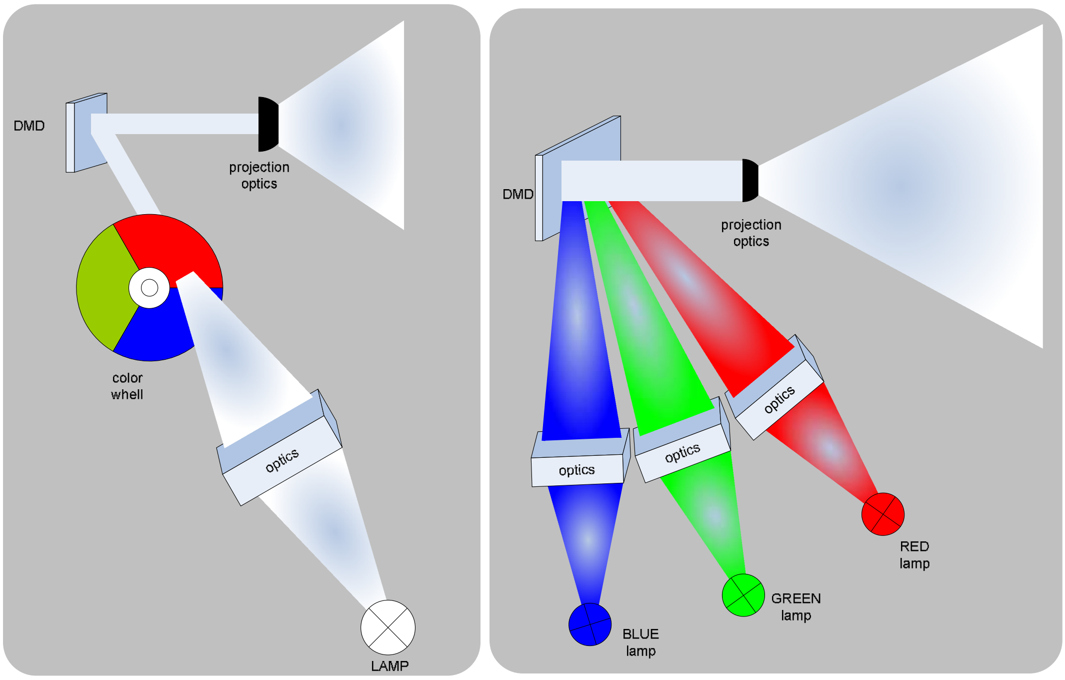


Figure 2.13 DLP projection

Digital Light Processing is a Texas Instruments technology that uses micro mirrors to create a picture and sends to a projection lens to project an image. Generally there are two types of DLP systems, three chips and a single chip Figure 2.13. In the single chip application there is a color wheel and white light goes through this wheel and DMD forward required color to the projection lens. DMD and the color wheel should be synchronized. Another type is 3 chip solutions; for each color of light, system has another DMD device to forward required light to projection optics. Three chip DLP has better color coordinates as they have used separate lamps for each color and provides better brightness level. Single chip versions provide good color coordinates but not as good three chip versions but this version provides better contrast level.

There are different types of illumination source inside the projector. As shown in Figure 2.14 metal halide is the most popular lamp source which produces light by an electric arc through a gaseous mixture of metal halides and vaporized mercury and (Grondzik, Kwok, Stein, & Reynolds, 2011; Hordeski, 2004). Metal halide lamps are type of high-intensity gas discharge (HID) lamp which are developed in the 1960s, and similar to mercury vapor lamps, but contain additional metal halide compounds to increase luminous efficiency (Grondzik et al., 2011) which is more efficient than mercury vapor lights generally lamp life is 6.000 to 15.000 hours (García, Gómez, Espín, & Rabaza, 2015). Due to their wide spectrum they have been using wide area overhead lighting of commercial, industrial, and public spaces. Metal halide lamps operate under high pressure it may reach up to 20 atmospheres so require special fixtures also needs electrical ballast. Metal atoms need a warm-up period which may require up to several minutes to reach full light output.

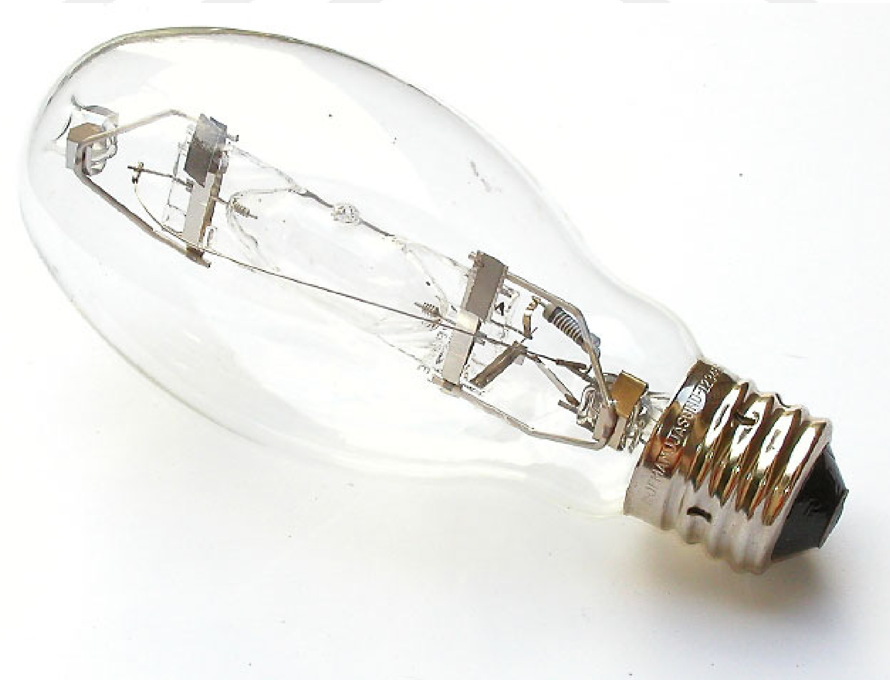

Figure 2.14 Metal halide lamp

Another lamp type is UHP lamp which is developed by Philips and more efficient alternative to the metal halide lamps so sometimes called as ultra-high pressure lamps because internal pressure may reach up to 250 atmospheres (Derra et al., 2005). UHP lamps are included most of the commercially available projectors. Their lifetime can reach up to 10000hrs (Pekarski et al., 2003).

Projector lamps provide wide range of spectral width which is very useful for street lighting but not efficient for display applications. The lifetime of these type of arc lamps not good enough and produces a lot of heat. Because of that projectors should have good ventilation, should be cleaned regularly, needs periodic air filter change if exist, and shouldn’t turn on and off rapidly. Moreover light output quality drops during lifetime.

### *2.3.2 Laser Projection*

Projection TVs, sometimes called as rear projection screens basically have a projector and projection optics inside the TV cabinet as shown in Figure 2.15. The projector is a lower power version of the front projector, which is mentioned in the previous chapter. Optic system may change due to the used system, sometimes one full projection can be handled by using only one mirror.

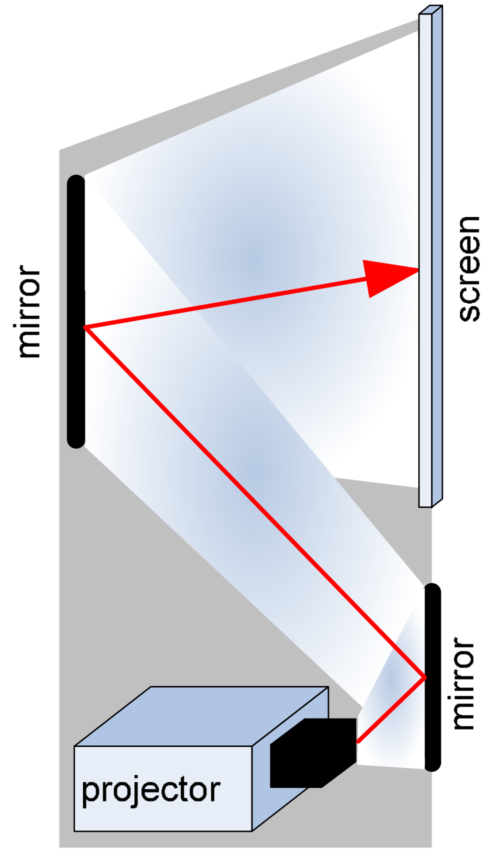


Figure 2.15 Rear projector TV

DLP, LCD, LCOS technology can be used inside the rear projection screen so the advantages coming from the technologies which are already mentioned at previous chapter can be used for rear projection systems.

### *2.3.3 Laser Based LCD*

General structure of LCD panel is given in Figure 2.16. The LCD non-emissive display always needs an independent illumination source called backlight unit (BLU).

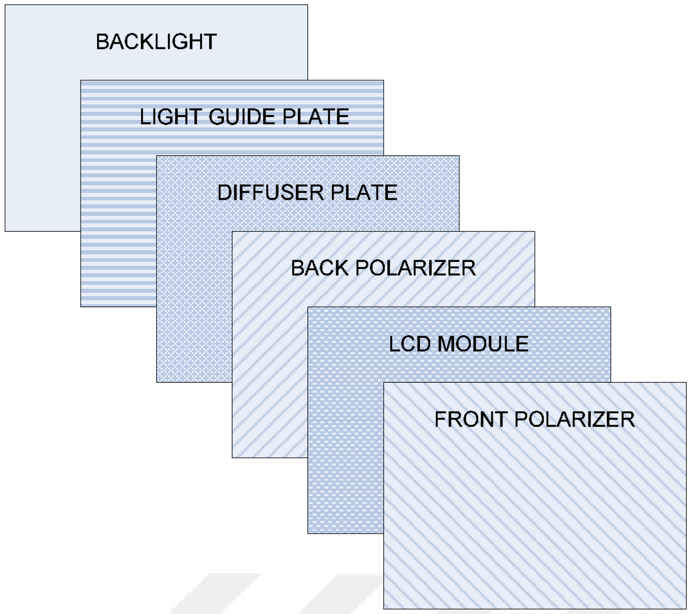


Figure 2.16 LCD panel structure

The function of BLU is to supply bright, white light. Light guide plate (LGP) and diffuser plate helps to get uniform illumination. Due to backlight structure LGB may not be used.

Inside the LCD module there are liquid crystal (LC) part, TFT array part and color filter part as shown in Figure 2.17. LC behaves as a light valve. If the voltage is applied to LC it changes the polarization of the light and allows the light pass through the front polarizer or vice versa, it doesn’t change the polarization and the light is blocked by the front polarizer.

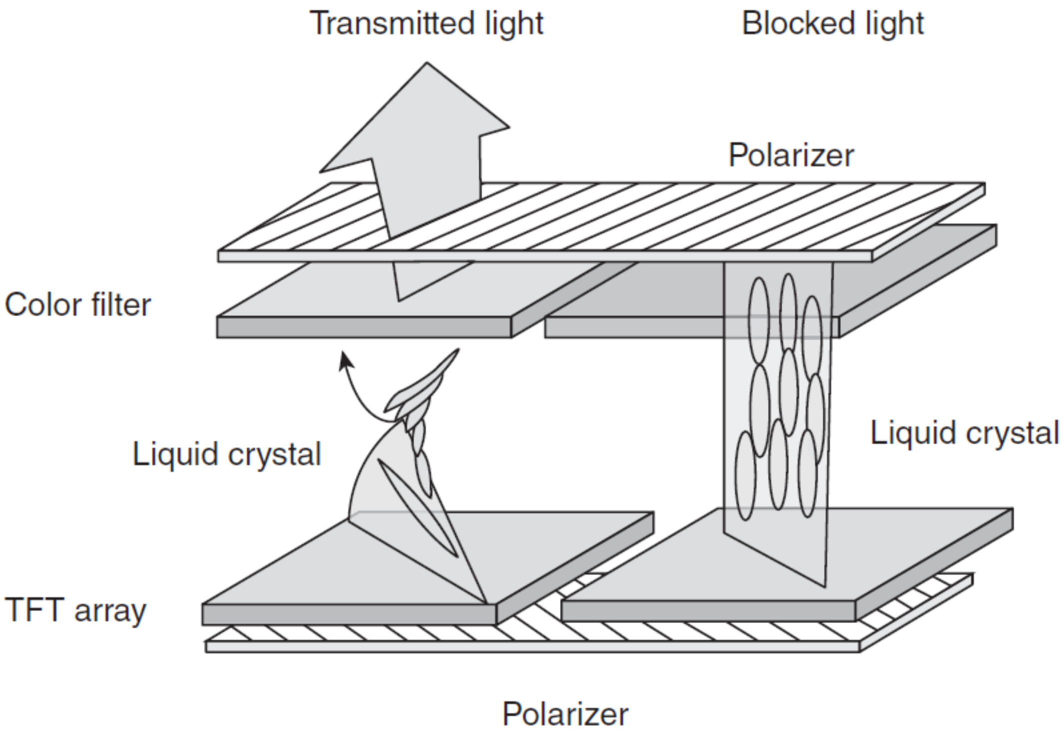


Figure 2.17 Liquid crystal as a light valve

LC orientations controlled by the thin film transistor (TFT), controls the amount of transmitted light through the corresponding pixel, up to this point transmitted light is white and the color filter on the front glass of the panel reshapes the spectrum of the incident white light.

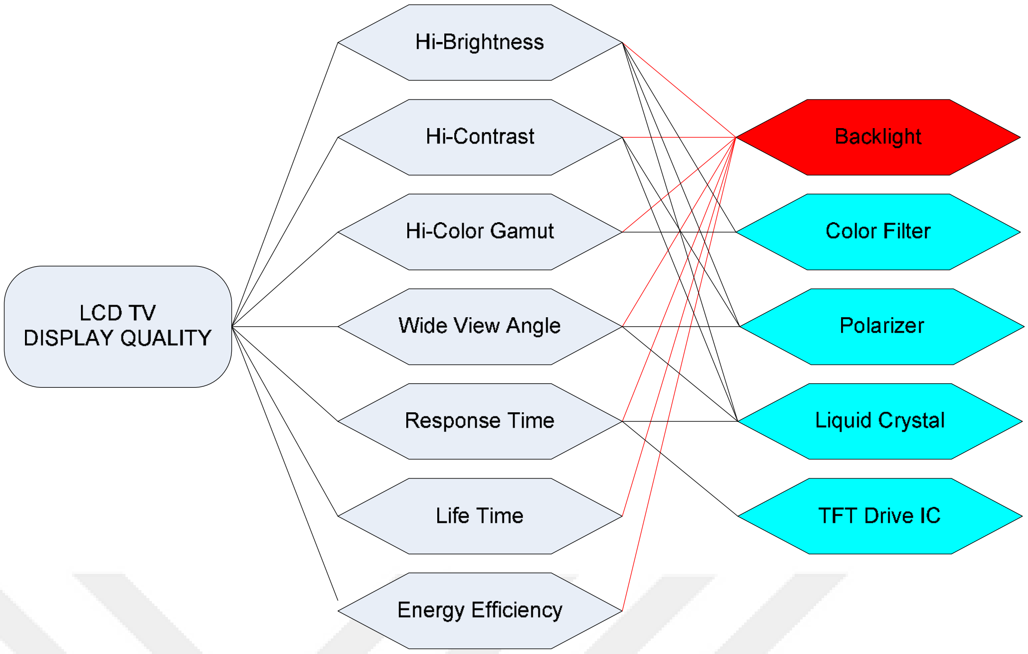


Figure 2.18 LCD TV features and panel components

As shown in Figure 2.18 BL is the key component of the LCDs. It affects almost all the quality features of the display. Brightness level is the direct consequence of the output power of backlight module. As mentioned previously contrast level is a measure of maximum luminance to minimum luminance so higher brightness level may increase contrast level more if light leakage doesn't disturb black level. Dynamic contrast range is related to dimming performance of backlight and its driver circuit with better dimming performance it is possible to obtain more black level which is increase dynamic contrast performance. Hi color gamut is directly related to backlight color coordinate performance, color gamut ratio is of the LCD is a measure of backlight capacity. Wide viewing angle related to incident light direction so backlight structure affects incident light. Response time related to how fast backlight can be turned off and on, this switch on and off performance decrease motion blurs and increase response time. Backlight is the heart of the LCD systems most of the time backlight has the shortest life time more over during the usage backlight quality may drop as a common problem with CCFL and LED backlights. Backlight consumes more power than other electronic parts in the LCD structure so energy efficient backlight structure is the most important parameter of the efficient LCD design.

As mentioned previously, lasers are very efficient light sources (Wisely, 2006) and they cover a wide range of color gamut, have high dimmable capacity, high switching frequency, high output power and stable output characteristics during their life time which makes them ideal candidates for backlight sources inside the LCD TV.

Due to mentioned advantages, lasers have been used as a backlight source inside several LCD TV system applications. As the lasers are already polarized they helps to remove back polarizer (Kurashima, Tagaya, & Koike, 2011). At some application lasers are used to increase color gamut as an example red laser diodes and cyan LEDs offers better color gamut (Okimoto, Maeda, Niikura, Sawanaka, & Kida, 2015).

Red and green lasers are commercially available with an affordable price but unfortunately blue laser still not very common. Red, green and blue lasers can be used together to produce white light for backlighting with the improvement of blue lasers or white laser helps to replace current backlight sources with lasers.

# CHAPTER THREE
# LASER

The laser term is an acronym for “light amplification by stimulated emission of radiation”. Laser which is a device that processes optical amplification and creates directional, high intensity beam with a very pure frequency or wavelength (Gould, 1959). Laser comes with several sizes in terms of power, wavelength and physical structure. It creates continuous waves or very short pulses. Due to these flexibilities and features lasers are used in several areas. Laser can be used for welding for different industrial area with better quality due to previous welding techniques (Zacharia, David, Vitek, & DebRoy, 1989). Lasers can be used to create three-dimensional holes with femtosecond laser pulses (Li et al., 2001), to detach tear retinas inside the human eye (Steinert, Puliafito, Kumar, Dudak, & Patel, 1991), myopic and hyperopic or astigmatism treatment of the eye (Mulhern, Condon, & Okeefe, 2001). Lasers are becoming key components of modern communication systems due to their high switching frequency and directional behavior (Killinger, 2002; Kim et al., 1998). Lasers have been used as a needle at compact disc players to read and write data (Pohlmann, 1989), and act as a special surgical knife for medical applications (Imagawa & Haga, 1984). Some of the military weapons include laser systems, such as range finders and target designators. Lasers can also be utilized in the generation of true random numbers for certain applications(Sabuncu, 2012, 2016).

Laser is just another type of light source and has many unique properties non similar other light sources. These properties make it special light source and enable several usage. In this chapter we will explain these important unique features.

## 3.1 Spontaneous Emission, Absorption and Stimulated Emission

As it is already known from atomic theory, an atom may emit or absorb a photon during transitions between its energy levels to conserve energy in the process. If we consider there are two energy modes E1 and E2 respectively and then the photon energy between these two energy levels can be described by Equation (3.1). Here $h$ is the Planck constant and $v$ is the frequency of the photon.

$$h.v = E2 - E1 \quad (3.1)$$

Due to phenomena of the photon position change between the energy levels there are three types of transitions.

### *3.1.1 Spontaneous Emission*

The atom could be poisoned initially in the upper energy level, it may drop to the lower energy level spontaneously and release its energy in the form of a photon Figure 3.1. The occurred photon energy which is already defined $h.v$ is added to the energy of the electromagnetic mode. This process is called as a spontaneous emission. At this emission mode transition is independent of the number of photons.

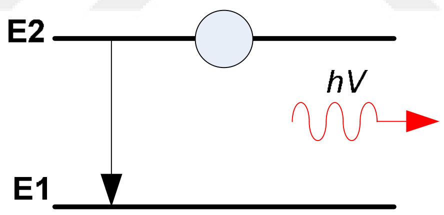


Figure 3.1 Spontaneous emission

### *3.1.2 Absorption*

The atom could be poisoned initially in the lower energy level and the radiation mode contains a photon, the atom absorbed the photon and an electron jump to upper energy level Figure 3.2. This process is known as absorption, which is induced by the photon. Absorption can occur when the mode contains a photon.

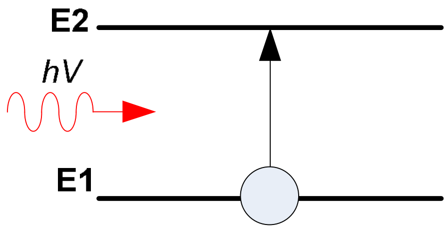


Figure 3.2 Absorption

### *3.1.3 Stimulated Emission*

Stimulated emission is the inverse of the absorption and is sometimes referred to negative absorption or induced emission. Originally atom is positioned at the upper energy level and the mode contains a photon, the atom may emit or induced another photon into the same mode as shown in Figure 3.3, this is known as stimulated emission. The new photon precisely has the same characteristics as the original photon, it has same frequency, propagation direction, and polarization briefly clone of it. This photon amplification phenomenon underlies the operation of laser amplifiers and lasers.

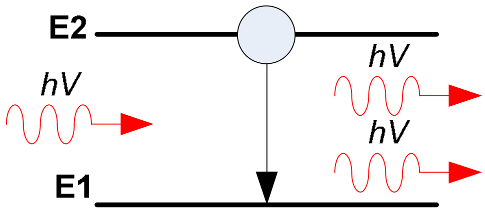


Figure 3.3 Stimulated emission

### *3.1.4 Population Inversion*

There are many atomic energy levels, and each one has its own decay time constant. The four level energy diagram which is representative of some real lasers shown in Figure 3.4 where E4>E3>E2>E1 and their populations N4, N3, N2 and N1 respectively. Electrons normally reside in the lowest available energy state then it is pumped (excited) into an upper level E4 by a collision with another atom or absorption of high-energy radiation then it decays to E3 while it is decaying from E4 to E3 there is no radiation., then to E2, and finally to the ground state E1. Assume that decay time from E3 to E2 much longer than E4 to E3 also E2 to E1 and a population accumulates at E3 which may drop to E2 by spontaneous or stimulated emission. Any atom at the E1 or E2 de-excited or pumped to E4 so the population at the E3 becomes greater than E2, N3>N2 and a stimulated emission occurs due to population inversion. Thus optical amplification, and laser action occurs.

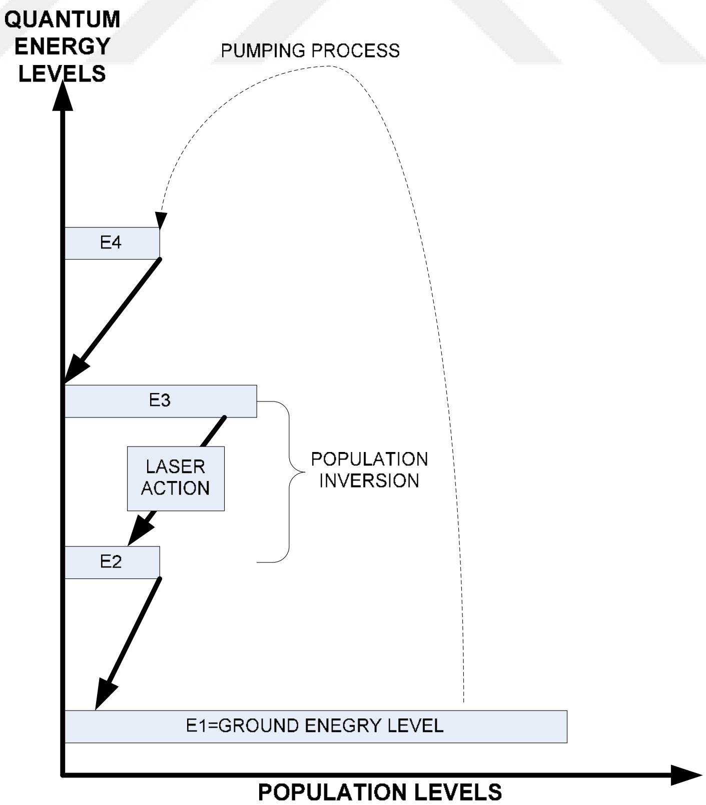


Figure 3.4 Population inversion

## 3.2 Definition of Laser

Lasers are devices that amplify light. Basically there are three essential elements of a laser device, as shown in Figure 3.5, these are laser medium, pumping process and suitable optical feedback elements. Pumping process is used to excite atoms into higher quantum-mechanical energy levels in the laser medium, optical feedback elements allow lasing amplification and lasing oscillation for inversion.

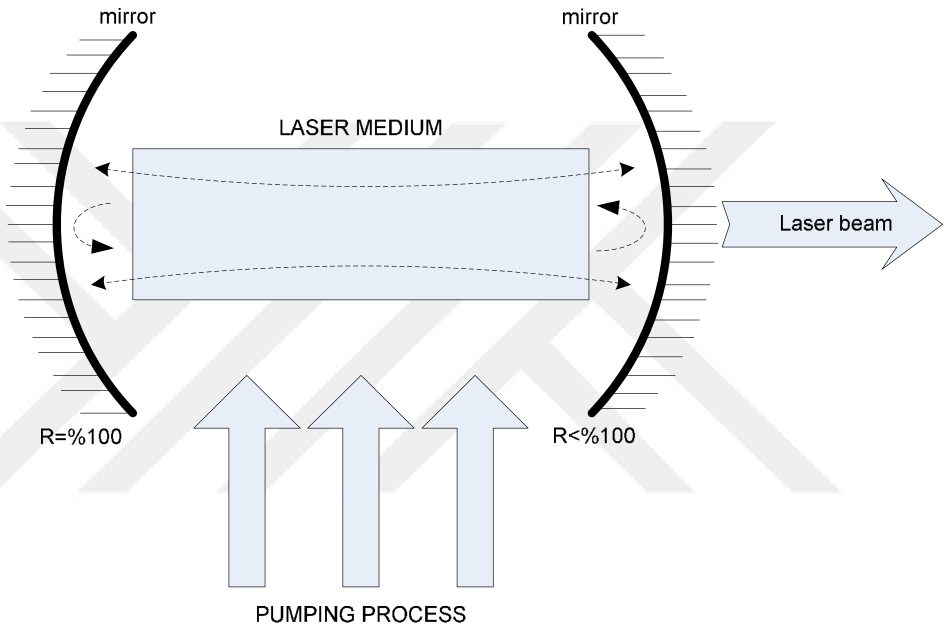


Figure 3.5 Laser elements

For the laser action, the pumping process must produce excited atoms in the laser medium. In the laser medium there are appropriate collections of atoms, molecules, ions, or a semiconducting crystal. A pumping process excites these atoms or other molecules in the laser medium into their higher quantum-mechanical energy levels. There could be many ways for pumping process but only pumping process is not enough to start laser action. There should be population inversion in the laser medium in which more atoms are excited into their higher quantum energy level than are in some lower energy level.

For the laser amplification population inversion is needed. Once it is obtained while certain narrow band of frequencies passing through this medium can be amplified coherently. Coherent amplification means output signals more or less exactly reproduce the input signal, with an amplitude increase. Amplification process may also add some amplifier noise and a small phase shift.

All types of oscillations need feedback system. In the optical system the feedback mechanism are mirrors which are placed at each end of the amplifying laser medium. These mirrors are carefully aligned to allow the travelling waves to bounce back and forth with very small loss per bounce. Each bounce of the coherent oscillation increases the amplitude of the laser beam, an output beam that is both highly directional and highly monochromatic can be coupled out of the laser oscillator, either through a partially transmitting mirror on either end. So the extremely bright or powerful lasers can be obtained by laser oscillation and amplification.

## 3.3 Properties of Laser Light

There are some special properties of laser light. Laser is monochromatic, highly coherent, directional, very bright and can have very short pulse duration.

### *3.3.1 Monochromaticity*

Monochromaticity is the most important parameter of the laser light, that arises from laser amplifying phenomena. Laser amplifier can amplify an em wave with frequency given by Equation (3.1). All the other frequencies oscillate inside the laser medium won’t be amplified. The second causative feature is the laser oscillation which is related to mirror arrangements as discussed previously. The laser oscillation can occur inside the laser cavity which correspond the resonant frequency of it.

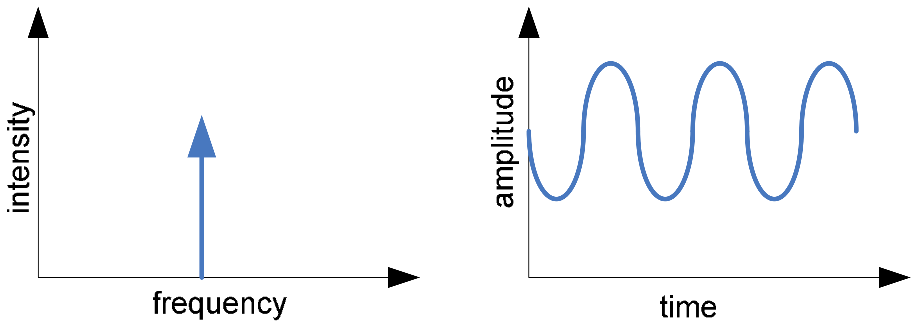


Figure 3.6 Laser monochromaticity

### *3.3.2 Interference and Coherence*

A light waves that is oscillating in more than one plane is called as unpolarized light, like as light emitted from the sun. If the light is oscillating in a direction it is called polarized light, like as laser light. When waves propagate in any medium interference may occur. But due to random phase delays and random wavelengths it is not easy to see this phenomenon all the time.

Assume that we have sinusoidal wave generator and it is continuously generate polarized waves with different phase delays in this case if the crest and the tough of the waves are cross each other it is possible to obtain amplified waves this phenomena is commonly called as constructive interference as shown in Figure 3.7.

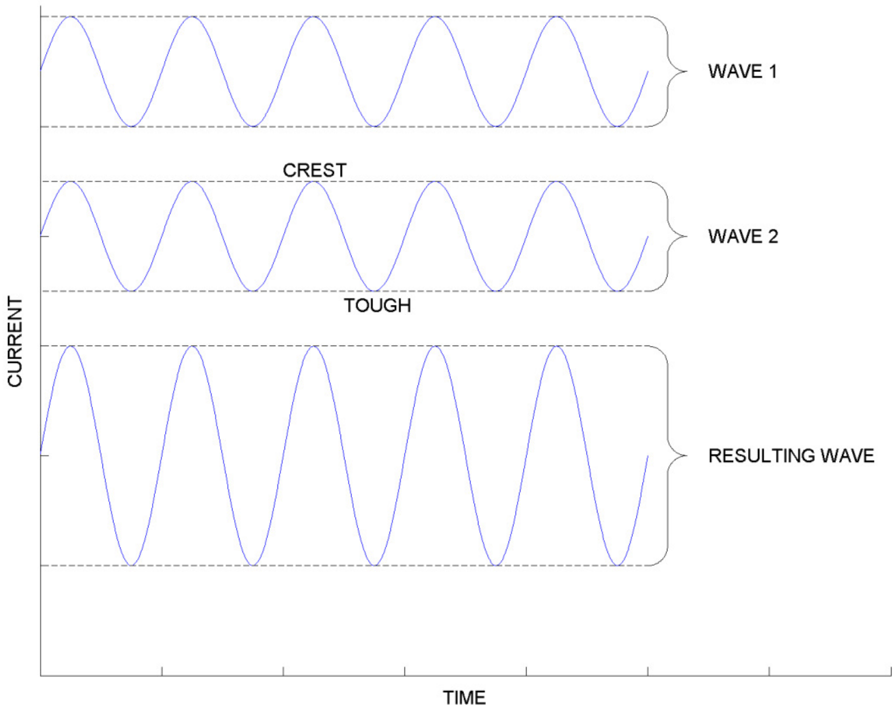


Figure 3.7 Constructive interference

Similarly if the 180 degree phase delay exists crest and the tough of the waves deconstructive interference may occur as shown in Figure 3.8.

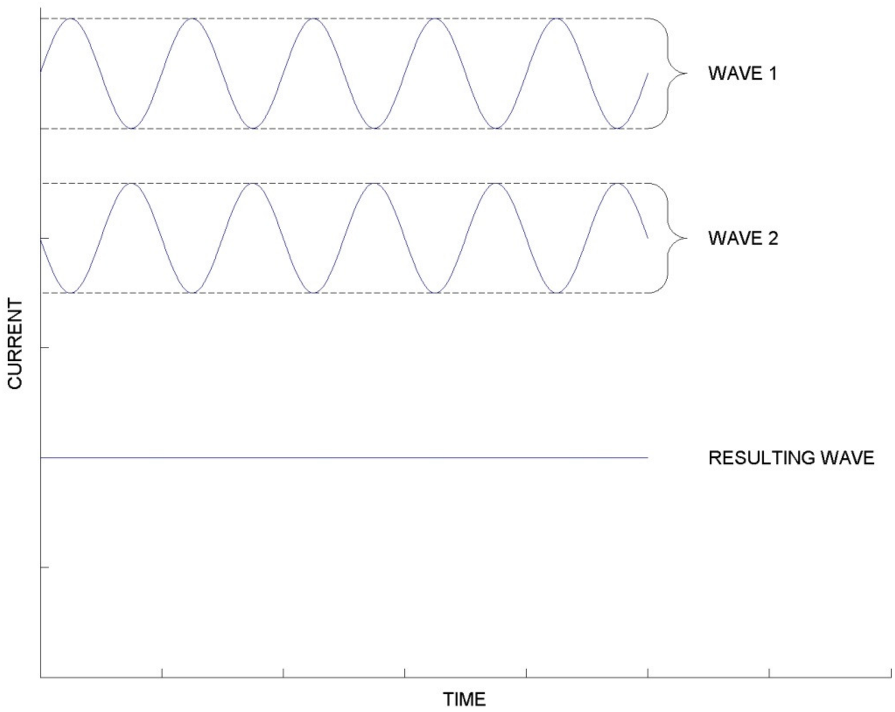


Figure 3.8 Deconstructive interference

Moreover different phase delays results different amplitudes at any time. In a mathematical sense, interference is just the addition of the waves if greater wave amplitude obtained than either one constructive interference occurs, if lesser wave amplitude obtained destructive interference occurs which are the limit cases and resulting of coherence.

There are two types of coherence, temporal and spatial. In any wave these coherence can exist together or separately namely spatial and temporal coherence, as shown in Figure 3.9. If two waves have a constant phase difference and the same frequency they are perfectly coherent.

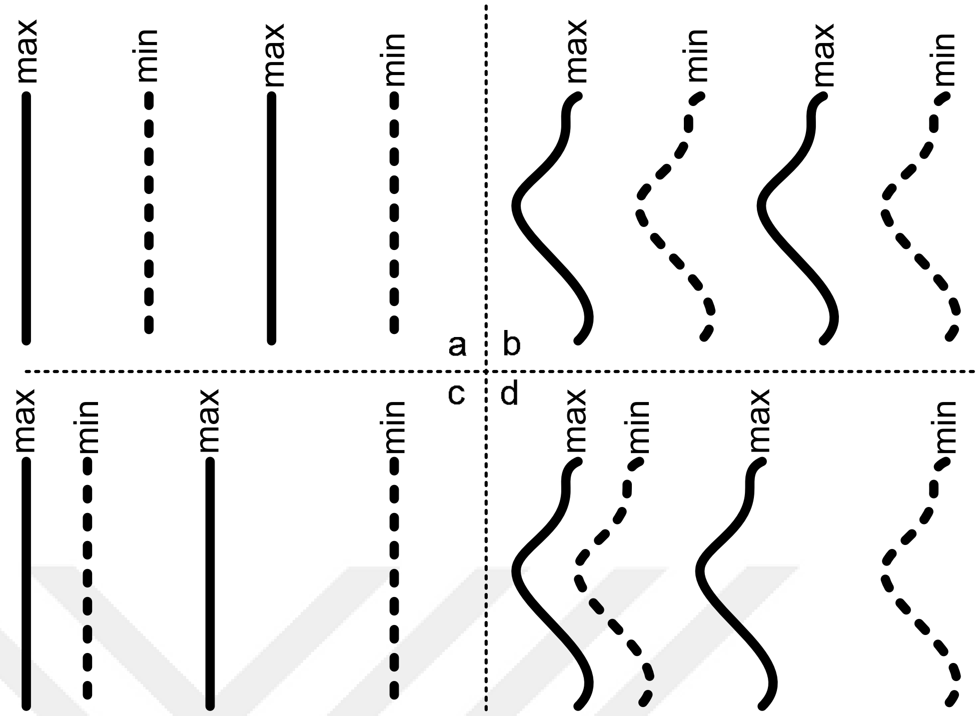


Figure 3.9 a)spatial and temporal coherence b) temporal coherence spatial incoherence c) temporal incoherence spatial coherence d) temporal and spatial incoherence

General spectral intensity profile of the laser source can be approximated to be Gaussian curve and shown in Figure 3.10. In this figure $\Delta\lambda$ is defined as full width half maximum (FWHM) which is a width of a spectrum curve measured between two points on the intensity-axis which are half the maximum amplitude. In free space temporal coherence is determined by coherence length ($L_c$) and given by Equation (3.2), $c$ is light velocity and note that $\Delta\lambda \ll \lambda_0$ then $\Delta f / f_0 = \Delta\lambda / \lambda_0$

$$L_c = \frac{c}{\Delta f} = \frac{(\lambda_0)^2}{\Delta\lambda} \tag{3.2}$$

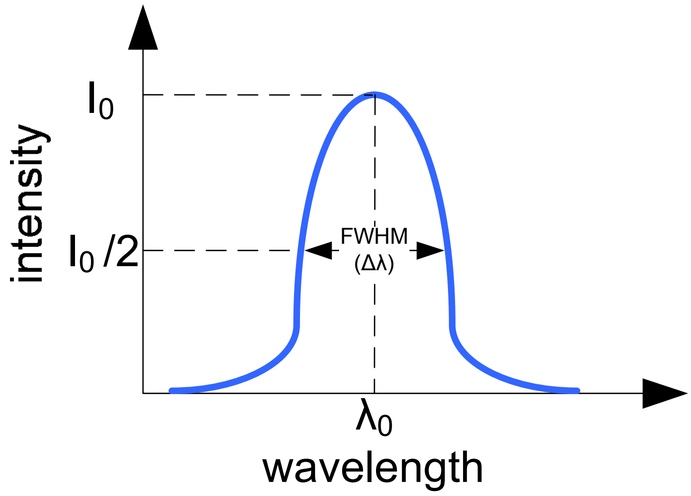


Figure 3.10 Spectral intensity profile

Both spatial and temporal coherence can be explained with interferometer experiments. Michelson interferometer explains temporal coherence when one of the mirrors is moved away gradually, the time for the beam travel increases and the fringes become blur and finally they get lost, showing temporal coherence. At Michelson interferometer given at Figure 3.11, has the path difference $\Delta L = 2L$. If the path difference is smaller than temporal coherence length, interference pattern occurs. As seen in Equation (3.2) in order to have long coherence length, the signal should have small $\Delta\lambda$.

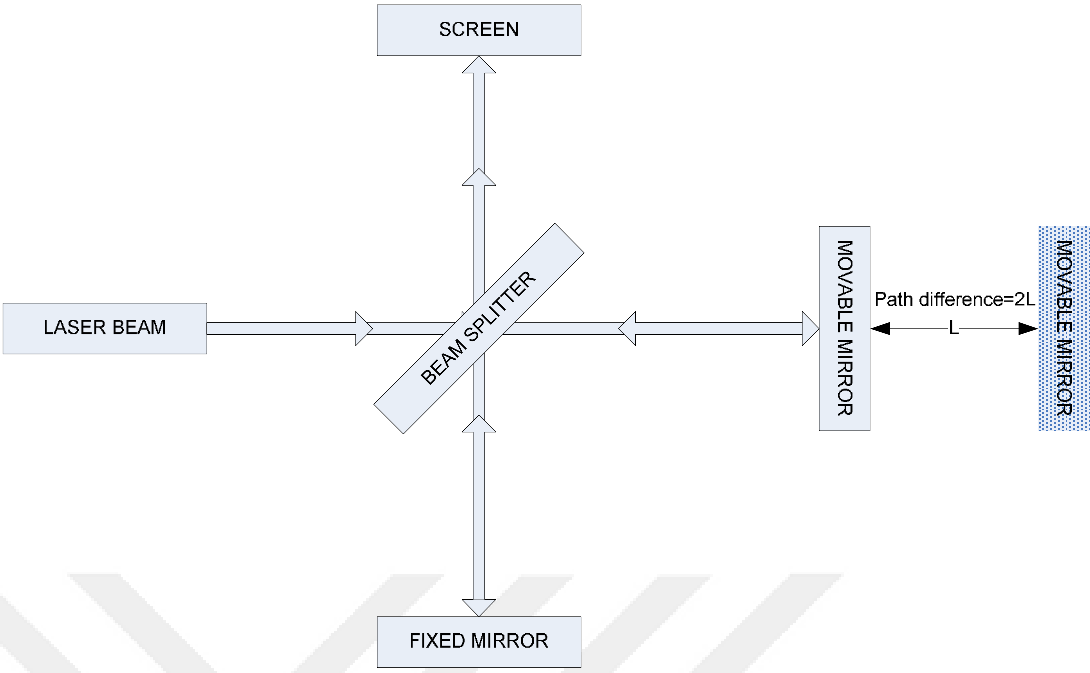


Figure 3.11 Michelson interferometer

Similarly for the Young interferometer if the space between the two slits is increased, the coherence dies gradually and finally the fringes disappear, showing spatial coherence. The distance shown as $d$ at Figure 3.12 can be increased up to $D$ after that level fringe pattern can't be observed so coherence area($A_c$) is given by Equation (3.3);

$$A_c = \pi D^2 \tag{3.3}$$

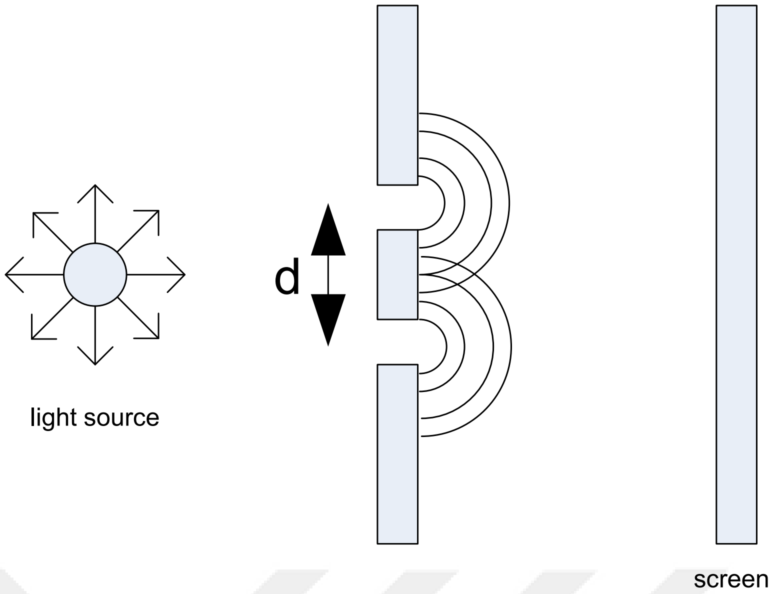


Figure 3.12 Young interferometer

A traveling plane wave can be expressed by Equation (3.4).

$$U(x, y, z) = A.e^{-j(k_x x + k_y y + k_z z)} \tag{3.4}$$

Where $A$ is a complex constant and $(k_x, k_y, k_z)$ are components of wave vector $\vec{k}$ and these components are related by Equation (3.5)

$$k_x^2 + k_y^2 + k_z^2 = \frac{w^2}{c^2} = \left(\frac{2\pi}{\lambda}\right)^2 \tag{3.5}$$

The temporal coherence function is,

$$G(\tau) = \left\langle U^*(t)\, U(t+\tau) \right\rangle \tag{3.6}$$

$G(0)$ contains information about the intensity where $G(0) = \mathrm{I}$. So complex degree of temporal coherence, which is not sensitive to intensity is given at Equation (3.7) (Saleh & Teich, n.d.).

$$g(\tau) = \frac{G(\tau)}{G(0)} = \frac{\left\langle U^*(\mathrm{t}) U(\mathrm{t}+\tau) \right\rangle}{\left\langle U^*(\mathrm{t}) U(\mathrm{t}) \right\rangle} \tag{3.7}$$

The mutual coherence function for temporal and spatial coherence is given by,

$$G(\mathrm{r}_1, \mathrm{r}_2, \tau) = \left\langle U^*(\mathrm{r}_1, \mathrm{t})\, \mathrm{U}(\mathrm{r}_2, \mathrm{t}+\tau) \right\rangle \tag{3.8}$$

Again normalized form of this function becomes,

$$g(\mathrm{r}_1, \mathrm{r}_2, \tau) = \frac{G(\mathrm{r}_1, \mathrm{r}_2, \tau)}{\sqrt{I(\mathrm{r}_1) I(\mathrm{r}_2)}} \tag{3.9}$$

And spatial coherence function can be expressed by setting time delay to zero $\tau = 0$ (Saleh & Teich, n.d.),

$$g(\mathrm{r}_1, \mathrm{r}_2, 0) = g(\mathrm{r}_1, \mathrm{r}_2) = \frac{G(\mathrm{r}_1, \mathrm{r}_2, 0)}{\sqrt{I(\mathrm{r}_1) I(\mathrm{r}_2)}} \tag{3.10}$$

### *3.3.3 Directionality*

Directionality is one of the important parameter of laser light which implies very small divergence. This is the direct consequence of laser cavity structure. As mirrors are placed as opposite ends of the laser cavity the laser beam travelling back and forth in order to increase intensity by stimulated emission these reflections from the mirrors collimate the laser light. So only the waves travelling along to optical axis can be sustained

Due to the high degree of collimation of the laser light final laser beam path is perpendicular to mirrors and parallel to optical path. Perfect collimated beam remains parallel to the optical path with distance which means zero divergence angle.

Diffraction is a very important factor to determine laser spot size at a given distance. Even though the oscillation in the laser cavity produce narrow beam, it starts diverging with some angle due to resonator design and the size of the output aperture. These diffraction effects can be explained by spreading effect of the light waves passing through a small opening.

As mentioned, divergence angle describes the directionality of the laser beam. For a perfect spatially coherent laser beam, diffraction limited divergence angle $\theta_d$ is given by Equation (3.11). Where λ is the wavelength and D is the diameter of laser beam. $\beta$ is a constant but it has relationship with wavelength. The relationship clearly demonstrates that beam divergence increases with wavelength, and a smaller diameter beam will suffer more divergence and greater spread with distance than a larger beam.

$$\theta_d = \beta . \frac{\lambda}{D} \tag{3.11}$$

As shown in the Figure 3.13 for a perfect Gaussian beam, the diffraction limited divergence angle, $\theta_d$ (half angle), is related to beam waist radius $w_0$ and $\lambda$, wavelength with Equation (3.12).

$$\theta_d = \frac{1}{\pi} \cdot \frac{\lambda}{w_0} \tag{3.12}$$

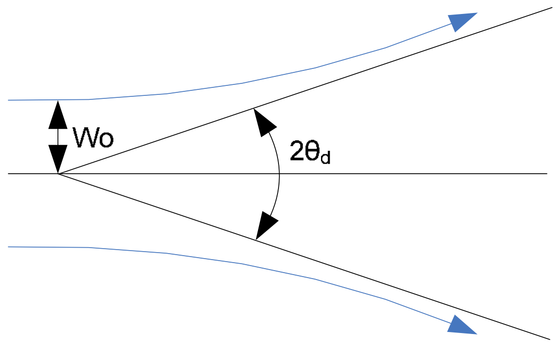


Figure 3.13 Gaussian beam

### *3.3.4 Brightness*

Brightness is defined as the power emitted per unit surface at a per unit solid angle. Let us consider beam power is $P$, its circular cross section is $D$, with a divergence angle $\theta$, the area of the beam is found $\pi D^2/4$ and since $\theta$ is very small emission solid angle $\pi\theta^2$. So $B$ is defined by Equation (3.13) which is beam brightness.

$$B = \frac{4P}{(\pi \mathrm{D} \theta)^2} \tag{3.13}$$

If the beam diffraction is limited, $\theta = \theta_d$ maximum brightness with the beam power $P$ by using Equation (3.11) becomes as given Equation (3.14).

$$B = \left(\frac{2}{\beta\pi\lambda}\right)^2 P \tag{3.14}$$

Due to Equation (3.14) a laser beam with a few miliwatts output has brightness level several orders of magnitude greater than conventional sources.

# CHAPTER FOUR
# LASER DRIVE BASICS

In some applications a typical voltage source is used to drive the laser module directly. As shown in Figure 4.1 the voltage source Vdc is used to drive laser diode (LD), and a resistor (R) is connected in series to adjust laser diode current. Simple voltage source with series resistor can't provide enough protection and control to LD. It should be driven with Constant Current or Automatic Power Control (APC) circuit. Selection of the suitable drive method depends on your application. All circuits should include protection from current or voltage spikes. Surges and transients need to be eliminated. Slow-start or soft-start circuitry helps protection from the initial transient. The vital point of the drive circuit is the instantaneous output power of the laser diode. Exceeding the maximum optical output power for even a nanosecond may damage the laser diode by damaging facets and mirror coating.

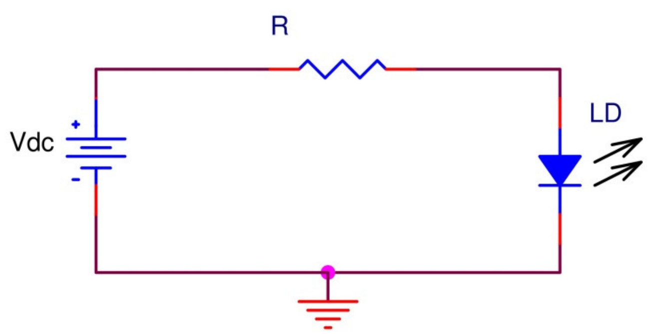


Figure 4.1 Voltage source laser driver

Laser output characteristics such as output power, wavelength, threshold current and efficiency are highly related to the laser case temperature. Therefore temperature control is needed for most of the applications. While low power laser diodes use simple heat sinks, high power laser diode arrays may require water cooling. In some applications high degree of temperature stability is needed. For such applications temperature control instruments that drive Peltier, or thermoelectric coolers may be used.

## 4.1 Current Source

Direct current control of laser diode is very important because laser output power is directly related to laser current. This mode is suitable where high speed modulation and low noise are required. As shown in Figure 4.2 current source (Idc) connected to laser diode In this type of operation current limiter is mandatory to protect the laser diode. It is better to add current limit just above predefined operating current.

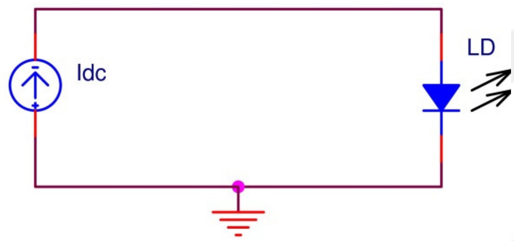


Figure 4.2 Laser diode current control

In general laser output power ( $Pout$ ) versus laser input power ( $Pin$ ) is shown in Figure 4.3 and Equation (4.1) where $\sigma_s$ is slope efficiency and $Pth$ is threshold power.

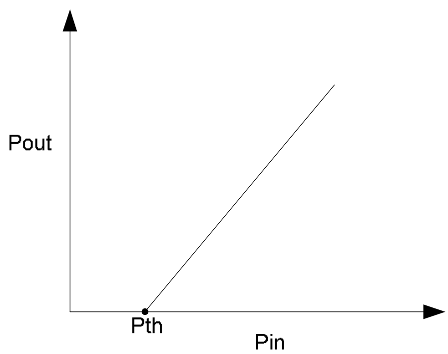


Figure 4.3 Pout versus Pin

$$Pout = \sigma_s (Pin - Pth) \quad (4.1)$$

## 4.2 Constant Power Operation

In some applications constant power mode operation is needed. For that purpose laser output can be monitored by photodiode current which is coupled laser diode as shown in Figure 4.4. There could be different photodiode configuration due to selected package type. Constant current operation is more accurate than constant power operation because at constant power operation mode, photodiode coupling linearity and efficiency effects drive circuit performance.

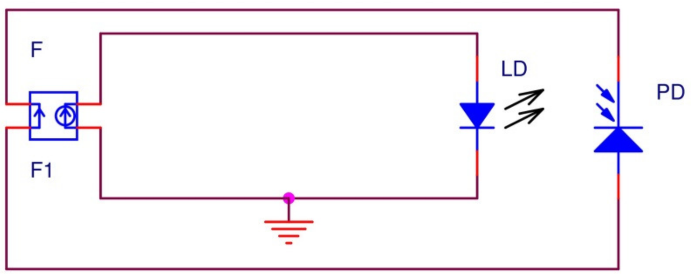


Figure 4.4 Laser diode power control

As we explain in the next section a new laser drive circuit based on current control is designed with the following protections; overvoltage, reverse voltage, power transient and over current.

## 4.3 Mode Hopping

Output spectrum of a semiconductor laser, depends strongly on case temperature and injection current(Marcuse & Lee, 1983; Marcuse, 1984). For example, for the HL6323MG which is a AlGaInP laser diode, the wavelength vs. temperature plot is given in Figure 4.5. As can be seen the wavelength increases with increasing temperature. Moreover in some regions the wavelength has discrete jumps. These jumps in wavelength occur when the laser switches from one longitudinal mode to another mode, and is referred as mode hopping. In other words, under some conditions laser may work on a single resonator mode for a while, but then another mode takes all optical power by switching to another mode(Herre & Barabas, 1989).

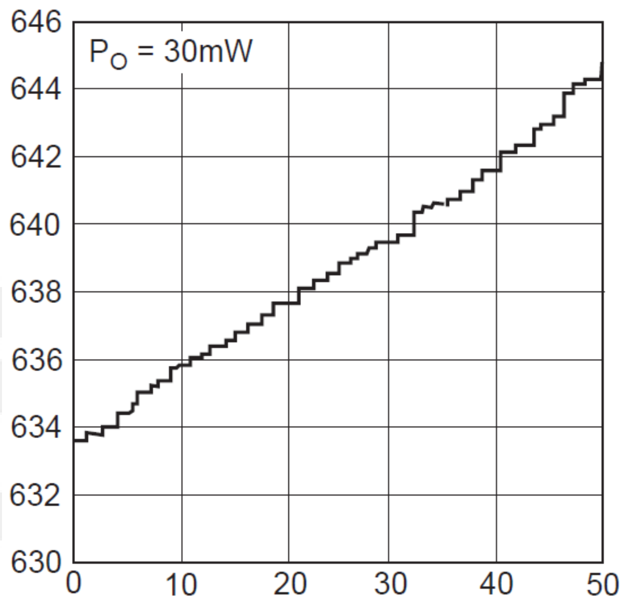


Figure 4.5 Case temperature vs wavelength of HL6323MG

Fluctuating electric field of spontaneous emission was discovered to trigger mode hoppings near critical temperatures or injection currents(Marcuse, 1984). In Fabry-Perot lasers, mode jumps can also be induced by optical feedback, while a modulation of the refractive index causes hysteresis effects (Biesterbos, Boef, Linders, & Acket, 1983; Lang & Kobayashi, 1980; Tromborg, Osmundsen, & Olesen, 1984).

Generally external effects trigger mode hops. These external effects could be temperature fluctuations, changes of pump power or optical feedback. Temperature drift in the gain medium shifts the wavelength of maximum gain while not shifting the resonator modes. Similarly length drifts of the laser resonator shifts the resonator mode frequencies without shifting the gain maximum (Ball & Morey, 1992).

Mode hopping is undesirable in many applications and sometimes called as non-ideal laser oscillations (Siegman, 1971) and it is the most examined part in the setting of single-frequency lasers (Silfvast, 1996). For example quality of the picture derived from the disk is reduced with decreasing signal to noise ratio (Gotoh, Ojima, Arimoto, & Chinone, 1982). Similarly intensity noise produced by mode hopping also effects data transmission via fiber optics (Sato, 1983). In telecommunications mode hopping affects the maximum data transmission rate, because different wavelengths have different velocities in single-mode fibers (Linke et al., 1985; Miller, 1989; Wentworth, Bodeep, & Darcie, 1992).

In general, mode hopping is an undesired effect for laser systems. In this work this phenomena plays a vital role. By modulating the laser diode current we deliberately create mode hopping and reduce speckle effect in laser based systems.

# CHAPTER FIVE
# LASER TV

In the previous chapter, we introduced display systems. Similar to CRT projection the laser is mounted on the back side of the projection screen. The laser scans all the screen periodically to produce a picture in a laser projection systems (Hallstein et al., 2007; Kruschwitz & Kurtz, 2003). Laser light can also be used inside the projector instead of Ultra High Fidelity (UHF) lamps.(Janssens & Malfait, 2009; Knize, 1994; Zheng et al., 2008). The most basic usage area of lasers is inside the LCD backlight system. It could be combined with traditional backlight source or used standalone (Nakano, Niikura, Murase, Nagase, Hanai, et al., 2013; Okimoto et al., 2015). In Figure 5.1 all these type of Laser TV systems are shown.

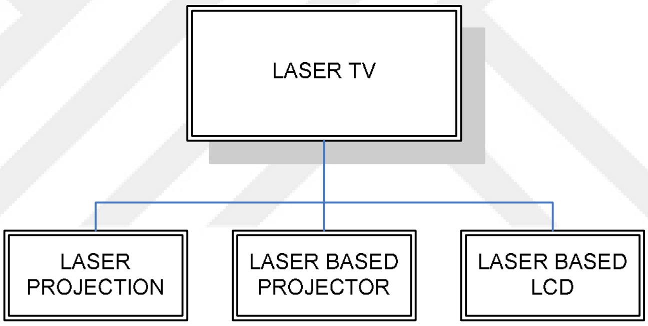


Figure 5.1 Types of Laser TV

Display systems that utilize lasers empower people to see conceivably 90% of the color gamut range that people can see, while without lasers they can just show around 40% of the color gamut (Morgenstern, 2007). There are several application examples;

52-inch High Definition Television (HDTV) is developed that adopts semiconductor lasers with main three colors red, green and blue as a light source. This adaptation of the semiconductor laser increases the color gamut of ITR-U BT.709 by 190%. While laser light increases the color gamut it may not offer the natural images without color matrix conversion, so a special color matrix conversion is adopted to utilize the color gamut (Someya et al., 2006). This projection type TV provides 500 cd/$m^2$ brightness which contains 635nm, 532 nm and 465 nm for red, green and blue light sources respectively. Each of the lasers has 6 watt optical output power. Similarly a 65-inch projection laser TV was announced that was only 255mm thick (Sugiura et al., 2008).

Liquid crystal on silicon (LCoS) or sometimes called as a spatial light modulator is a miniaturized reflective active-matrix liquid-crystal display which reflects required part of receiving light to a projection screen and create the picture. Generally they use laser modules as a light source (Janssens & Malfait, 2009).

Backlight outputs of commercially available LCDs are randomly polarized so two polarizers are used, making the efficiency very low. Since laser light is already polarized the rear polarizer can be removed and realized with better light usage efficiency and better color gamut (Kurashima et al., 2011).

Instead of using separate red green and blue laser it is possible to use red laser as a companion to a cyan LED. This approach also increase the color gamut of LCD TVs (Nagase, Niikura, Shinozaki, Nagayasu, & Kondo, 2013; Nakano, Niikura, Murase, Nagase, Sakamoto, et al., 2013).

Light guide plate (LGP) is an important element of LCD which is used in the backlight structure. There could be several illumination sources inside the backlight structure and LGP provides uniform distributions of the emitted light with maximum efficiency. Separate laser modules are used to illuminate LGP modules as a backlight source (Feng, 2014; Yankov, Goltsov, Ivonin, Kravtsov, & Velikov, 2013).

Popular light sources of projection, projector and LCD based systems are CCFL, LED and LASER, their comparison chart is given at Table 5.1.

Table 5.1 Comparison of light sources

| **Item** | **CCFL** | **LED** | **LASER** |
|---|---|---|---|
| Price | Moderate cost | Low cost | High cost |
| Color Gamut | Small area | Big area | Very big area |
| Dirve Circuit Complexity | High | Moderate | Moderate |
| Transimission Distance | Low range | Medium range | Long range |
| Life Time | Short | Long | Long |
| Light Output Bandwidth | Wide | Moderate | Narrow |
| Dimming Feature | Low Dimming Range | High Dimming Range | High Dimming Range |
| Quality Drop During Lifetime | Yes | Yes | No |
| Speckle Noise | No | No | Yes |

## 5.1 Advantages of Laser TV

There are several advantages of Laser TV which comes from laser's own properties.

Laser based systems offer more vivid colors which are unachievable with traditional screens. This is the biggest advantage of laser based display and is shown in Figure 5.2. With the laser based systems it is possible to reach two times of the nearest technology (Chellappan et al., 2010; Kojima & Miyata, 2009; Someya et al., 2006).

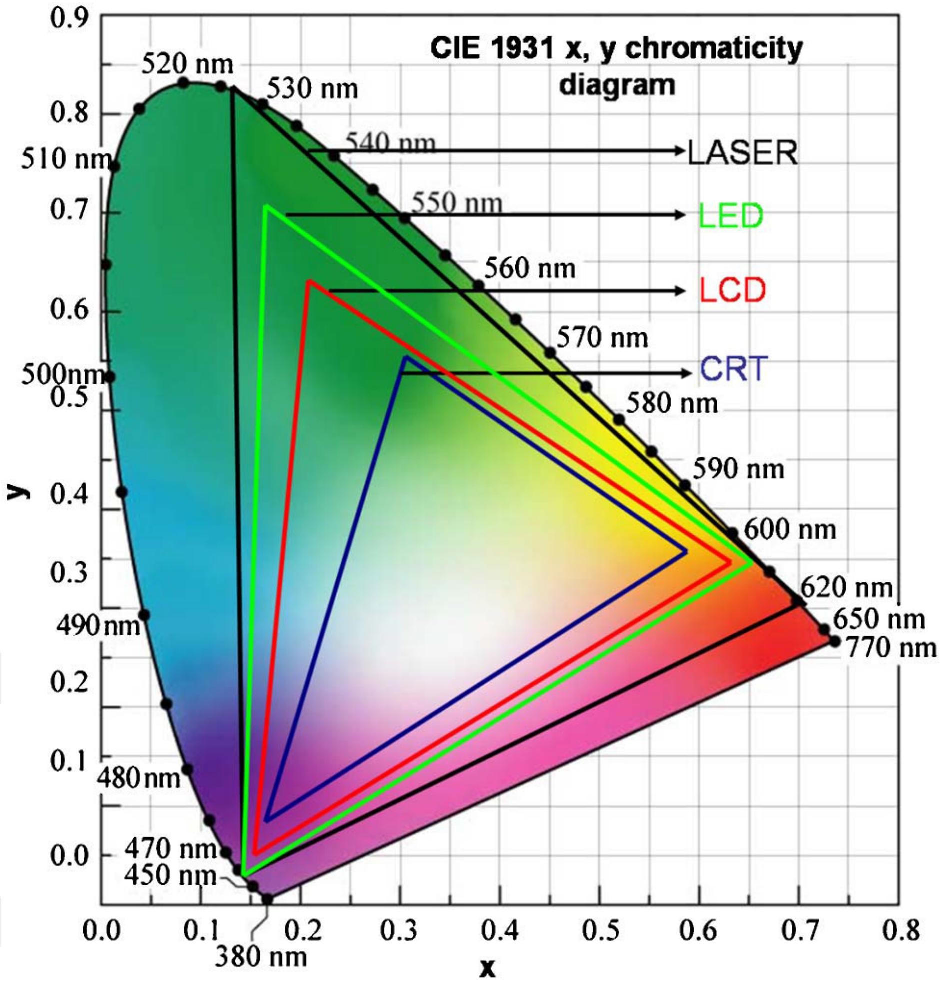


Figure 5.2 1931 CIE xyY chromaticity diagram. The color gamut possible with CRT, LCD, LED, and laser-based displays is shown (Chellappan et al., 2010).

In order to increase the color gamut of the laser based systems without losing the brightness level four or more primary colors are used instead of three colors. So you can cover more area on the color gamut instead of triangular shape with quadrangular or pentagonal shape (Roddy, Zolla, & Markis, 2003; Roth, David, Chorin, Eliav, & David, 2003).

Due to small divergence angle of laser with respect to other light sources it can be used far smaller optical system and resulting compact solutions example is given in Figure 5.3 with the comparison of projection lenses (Kojima & Miyata, 2009).


Figure 5.3 Projection lens

As the laser high luminous efficiency power consumption of the laser TV is very low when compared with the other technologies at the same screen size (Someya et al., 2006).

Light output of laser can be modulated easily so they can be used high bitrate telecommunication applications (Lichtenstein et al., 2004). This fast turn on and off characteristic of laser light brings more clear picture without motion blur problems(Sugiura et al., 2008)

In a LCD display system backlight source can be cathode fluorescent lamp (CCFL), LED or any other visible light source. The unpolarized light generated by the backlight is passed through a polarizer, only permits light polarized in first polarization direction to pass. Thus, useful light may be lost in the polarizer. Then polarized light send to front polarizer with liquid crystal. The liquid crystal structure may change to polarization direction, so light pass through from front polarizer, or it doesn’t change the polarization and front polarizer block the light. Passing light components send to the optical bandpass filter then filters out wavelengths other than a desired wavelength band and, resulting in light output by the pixel with a desired wavelength.

As laser is already polarized in one direction, back polarizer can be removed, even it is not removed polarizer allows to pass more light if laser polarization direction is positioned in a suitable direction. Moreover as the laser light has very narrow bandwidth optical filter allows more light to pass through (Hutchins, 2009). So if laser light used as a backlight source, we may decrease system cost with removing one polarizer and increase optical efficiency with laser light predefined wavelength and polarization.

Moreover, it is likewise conceivable to show 3 Dimensional stereoscopic pictures utilizing lasers (Koba, 2004). Every one of these properties make laser a perfect light source for display and projection applications (Chellappan et al., 2010; Fujieda et al., 2009; Zheng et al., 2008).

As an illumination source of projector, projection and an LCD backlight CCFL was the common backlight source some years ago. But because CCFL devices have numerous drawbacks, the CCFL technology lost its popularity. As CCFL devices may contain Mercury it has been banned for TV applications. CCFL devices have poor efficiency at low ambient temperatures, to compensate this extra circuit is needed such as preheat circuit and current boost circuit. Also operating voltage may reach several kV level and operating frequency could be around several kHz which requires high voltage control systems and special safety actions also need some special Electromagnetic Compatibility (EMC) modifications (Akpinar & Yilmazlar, 2007; Weindorf & Zysnarski, 2005). Dimming of CCFL lamps requires complex frequency and voltage control circuit (Hwu & Chen, 2010). Moreover due to this complex structure and gas discharge behavior their life time is shorter than other competitive technologies (Harbers & Hoelen, 2001).

Due to LEDs high dimmable performance and better color gamut with respect to old CCFL and other gas discharge technologies it becomes common backlight source for active matrix liquid crystal displays and other display applications. LED technology provides better color gamut, simpler electronic circuit to drive LEDs so offers better efficiency up to %95 (Lee, Kwon, Kim, Choi, & Byun, 2006). But may be biggest disadvantage of LED based systems are quality drop of screen with time (Narendran & Gu, 2005)

Maybe in the near future, with the development of laser production technology, they will replace existing solutions. With the latest development, commercial lasers can reach above 50.000 hours life time which is much better than other light sources. Moreover maybe one of the biggest advantage unlike other technologies, laser output power does not drop during its lifetime (Schulze & Masters, 2006) which brings first day brightness and contrast level experience to the end user. Also the laser keeps its other quality factors such as color saturation during its lifespan which is directly related to wavelength (Hollemann et al., 2000).

## 5.2 Disadvantages of Laser TV

Beside the advantage of laser TV which are mentioned in the previous chapter there are some disadvantages. Currently lasers are not produced in large numbers like LEDs so production cost is higher than other possible light sources.

The most important risk of laser use is the possibility for eye and skin hazards. If laser output has sufficient optical power with the high level of exposure time can cause corneal and retinal burns or cataracts. Skin burns or skin carcinogenesis are triggered with the exposure of ultraviolet wavelengths (Niemz, 2013). Even though the laser based systems use visible laser source between 400 to 700nm there might be spurious emission in the range of infrared or ultraviolet due to nonlinear effects such as second harmonic generation or sum and difference frequency generation to generate primary colors. All these unwanted radiations should be filtered out by appropriate filters. American National Standards Institute (ANSI) classifies and control measures of lasers based on wavelength and optical power and hazard potential. International Commission on Nonionizing Radiation Protection (ICNIRP), and the International Electrotechnical Commission (IEC) provides safe using guide of laser. For the evaluation of hazard potential of laser based systems, the maximum permissible exposure (MPE) is defined for eye safety. (Matthes et al., 2000; Schulmeister, Stuck, Lund, & Sliney, 2011; Sliney et al., 2005).

The third and maybe the biggest weakness of laser based systems are the interference phenomena that creates speckle noise which reduces the picture quality. Because all imaging systems that employ lasers suffer from speckle noise, it is essential to combat with this undesired effect (Brennesholtz, 2008; Chen et al., 2012; Liren, 2011; Rafiee et al., 2004). Until date a lot of techniques have been applied successfully to solve the speckle noise problem (HAO et al., 2006; Li et al., 2008; Xu et al., 2014). In the next chapters, we will introduce speckle phenomena and propose efficient speckle reduction method.

# CHAPTER SIX
# SPECKLE

Interference phenomena is easily obtained when laser light illuminates a surface or propagates in a nonhomogeneous medium and causes speckle. As shown in the left hand side picture of Figure 6.1, laser light reflects from the surface and goes to observation point due to surface roughness, different path lengths and random phase delays occur which causes interference effect. At the imaging system, as shown on the right hand side of Figure 6.1, surface roughness of the imaging sensor and different traveling time inside the optical system creates random phase delays so interference effect can be seen in imaging systems.

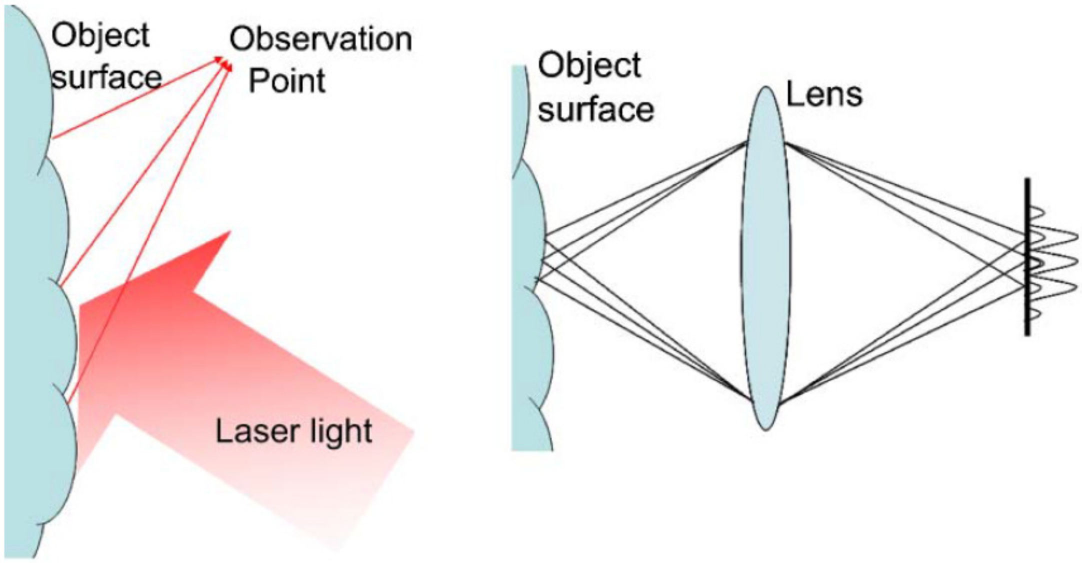


Figure 6.1 Speckle formation in free space and optical system (Chellappan et al., 2010)

Speckle may contain many useful information and it can be used as input signal of medical imaging or measurement systems (Fujii, Nohira, Shintomi, Asakura, & Ohura, 1985; Pižurica, Philips, Lemahieu, & Acheroy, 2003). But speckle causes noise and debases picture quality in display systems. This is shown in Figure 6.2 (Florence, 1994; George, Christensen, Bennett, & Guenther, 1976).

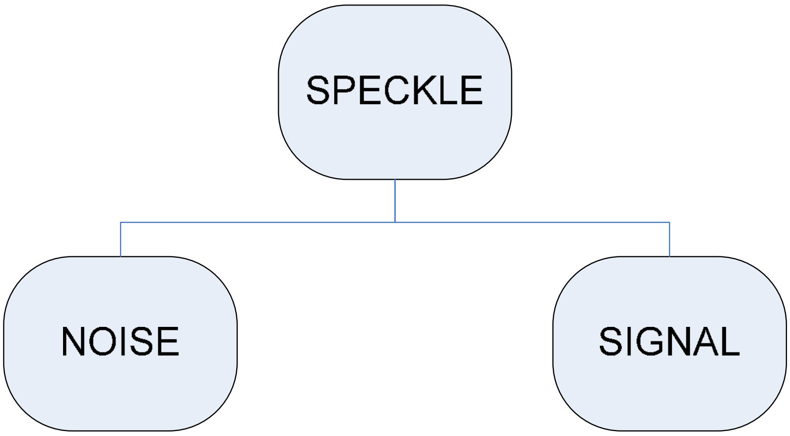


Figure 6.2 Speckle noise or signal

Typical speckle pattern can be seen in Figure 6.3.

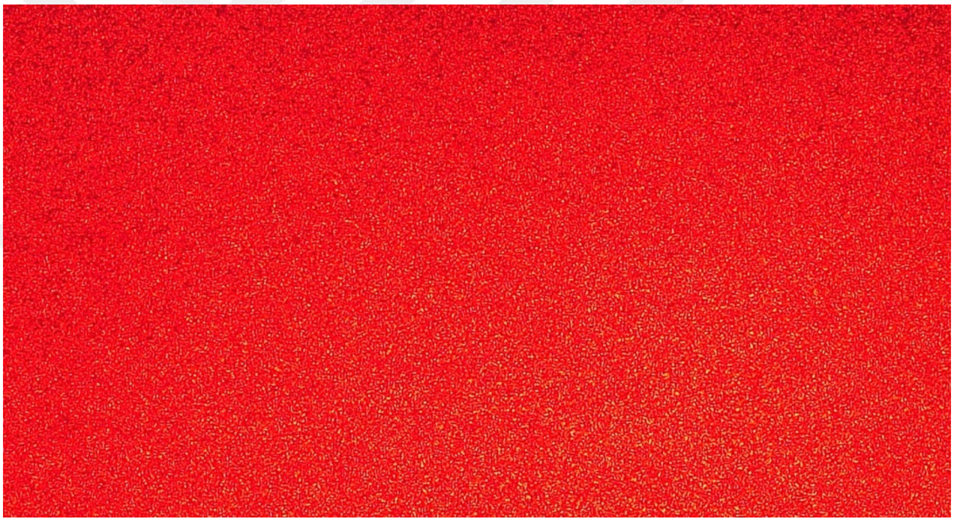

Figure 6.3 Typical speckle pattern

## 6.1 First Order Statistical Properties of Speckle

Speckle can be mathematically expressed by the speckle contrast ratio ($C$) with the Equation (6.1) (Goodman, 2007);

$$C = \frac{\sigma}{\overline{I}} \tag{6.1}$$

$\sigma$ : standart devitaion of picture

$\bar{I}$ :mean intensity of picture

Typically for the still picture, speckle disturbance limit is defined 4% (Wang, Tschudi, Halldorsson, & Petursson, 1998). It was very recently found that speckle disturbance limit for sequential images, such as those in movies, turns out to be substantially larger than that for still images. For a red color projector for example the speckle noise limit can be as high as 10% (Verschaffelt et al., 2015);

For the paraxial waves, we can represent intensity in general case,

$$I = |A_x|^2 + |A_y|^2 \text{ for an unpolarized wave} \tag{6.2}$$

Where the quantity $A$ corresponds to the complex amplitude of the field along the direction of polarization. As a special case of polarized wave,

$$I = |A|^2 \text{ for the polarized wave} \tag{6.3}$$

Assume that $u$ and $v$ are random variables and related to each other with $v = f(u)$. The probability density function of $v$ can be found from the probability density function of $u$. If we know the probability density function of $A$ we can find the corresponding probability density function of $I$

$$p_V(\mathrm{u}) = p_U(\mathrm{f}^{-1}(\mathrm{v}))\left|\frac{du}{dv}\right| \tag{6.4}$$

$$I = f(\mathrm{A}) = \mathrm{A}^2 \tag{6.5}$$

$$p_I(I) = p_A(\sqrt{I})\left|\frac{dA}{dI}\right| = \frac{1}{2\sqrt{I}} p_A(\sqrt{I}) \tag{6.6}$$

Large number of random phasors randomly distributed between $-\pi$ and $+\pi$ have Rayleigh distributed probability density function of the amplitude.

$$p_A(\mathrm{A}) = \frac{A}{\sigma^2}\exp(-\frac{A^2}{2\sigma^2}) \tag{6.7}$$

By using Equation (6.6) intensity distribution can be found,

$$p_I(\mathrm{I}) = \frac{\sqrt{I}}{\sigma^2}\exp(-\frac{I}{2\sigma^2})\frac{1}{2\sqrt{I}} = \frac{1}{2\sigma^2}\exp(-\frac{I}{2\sigma^2}) \tag{6.8}$$

With the direct integration moments of the distribution can be found

$$\overline{I^q} = (2\sigma^2)^q q! \tag{6.9}$$

So the mean intensity ($\bar{I}$) is $2\sigma^2$ and the probability density function of intensity can be written as

$$p_I(I) = (1/\bar{\mathrm{I}})\exp(-\mathrm{I}/\bar{\mathrm{I}}) \tag{6.10}$$

### 6.2 Sum of Uncorrelated Speckle Intensities

The mathematical results of speckle pattern summation creates speckle reduction.

There are many ways to create independent speckle patterns such as different wavelength of lights, angle and polarization illumination. In this section, we first analyze two independent speckle patterns and then we will generalize the results with N independent intensities.

### *6.2.1 Sum of Two Independent Speckle Intensities*

When a detector integrates two independent speckle patterns resulting response is proportional to sum of them. So total intensity $I_s$ ;

$$I_s = I_1 + I_2 \tag{6.11}$$

Assume that $I_1$ and $I_2$ are fully developed speckle patterns so their probability density functions can be given follows;

$$p_1(\mathrm{I}_1) = \frac{1}{\overline{I_1}} \exp(-I_1/\overline{I_1}) \tag{6.12}$$

$$p_2(\mathrm{I}_2) = \frac{1}{\overline{I_2}} \exp(-I_2/\overline{I_2}) \tag{6.13}$$

Due to convolution and probability theorem characteristic function of sum is the product of the components. $M_s$ , $M_1$ and $M_2$ are represent characteristic function of $I_s$, $I_1$ and $I_2$ respectively.

$$M_s = M_1 M_2 \tag{6.14}$$

$$M_1 = \frac{1}{1 - jw\overline{I_1}} \tag{6.15}$$

$$M_2 = \frac{1}{1 - jw\overline{I_2}} \tag{6.16}$$

So $M_s$ ;

$$M_s = \frac{1}{1 - jw\overline{I_1}} \frac{1}{1 - jw\overline{I_2}} \tag{6.17}$$

And inverse fourier transform

$$p_s(\mathrm{I}_s) = \frac{1}{\overline{I_1} - \overline{I_2}}[\exp(-\frac{I_s}{\overline{I_1}}) - \exp(-\frac{I_s}{\overline{I_2}})] \text{ if } \overline{I_1} \rangle \overline{I_2} \tag{6.18}$$

$$p_s(\mathrm{I}_s) = \frac{I_s}{\overline{I}^2} \exp(-\frac{I_s}{\overline{I}}) \text{ if } I_1 = I_2 \tag{6.19}$$

As we reach speckle information from first and second moment;

$$\overline{I_s} = \overline{I_1 + I_2} = \overline{I_1} + \overline{I_2} \tag{6.20}$$

$$\overline{I_s^{\,2}} = \overline{(I_1 + I_2)^2} = \overline{I_1^{\,2}} + \overline{I_2^{\,2}} + 2\overline{I_1 I_2} \tag{6.21}$$

Using the independence and exponential statistics of $I_1$ and $I_2$ ;

$$\sigma_s^{\,2} = \overline{I_s^{\,2}} - \overline{I_s}^2 = \overline{I_1}^2 + \overline{I_2}^2 \tag{6.22}$$

Assume that $r = \overline{I_2} / \overline{I_1}$ so speckle contrast $C$ is;

$$C = \frac{\sigma_s}{I_s} = \frac{\sqrt{\overline{I_1}^2 + \overline{I_2}^2}}{\overline{I_1} + \overline{I_2}} = \frac{\sqrt{1 + r^2}}{1 + r} \tag{6.23}$$

By using Equation (6.23) the plot of intensity ratio versus speckle contrast ratio is given in Figure 6.4. The minumum contrast ratio of 0.71 happens if the two intensity levels are equal to each other.

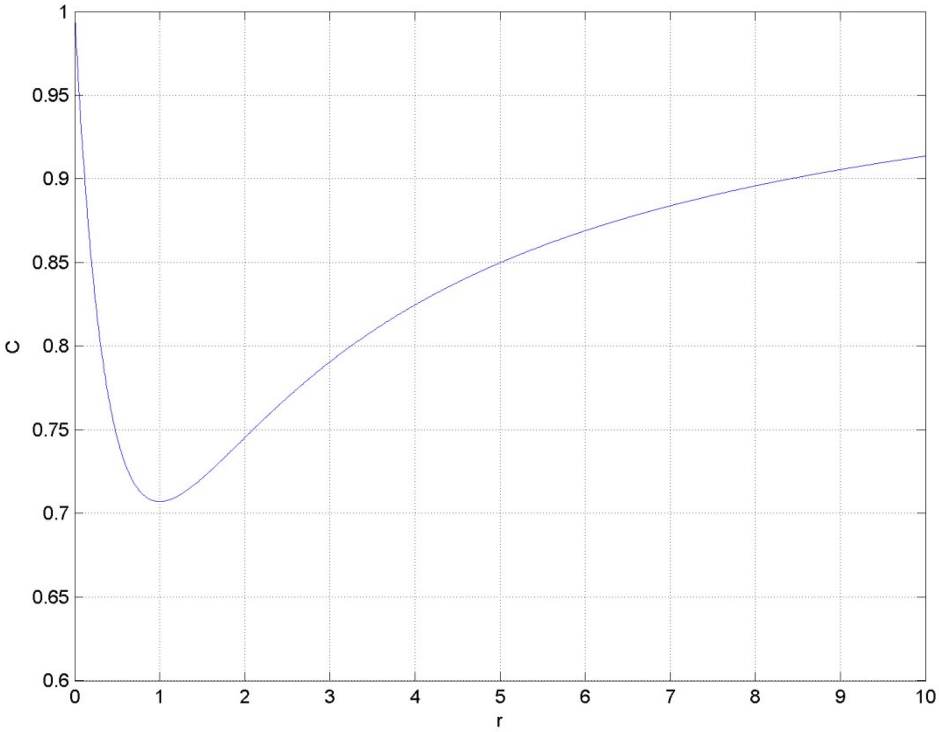


Figure 6.4 Intensity ratio vs speckle contrast ratio

### *6.2.2 Sum of N Independent Speckle Intensities*

By using the previous section results we will generalize them for N independent speckle patterns. The total intensity is;

$$I_s = \sum_{n=1}^{N} I_n \tag{6.24}$$

Again using the statistical independence and convolution theorem;

$$M_s(\mathrm{w}) = \prod_{n=1}^{N} M_n(\mathrm{w}) = \prod_{n=1}^{N} \frac{1}{1 - jw\overline{I_n}} \tag{6.25}$$

Fourier inversion of Equation (6.25) gives the probability density function of the total intensity. The form of this function is related to the average intensity of each pattern.

The mean value of total intensity;

$$\overline{I_s} = \sum_{n=1}^{N} \overline{I_n} \tag{6.26}$$

The second moment is given by;

$$\overline{I_s^2} = \sum_{n=1}^{N} \sum_{m=1}^{N} \overline{I_n I_m} = \sum_{n=1}^{N} \overline{I_n^2} + \sum_{n=1}^{N} \sum_{m=1,\mathrm{m} \neq \mathrm{n}}^{N} \overline{I_n}.\overline{I_m} \tag{6.27}$$

Due to the properties of negative exponential probability distributions $\overline{I_n^2} = 2\overline{I_n}^2$ then the expression becomes;

$$\overline{I_s^2} = 2\sum_{n=1}^{N} \overline{I_n}^2 + \sum_{n=1}^{N} \sum_{m=1,\mathrm{m} \neq \mathrm{n}}^{N} \overline{I_n}.\overline{I_m} = \sum_{n=1}^{N} \overline{I_n}^2 + \overline{I_s}^2 \tag{6.28}$$

So the variance of total intensity is;

$$\sigma_s^2 = \sum_{n=1}^{N} \overline{I_n}^2 \tag{6.29}$$

And the speckle contrast;

$$C = \frac{\sigma_s}{\overline{I_s}} = \frac{\sqrt{\sum_{n=1}^{N} \overline{I_n}^2}}{\sum_{n=1}^{N} \overline{I_n}} \tag{6.30}$$

As a special case, if all the intensities are equal to each other;

$$C = \frac{1}{\sqrt{N}} \tag{6.31}$$

As while the number of independent pattern increase the speckle contrast decreases.

## 6.3 Speckle Reduction Methods

Until date a variety of different methods have been suggested in order to reduce speckle noise for display systems.

All speckle reduction methods rely on diversification of angle, polarization or wavelength of the laser light (Trisnadi, 2002). Combination of these methods can be used to obtain better speckle reduction.

### *6.3.1 Angular Diversification*

Angular diversification based speckle reduction was realized for example via two fast vibrating piezoelectric benders that modulated the angle of laser beams and create angle diversity so reducing speckle by temporal average in the time integration (Ouyang, Akram, Wang, Tong, & Chen, 2013). Another application is fast two dimensional micromirror used to steer laser beam utilize spatial and angular diversity to create speckle reduction in laser illumination both imaging and free space geometry with the integration time of the detector (Akram, Tong, Ouyang, Chen, & Kartashov, 2010). Significant speckle reduction achieved by using a vibrating multimode optical fiber bundle. Two independent lasers illuminated the optical fiber bundle with normal and oblique incidence, diffusers used at the input and output of the fiber bundle so spatial as well as angular diversity created and the resulted speckle reduction is very close to white light illumination (Mehta, Naik, Singh, & Takeda, 2012) In another demonstration researchers made use of MEMS based systems to create angular diversity (Peled, Zenou, Greenberg, & Kotler, 2009). A research group recently improved an optical coherence tomography imaging system by reducing the speckle noise via angle diversification generated by utilizing a scanning protocol with fast beam deflection (Szkulmowski et al., 2012). Movement of the screen, the diffuser and the aperture have all been used to suppress speckle noise (Curtis, Coleman, & Sharp, 2015; Lowenthal & Joyeux, 1971; McKechnie, 1975; Rawson, Nafarrate, Norton, & Goodman, 1976; Tingmei, Ying, Tianshi, & others, 2008). A powerful white light is generated by using a yellow-emitting phosphor excited by the blue laser diode (Ryu & Kim, 2010) this phosphor plate vibrated to decrease speckle noise (Tu, Lin, & Lee, 2015). Dynamic deformable mirror is also used to create angular diversity (Svensen, Chen, Akram, & others, 2016).

### *6.3.2 Polarization Diversification*

Polarization diversity has also been used effectively by different groups in order to reduce speckle noise. Any polarized beam reflected from rough surface or while transmitting from trough nonhomogeneous medium depolarizing occurs. Resulting speckle pattern will be composed from two orthogonal polarizations so the resulting reduction factor becomes $\sqrt{2}$, if two independent sources are used total reduction factor becomes 2 as half of the reduction comes from polarization other half comes from independent source. A research group for example improved their OCT(optical coherence tomography) instrument by reducing speckle noise via polarization diversity (Storen, Royset, Giskeodegard, Pedersen, & Lindmo, 2004). Moreover speckle reduction was suggested for an OCT system (Tingmei et al., 2008) and implemented using a vibrating light pipe (Mingjie, Kanglong, & Zhaokui, 2013).

### *6.3.3 Wavelength Diversification*

Wavelength diversity can also be used to reduce speckle noise. Kuksenkov et al. demonstrated a laser source that simultaneously emitted at three separate wavelengths with 0.5 nm separation and nearly equal intensity. This novel laser source is expected to suppress speckle noise by a factor of $\sqrt{3}$ (Kuksenkov, Roussev, Li, Wood, & Lynn, 2011). Another technique achieved wavelength diversification based speckle reduction by creating a shift in the lasing wavelength of a VCSEL by driving it to work in the spatially incoherent emission regime (Craggs, Verschaffelt, Mandre, Thienpont, & Fischer, 2009). Speckle contrast reduction based on widening of the laser emission spectrum was also demonstrated for edge emitting broad-area laser diodes (Riechert, 2009). Similarly another method is to use a broad wavelength light source in OCT to prevent having speckle noise in the images (Sabuncu & Akdogan, 2015; Sabuncu & Akdogan, 2014; Sabuncu & Özdemir, 2015). By using multiple laser diodes with different type and selecting appropriate wavelength, broad illumination and better speckle contrast reduction obtained (Svensen et al., 2016). Broad-area edge-emitting semiconductor laser diode in continuous wave emission regime are investigated experimentally (Xu, Gao, Shi, Liu, & Chen, 2016).

### *6.3.4 Combination of Reduction Factor*

Angle, wavelength and polarization scrambling based methods can be used in combination such that the resulting speckle reduction will be more than when each method is used separately (Goodman, 2007). To create angle, wavelength and polarization scrambling there could be different methods. If we define reduction factor of these methods as $R_1$, $R_2$, $R_3 \ldots R_n$ the resulting reduction factor $R$ can be expressed by using Equation (6.32).

$$R = R_1 \cdot R_2 \cdot R_3 \cdots R_n \tag{6.32}$$

The final resulting speckle ratio $C_f$ and the initial speckle ratio is $C_i$ are related by (Goodman, 2007; Tran, Chen, Svensen, Akram, & others, 2014; Yilmazlar & Sabuncu, 2015a, 2015b)

$$R = \frac{C_i}{C_f} \tag{6.33}$$

### *6.3.5 Speckle Reduction Factor with Mode Hopping*

Our method relies on wavelength diversification of the laser source. We achieve wavelength diversification by deliberately causing mode hopping in the laser diode which will be explained with more detail at next section. Mode hopping causes sudden jumps in the emission wavelength, as the laser shifts to a new longitudinal mode. It is therefore possible to excite independent modes by changing the injection current in the laser diode. This is the basis of our speckle reduction scheme based on modulating the drive current of the laser diode. The speckle reduction factor will depend on the number of the different excited modes and their relative intensities. The theoretical expression for the reduction factor will be given by (Goodman, 1976, 2007)

$$R = \frac{\sum_{n=1}^{N} \overline{I_n}}{\sqrt{\sum_{n=1}^{N} \overline{I_n}^2}} \tag{6.34}$$

In this formula $I_n$ denotes the intensity of the $n_{th}$ mode. From this formula we conclude that, to have a higher speckle reduction factor we need to have as many modes as possible. And the closer the intensities of the independent modes caused by mode hopping the higher the resulting speckle reduction.

## CHAPTER SEVEN
## EXPERIMENTAL SETUP

### 7.1 Laser Drive for Experimental Realization

Our laser drive block diagram is shown in Figure 7.1. The designed circuit includes required protection blocks as mentioned in the previous section. For power transient protection current limiter is used.

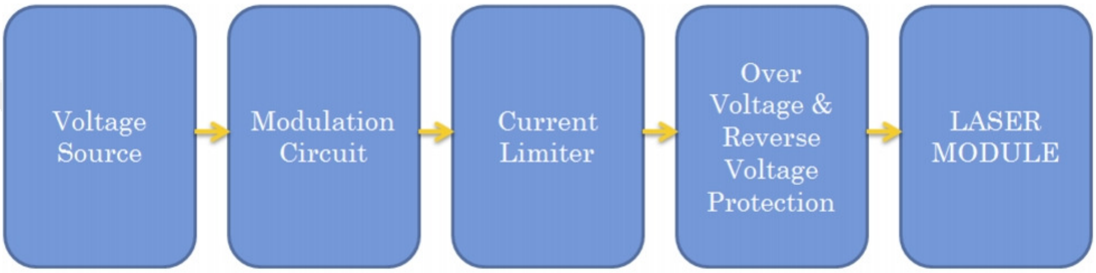


Figure 7.1 Block diagram

Required schematic due to the block diagram given above is shown in Figure 7.2.

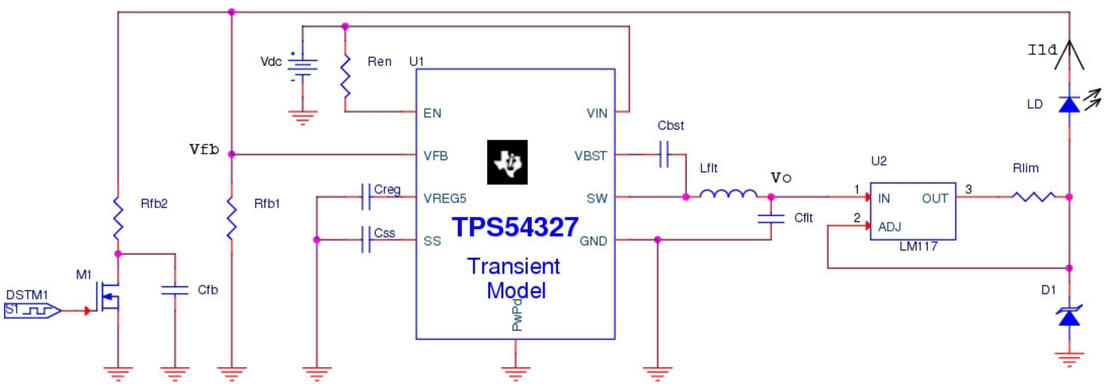


Figure 7.2 Laser drive circuit

The first part is the voltage source which provides dc supply voltage $V_{dc}$. For the modulation circuit $U_1$ and its peripheral components $R_{en}$, $C_{reg}$, $C_{ss}$, $C_{bst}$, $L_{flt}$ and $C_{flt}$ are used. Output of the modulation circuit is denoted by $V_o$. $R_{fb1}$, $R_{fb2}$, $C_{fb}$,

$M_1$ and $DSTM1$ are used as part of the modulation circuit and they determine the shape and level of the laser diode current. $U_2$ and $R_{\lim}$ are used to limit the current. $D_1$ protects the circuit from overvoltage and reverse voltages. The final part of the block diagram is the laser module which is denoted by LD in the circuit schematic. The laser diode emits visible light centered around a wavelength of 637 nm.

The output voltage of the regulator $V_o$ is related to the laser diode current $I_{ld}$.

LM117 integrated circuit $U_2$ and the limiting resistor $R_{\lim}(\Omega)$ are used to limit the maximum allowed current of the laser diode. $I_{\lim}(A)$ denotes the limiting current and it is adjusted to the 100 mA level by the Equation (7.1);

$$I_{\lim} = \frac{1.25}{R_{\lim}} \tag{7.1}$$

In this project current control method used, since it enabled the direct modulation of the diode current. The laser current was kept constant at a DC value, modulated with a square wave (switched on-off), or modulated with a triangular wave continuously.

Three modes of operation can be achieved using this circuit as follows:

### *7.1.1 Constant Current Mode*

In order to operate the circuit at constant current mode (drive current at dc value) as shown in Figure 7.3 it is necessary to connect the gate of $M_1$ to ground. In this mode of operation the direct current is given by;

$$I_{ld} = I_{dc} = \frac{V_{fb}}{R_{fb1}} \tag{7.2}$$

$U_1$ step down converter feedback input $V_{fb}$ is kept at 0,765 V so $I_{ld}$ can be tuned easily by changing $R_{fb1}$ .

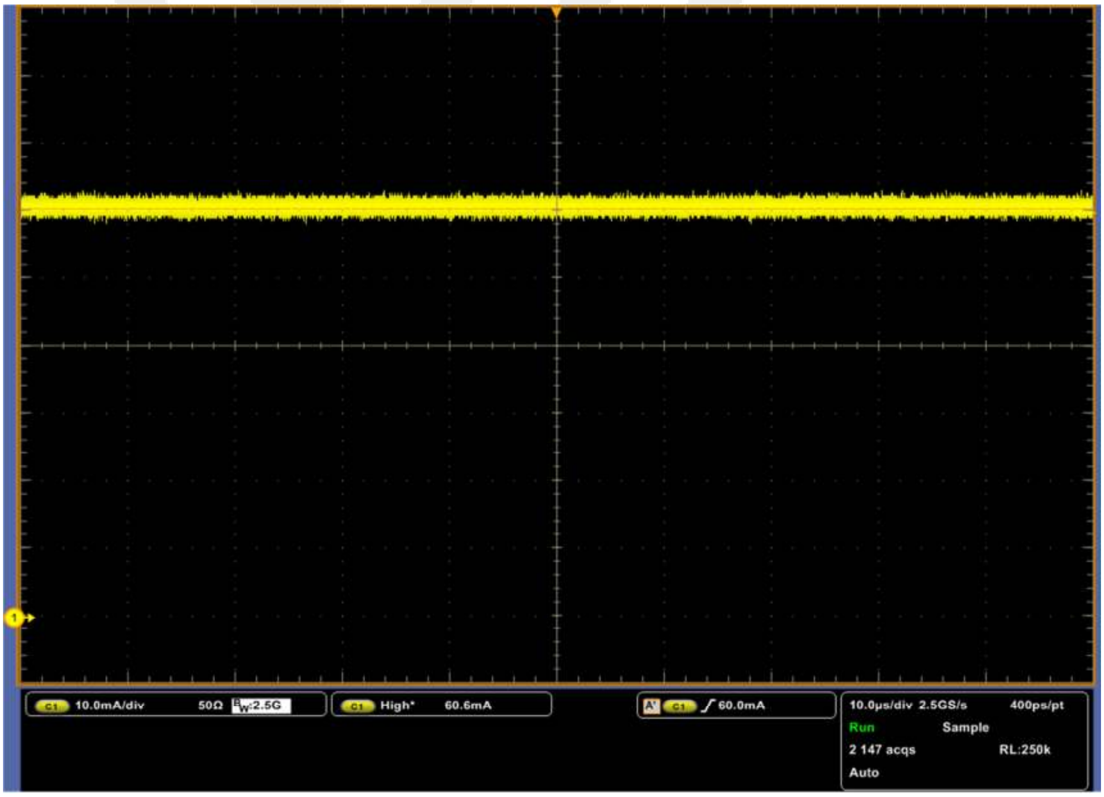


Figure 7.3 Constant current

### *7.1.2 Square Wave Modulation*

If a square wave is applied by the $DSTM1$ to the gate of $M_1$ while $C_{fb}$ is disconnected, then the laser diode current is modulated in a square wave form as shown in Figure 7.4. The maximum value of the current is determined by:

$$I_{high} = \frac{V_{fb}}{R_{fb1} // R_{fb2}} \tag{7.3}$$

And the minimum value of the current is given by

$$I_{low} = \frac{V_{fb}}{R_{fb1}} \tag{7.4}$$

The frequency of the modulated current waveform is equal to the frequency of the square wave applied to the M1 gate.

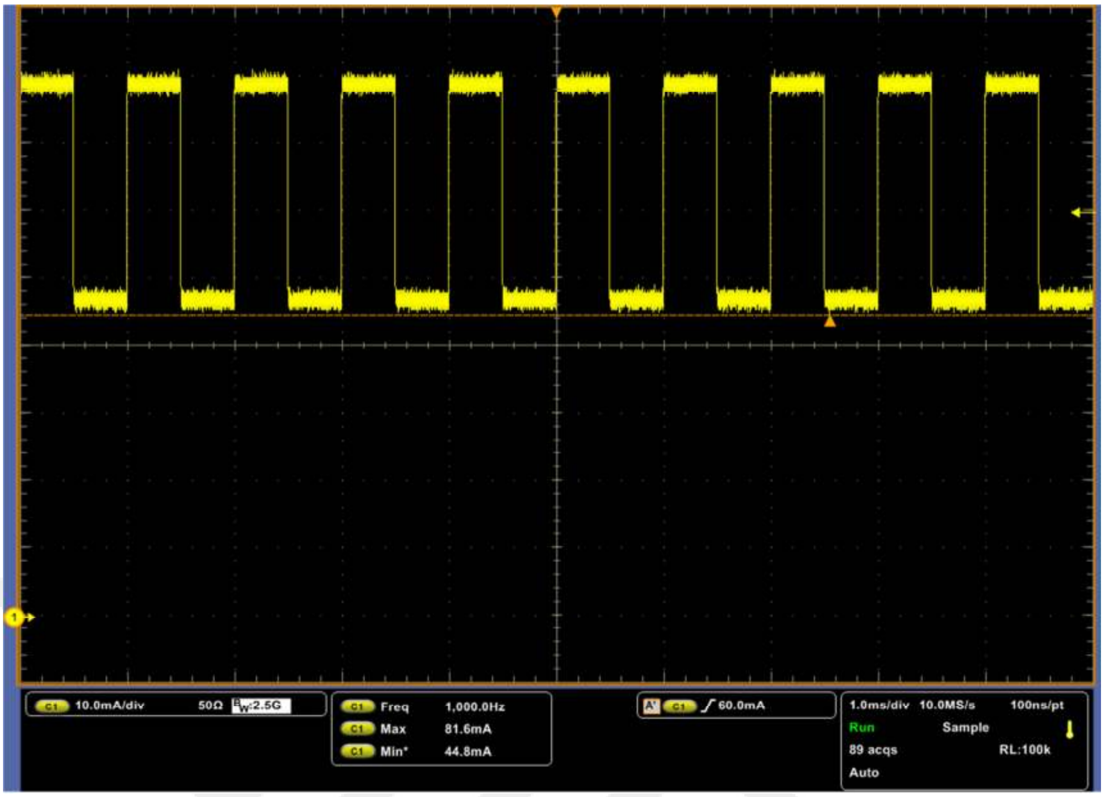


Figure 7.4 Square wave

### *7.1.3 Triangular Wave Modulation*

If a square wave is applied to the gate of M1 with DSTM1, while Cfb is connected then the laser diode current is modulated in the triangular shaped wave form as shown in Figure 7.5. The slope of the wave can be adjusted by Cfb. The maximum and minimum values of the drive current are determined in the same way as with the square modulation

$$I_{high} = \frac{V_{fb}}{R_{fb1} // R_{fb2}} \quad (7.5)$$

And the minimum value of the current is given by

$$I_{low} = \frac{V_{fb}}{R_{fb1}} \quad (7.6)$$


Figure 7.5 Triangular wave

## 7.2 Speckle Measurement Setup

In the experimental setup, seen in Figure 7.6 the laser diode case was mounted on a thermoelectric controller to keep the case temperature constant at 25 °C. Standard white working paper (80 g/m2office paper) was illuminated from 40 cm distance and camera was located 20 cm away from the reflection surface, SONY DSC-H5 camera is used for measurement. The camera integration time was set to 20 ms which is close to the human eyes temporal integration time (Riechert et al., 2008). The focal length of the camera was 6 mm and F-number is F/8 so entrance pupil is $8/6=1.33$ mm.

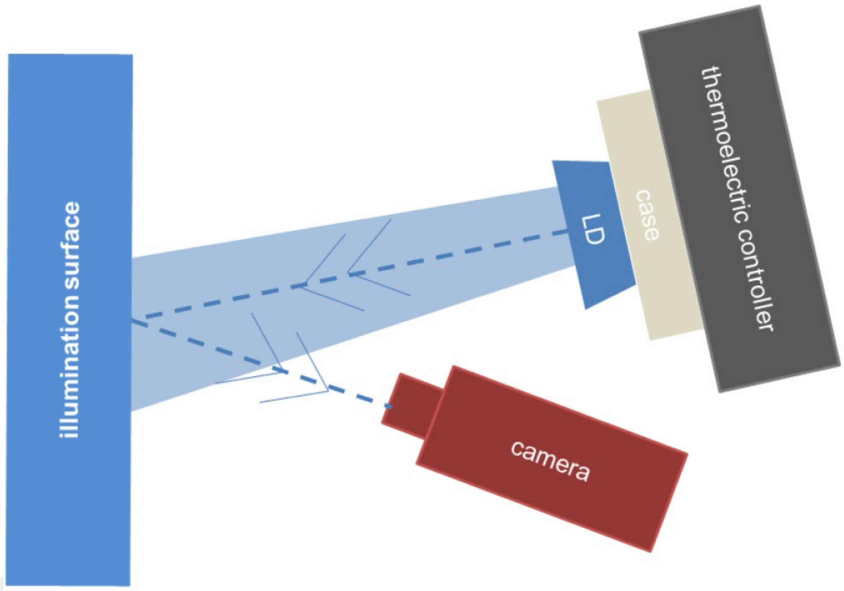


Figure 7.6 Measurement setup

Laser mounted TCLDM9 diode mount to keep case temperature constant at 25 Celsius with TCM1000T TEC Control Module. The TCLDM9 mount by Thorlabs is suitable for temperature-controlled operation of different kind of laser diodes. The TCM1000T thermoelectric cooler control module control current through a TCLDM9 in order to maintain a constant temperature on the device. TCM1000T can provide up to 3 Watts of power. The module is designed to maintain temperature based on feedback provided from a 10KΩ NTC type thermistor sensor. Temperature is set and monitored using a scaled voltage based on the thermistor. As given in spec sheet of TCM1000T and given in Figure 7.7.

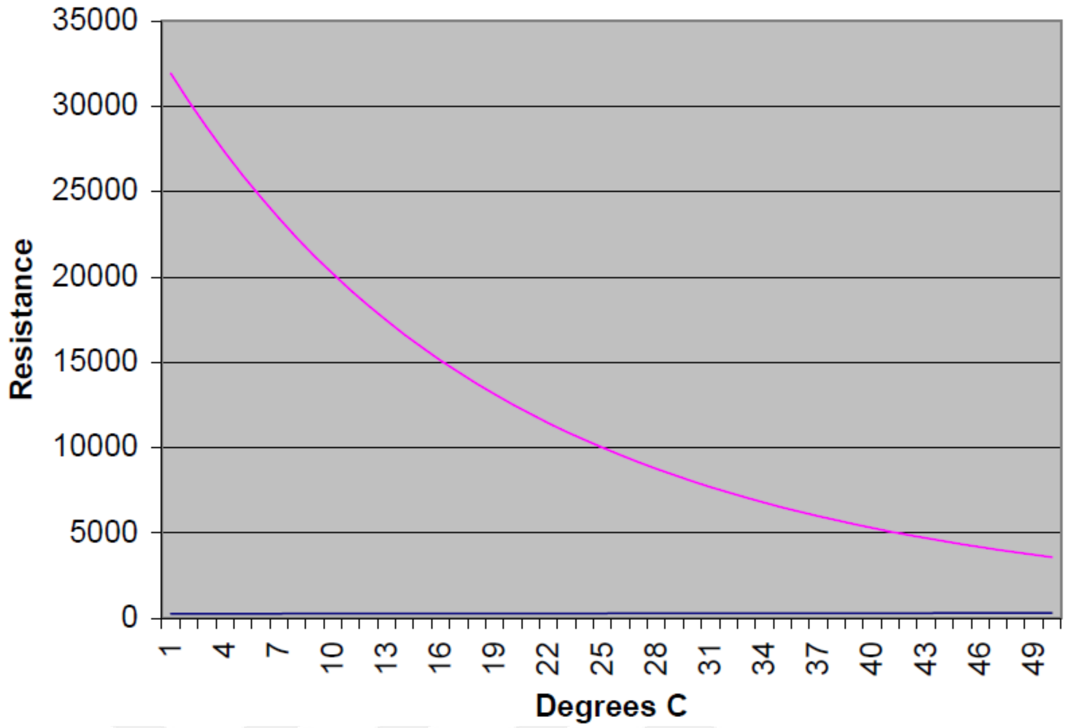


Figure 7.7Thermistor curve

## 7.3 Laser Diode Features

There are three main colors red, green and blue for the imaging system. As red color has higher wavelength speckle is more observable so red laser diode is selected for experimental setup. Laser diode part name is HL6323MG which is a 0.63 micrometer band AlGaInP laser diode with multi-quantum well structure. Some important parameters are given in Table 7.1.

Table 7.1 HL6323MG properties

| Item | Symbol | Min | Typ | Max | Unit |
|---|---|---|---|---|---|
| Optical output power | $P_o$ | - | - | 35 | $mW$ |
| Threshold current | $I_{th}$ | 30 | 45 | 60 | $mA$ |
| Slope efficiency | $\eta s$ | 0.4 | 0.6 | 0.9 | $mW\ /\ mA$ |
| Operating current | $I_{op}$ | - | 95 | 130 | $mA$ |
| Operating voltage | $V_{op}$ | - | 2.3 | 2.8 | $V$ |
| Lasing wavelength | $\lambda p$ | 635 | 639 | 642 | $nm$ |
| Monitor current | $I_s$ | 0.05 | 0.15 | 0.25 | $mA$ |

## 7.4 Spectrometer

The CCS Series Spectrometer is designed by Thorlabs for general laboratory use. It allows averaging, smoothing, peak indexing, as well as saving and recalling data sets.


Figure 7.8 Thorlabs CCS100 spectrometer

The feature list for the CCS100 spectrometer is given as follows,

- Visible spectral range between 350 and 700 nm also NIR or UV Spectral Ranges available
- No Moving Parts
- FWHM Spectral Accuracy is less than 0,5nm
- Auto Compensation for Dark Current Noise
- Amplitude Corrected with Calibration Report
- High-Speed USB Connection which Allows up to 200 Scans per Second
- Trigger Input for External Synchronization (TTL)
- 16-Bit A/D-Converter
- 3648 Pixel CCD Line Array
- Includes Multimode Fiber Patch Cable
- Integration time starts from 10 us up to 60 sec.
- Cosine Correctors Available Separately Allow Free-Space Input

The Statistics function SW of Thorlabs spectrometer displays statistical values of the acquired spectral intensities over the specified wavelength range as given Figure 7.9.

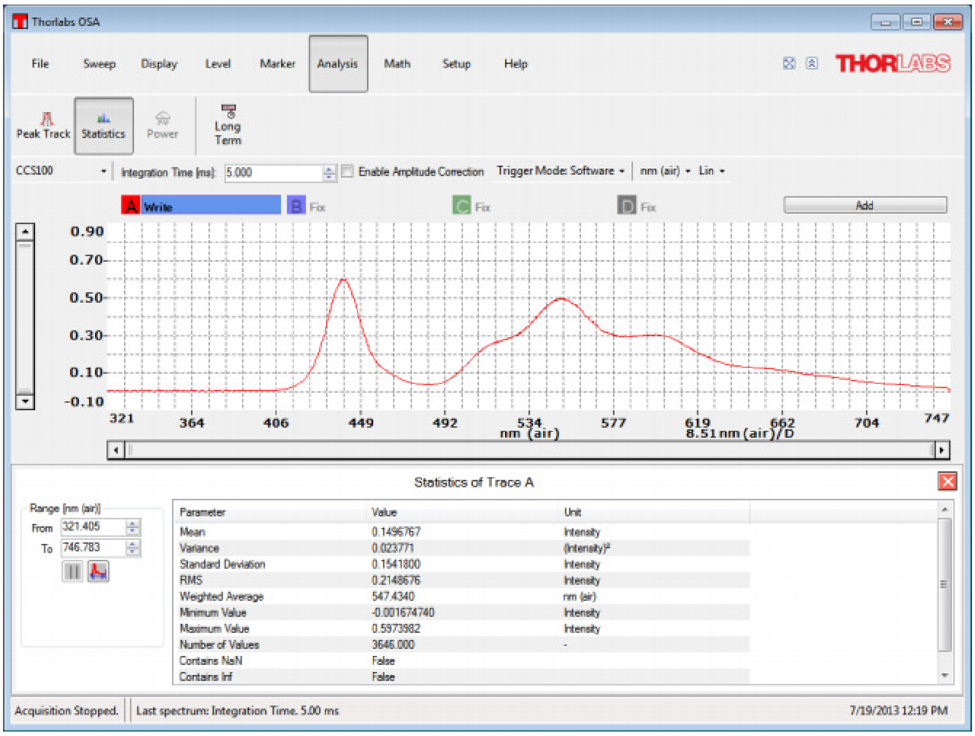


Figure 7.9 Statistic analysis of spectrometer

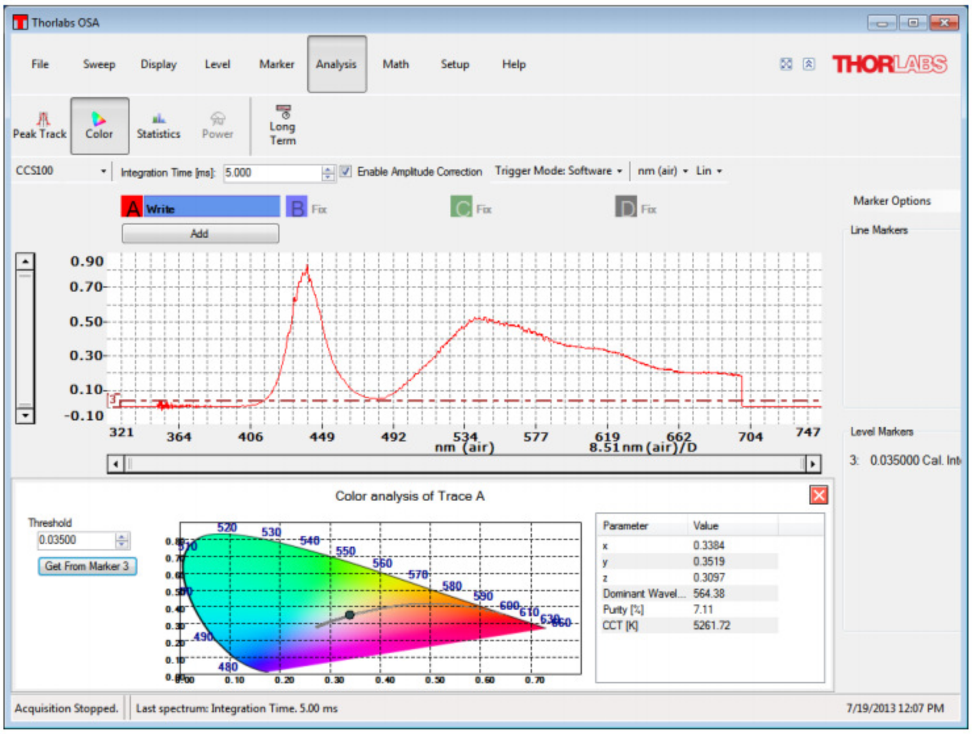


Figure 7.10 Color analysis with spectrometer

The Color Analysis tool performs a color analyzing of the currently active trace as shown in Figure 7.10. The analysis tool calculates the chromaticity coordinates (x, y, and z) and the main wavelength in the spectrum. The Thorlabs software calculates the correlation between the collected spectrum and the three color matching functions $x(\lambda)$, $y(\lambda)$, and $z(\lambda)$ defined from the CIE 1931 standard. These are then normalized to obtain the chromaticity coordinates x, y, and z.

# CHAPTER EIGHT
# RESULTS

Lasing wavelength of laser diode is not fixed due to mode hopping. By using the spectrometer and changing the dc drive current of laser diode slowly we found five different lasing wavelengths as given in Figure 8.1.

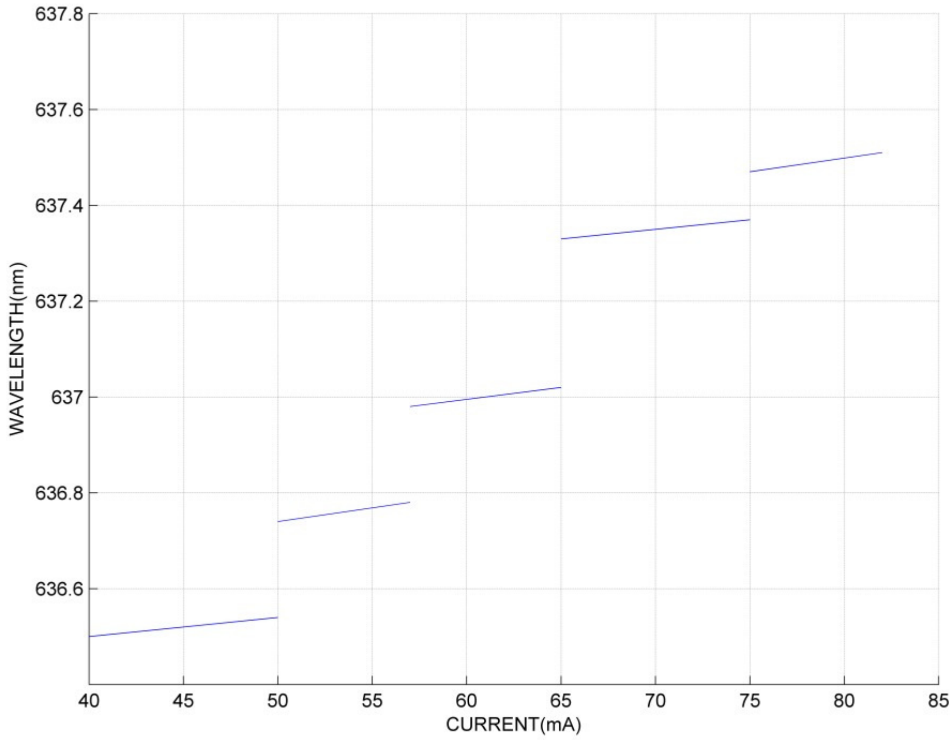


Figure 8.1 Lasing wavelength and current

Each mode behaves as an independent mode and can be used to reduce speckle phenomena. By using the different driving conditions and temporal integration we will examine speckle reduction effect in next sections. We prepare setup which is shown in Figure 7.6 and analyze images taken by camera using Matlab to define speckle contrast ratio and mean value which correspond intensity. Under different driving conditions we obtain different speckle ratio and mean value as given in Table 8.1;

Table 8.1Speckle Measurement Results at Different Driving Conditions

| **Measurement Number** | **Drive Condition** | **Mean Value of Picture** | **Speckle Contrast Ratio** (C) % |
|---|---|---|---|
| **1** | 45 mA dc current | 31.66 | 14.43 |
| **2** | 55 mA dc current | 53.85 | 17.61 |
| **3** | 60 mA dc current | 62.73 | 20.29 |
| **4** | 70 mA dc current | 72.27 | 28.51 |
| **5** | 80 mA dc current | 79.66 | 30.09 |
| **6** | 250hz square current between 80 mA and 45mA | 65.59 | 22.80 |
| **7** | 1kHz square current between 80 mA and 45mA | 65.85 | 22.14 |
| **8** | 1,5kHz triangular current between 80 mA and 45mA | 65.02 | 13.93 |

As can be seen from the table measurement 5 is the most dominant condition so all reduction factor will be calculated with respect to this one. As seen from the measurement number 6 and 7 changing the modulation frequency doesn't affect speckle contrast ratio as camera integration time is bigger than modulation frequency. Due to our experimental results modulation frequency should be at least ten times bigger than camera integration time to see stable results at speckle measurement. By using Equation (6.33);

Square wave reduction factor can be found,

$$R = \frac{C_i}{C_f} = \frac{30.09}{22.80} = 1.32 \tag{8.1}$$

Triangular wave reduction factor can be found,

$$R = \frac{C_i}{C_f} = \frac{30.09}{13.93} = 2.16 \tag{8.2}$$

## 8.1 DC Current

With DC current there is only one mode so there is no speckle reduction for this mode. So;

$$R = 1 \tag{8.3}$$

And

$$C_i = C_f \tag{8.4}$$

## 8.2 Square Wave Modulation

For square wave modulation there are two modes at two different current levels as shown in Figure 8.2 and speckle reduction factors depends on the intensity levels of each mode. To calculate speckle reduction from intensity level we may use mean level of picture or laser diode current.

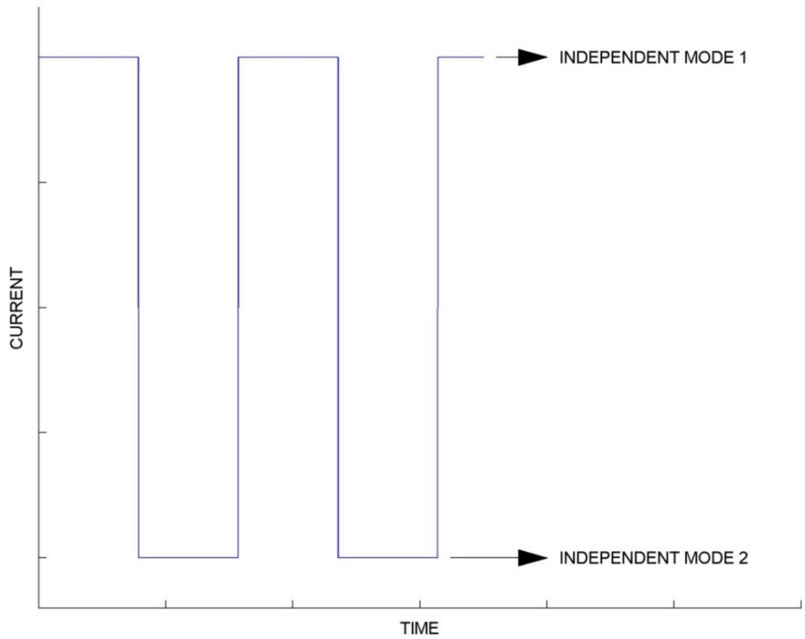


Figure 8.2 Square wave modulation and independent modes

As mentioned in the previous chapter if we use mean values to calculate reduction factor for the measurement 7;

$$R = \frac{31.66 + 79.66}{\sqrt{(31.66)^2 + (79.66)^2}} = 1.3 \tag{8.5}$$

If we use current levels;

$$R = \frac{45 + 80}{\sqrt{(45)^2 + (80)^2}} = 1.36 \tag{8.6}$$

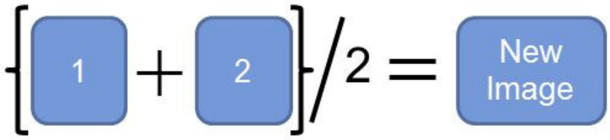

Figure 8.3 Square wave image formation by image processing toolbox

As an alternative approach to show two modes are independent, we used the image processing toolbox to add two images which are taken at measurement 1 and measurement 5 at DC drive current measurements and we create a new image as shown in Figure 8.3 . These images were taken by the camera with 20ms integration time and combined for speckle analysis. The speckle ratio of the new image was found to be 0.22 and reduction factor 1.36. So from this result speckle patterns of measurement 1 and measurement 5 (corresponding to DC drive currents of 45mA, and 80mA) are independent.

### 8.3 Triangular Wave Modulation

When using triangular wave due to mode hopes there could be many modes as shown in Figure 8.4 and depends on laser diode. At HL6323MG independent number mode number is 5 between 45 and 80 mA.

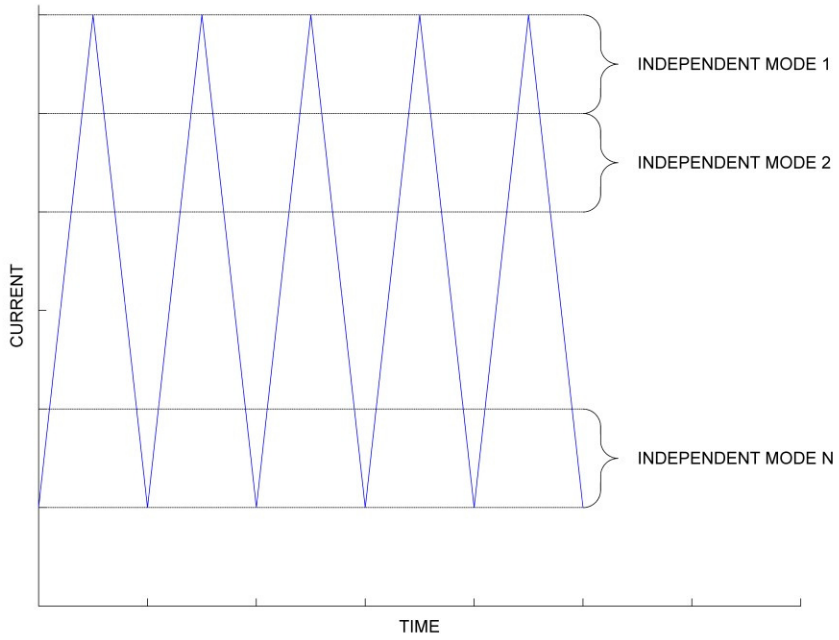


Figure 8.4 Triangular wave modulation and independent modes

As mentioned in the previous chapter if we use mean values to calculate reduction factor;

$$R = \frac{31.66 + 53.85 + 62.73 + 72.19 + 79.66}{\sqrt{(31.66)^2 + (53.85)^2 + (62.73)^2 + (72.19)^2 + (79.66)^2}} = 2.15 \quad (8.7)$$

If we use current levels;

$$R = \frac{45 + 55 + 60 + 70 + 80}{\sqrt{(45)^2 + (55)^2 + (60)^2 + (70)^2 + (80)^2}} = 2.2 \quad (8.8)$$

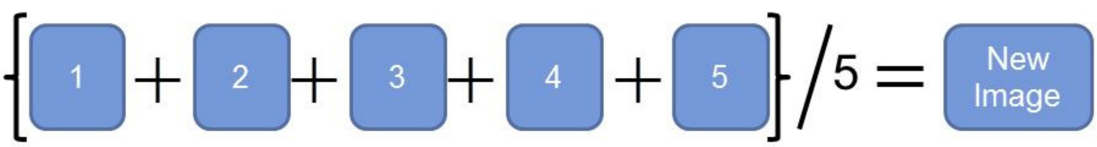


Figure 8.5 Triangular wave image formation by image processing toolbox

Similarly at the square wave section to show five modes are independent, we used the image processing toolbox to add five images which are taken at measurement 1 to measurement 5 at DC drive current measurements and we create a new image as shown in Figure 8.5. These images were taken by the camera with 20ms integration time and combined for speckle analysis. The speckle ratio of the new image was found to be 0.14 and reduction factor 2.14. So from this result speckle patterns of measurement 1-5 (corresponding to DC drive currents of 45mA, 55 mA, 60 mA, 70 mA and 80mA) are independent.

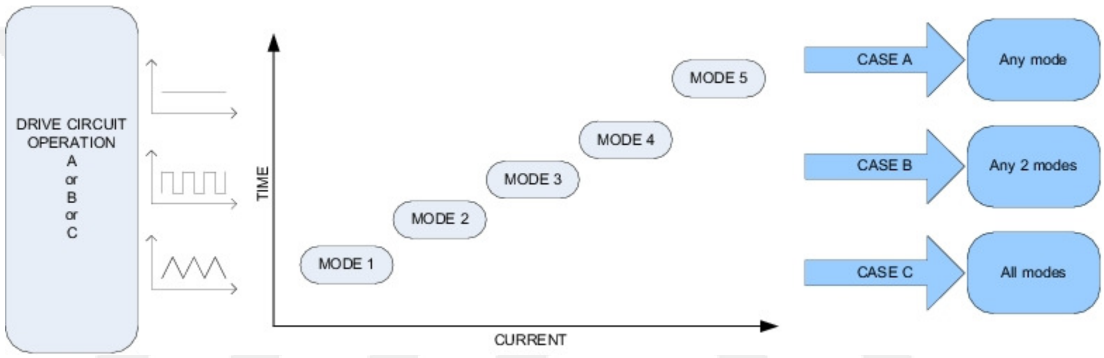


Figure 8.6 Mode selection depending on current modulation

As shown in Figure 8.6 different modulation technique results to use different mode at speckle pattern. At square wave modulation resulting speckle pattern may use any of the two modes with corresponding current. At triangular wave modulation depends on maximum and minimum current there could be many modes in our case mode number is 5. So maximum reduction factor at square wave could be $\sqrt{2} = 1.41$ and triangular wave $\sqrt{5} = 2.24$ but as we don't have equal intensities due to current modulation real reduction factors are lower than these values.

Table 8.2 Results of speckle reduction factors

| | **R measurement** | **R theory from current levels** | **R theory from mean intensity** | **R theory from image processing toolbox** |
|---|---|---|---|---|
| **DC current** | 1 | 1 | 1 | 1 |
| **Square Modulation** | 1.32 | 1.36 | 1.3 | 1.36 |
| **Triangular Modulation** | 2.16 | 2.2 | 2.15 | 2.14 |

# CHAPTER NINE
# CONCLUSIONS

As mentioned in this thesis, due to lasers own properties, laser based display systems have many important advantages. But as shown, lasers create speckle noise due to coherence of laser light. In this thesis a new speckle reduction method and a new drive circuit proposed and demonstrated.

We analyzed some features of display systems and compared current technologies of display types and then introduced laser based display systems. For better understanding of laser based systems the laser operation principle is explained. In chapter four, general laser drive methods are introduced. In chapter 5, we look into the advantages and disadvantages of laser based display systems. The biggest disadvantage of laser based display systems is speckle noise. In chapter 6, we perform a mathematical analysis of speckle. Also possible speckle reduction methods in the literature are introduced at this chapter. In chapter 7, a new laser diode drive circuit is introduced and different working modes are explained in detail. For different working modes of drive circuit, we obtained several speckle reduction ratios. All the results are reported in chapter 8.

The drive circuit which is developed and mentioned in chapter 7 allows driving the current of a laser diode in constant dc, square wave or triangular waveform. By using square wave and triangular wave we deliberately create mode hopping in the laser diode which decrease speckle noise. This method can be classified as a wavelength diversification based speckle reduction method such as the specially tailored laser diode based systems (Furukawa et al., 2008; Johansson, 2007).

By modulating laser diode current continuously, independent longitudinal modes created which arise from mode hopping. Since these modes have no fixed relationship between each other they act as independent sources which results in speckle reduction in the image. Usually mode hopping is undesired when operating laser systems and a lot effort is put into trying to prevent mode hopping. Our results are therefore interesting; because they show that mode hopping can be beneficial in reducing speckle noise in laser based display and projection systems.

For the square wave and the triangular wave we obtain speckle reduction factor 1.32 and 2.16 respectively, these results has excellent agreement with our theoretical expectations. We performed a MATLAB analysis, on the intensity measurement of pictures and current level approximations.

With improvements in laser technology, new powerful laser sources at several wavelength range becomes commercially available such as optical pumped semiconductor laser(OPSL) and Vertical External-cavity Surface-emitting Lasers(VECSEL) (Chilla et al., 2004; Iga & Li, 2003; Kuznetsov, Hakimi, Sprague, & Mooradian, 1997). These OPSLs are already used in the display systems in some applications (Chilla et al., 2005) but, they are not price competitive yet (Schulze & Masters, 2006). Mode hopping also exist in these laser types so similar drive approach may be used for speckle noise elimination. A powerful white light is generated by using a yellow-emitting phosphor excited by the blue laser diode(Ryu & Kim, 2010) this blue laser diode current may also be modulated for better picture quality.

In this thesis, we have reported the implementation of a modulator that allows for modulating the drive current of a laser diode in different modes and within predetermined limits. Our proposed scheme has been successful in suppressing the speckle noise electronically when applied to a laser projector system.

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