

**Green Diode Pumping of Femtosecond Ti³⁺:sapphire Lasers
and The First Demonstration of 2.3-μm Laser Operation in
Trivalent Thulium-doped KY₃F₁₀ and BaY₂F₈ Fluoride
Crystals**

by

Abdullah Muti

A Dissertation Submitted to the
Graduate School of Sciences and Engineering
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the Degree of
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in

Physics



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September 4, 2020

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Koç University

Graduate School of Sciences and Engineering

This is to certify that I have examined this copy of a doctoral dissertation by

Abdullah Muti

and have found that it is complete and satisfactory in all respects, and
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examining committee have been made.

Committee Members:

Prof. ALPHAN SENNAROĞLU

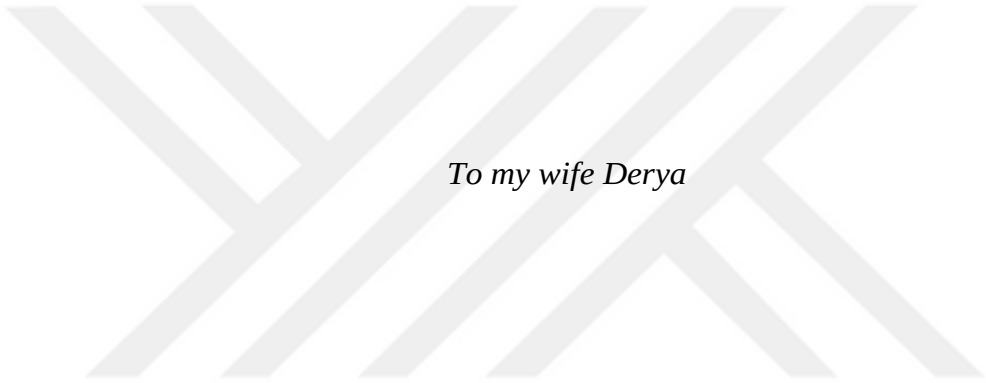
Assist. Prof. AŞKIN KOCABAŞ

Prof. MEHMET BURÇİN ÜNLÜ

Assoc. Prof. ÜMİT DEMİRBAŞ

Prof. FUNDA ACAR YAĞCI

Date:



To my wife Derya

ABSTRACT

Green Diode Pumping of Femtosecond Ti^{3+} :sapphire Lasers and the First Demonstration of 2.3- μm Laser Operation in Trivalent Thulium-doped KY_3F_{10} and BaY_2F_8 Fluoride Crystals

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This thesis aims at the development of new femtosecond laser architectures in the near infrared and mid infrared regions of the electromagnetic spectrum. The first part focuses on direct green diode pumping of a Ti^{3+} :sapphire laser by using recently developed 520-nm laser diodes. The second part of the thesis explores 2.3 μm laser operation of new fluoride hosts doped with Tm^{3+} ion. Tunable laser operation near 2.3 μm was demonstrated for the first time in the fluoride hosts KY_3F_{10} and BaY_2F_8 doped with trivalent Tm ion. In the particular case of Tm^{3+} doped KY_3F_{10} laser, graphene saturable absorber mode locking was further demonstrated yielding sub-picosecond pulses at 2.3 μm . The final part of the thesis describes the construction of a homemade experimental setup which employs 808 nm and 640 nm lasers for the evaluation of photothermal therapy and photodynamic therapy potential of various nanoparticles.

In the first part of the thesis, direct green diode pumping of a Ti^{3+} :sapphire laser was investigated near 800 nm by using a short x-cavity and an extended multipass cavity (MPC) configuration. The continuous wave (cw) power performance of the short cavity and MPC was first optimized. A paraxial beam propagation algorithm based on the ABCD method was used to obtain the best mode matching between the 520-nm diode and Ti^{3+} :sapphire cavity. The optimized short cavity produced 90 mW of output power at 780 nm with 880 mW of diode pump power with the 3% output coupler. The short x-cavity was then extended with an MPC to lower the pulse repetition rate of the composite laser to 5.8 MHz during Kerr lens mode-locked operation. With 860 mW of diode pump power, the mode-locked MPC Ti^{3+} :sapphire laser generated 95-fs pulses with a pulse energy of 5.1 nJ. These results represent the highest pulse energy obtained to date with a single diode pumped Ti^{3+} :sapphire laser.

In the second part of the thesis, laser action at 2.3 μm was demonstrated for the first time in the fluoride host KY_3F_{10} doped with Tm^{3+} ion. In the experiments 8 at.% Tm^{3+} : KY_3F_{10} crystal was pumped with a homemade, tunable Ti^{3+} :sapphire laser. Excitation spectrum, tunability and laser power performance of the Tm^{3+} : KY_3F_{10} laser was investigated in the cw regime. With a 1% output coupler, the Tm^{3+} : KY_3F_{10} laser produced 31 and 122 mW of output

power in single-end and double-end pumping configurations, respectively. In addition, the output wavelength of the laser was continuously tuned over a range of 125 nm between 2260 and 2385 nm. Furthermore, the lifetime of the upper laser level ($^3H_4$) was measured to be 16 μ s. By using the lasing threshold data the stimulated emission cross section of the 2.3 μ m laser transition was determined to be $(1.62 \pm 0.09) \times 10^{-24} \text{ m}^2$. After the continuous wave laser characterization, mode-locked operation was obtained by extending the cavity length and by adding a graphene saturable absorber. The graphene mode-locked $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser produced 739-fs pulses at 2340 nm at a pulse repetition frequency of 54 MHz. These results represent the first experimental demonstration of continuous wave laser operation and graphene mode-locked operation of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ gain medium around 2.3 μ m.

The third part of the thesis focuses on experiments where 2.3 μ m lasing was demonstrated for the first time in Tm^{3+} doped BaY_2F_8 crystal. Since the BaY_2F_8 crystal was anisotropic, two different pumping polarizations (E//x and E//y) were investigated and lasing was obtained at 2290 nm for both cases. Power efficiency and excitation spectrum measurements were then performed each pumping configuration. For E//x pumping configuration, 42 mW (100 mW) of output power was obtained in single-end (double-end) pumping scheme. For E//y pumping, 43 mW of output power was obtained in double-end pumping scheme. The remaining power characterization was performed for E//x pumping. Tunable operation was obtained over a range of 152 nm between 2233 and 2385 nm. Absorption saturation measurements were further carried out to determine the saturation intensity and the absorption cross section of the gain medium. The lifetime of the upper laser level was measured to be 292 μ s. The emission cross section for the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ gain medium was found to be smaller $((0.66 \pm 0.06) \times 10^{-24} \text{ m}^2)$ than that of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ medium $((1.62 \pm 0.09) \times 10^{-24} \text{ m}^2)$.

The final part of the thesis describes an emerging application of near infrared lasers in photothermal therapy (PTT) and photodynamic therapy (PDT). In the experiments, a homemade setup was constructed for the evaluation of the PTT and PDT potential of different nanoparticles irradiated with 640 nm and/or 808 nm lasers. A dichroic mirror was used to combine the 640 and 808 nm beams so that they can be applied simultaneously or individually. During the PTT measurements, the temperature increase of the nanoparticle solutions was recorded as a function of time to determine the PTT efficiency. A tunable $\text{Ti}^{3+}:\text{sapphire}$ laser was also used to explore the wavelength dependence of the PTT efficiency. PTT measurements were further carried out by irradiating nanoparticles injected into cancer cell cultures, bacteria cultures and bacteria biofilms in 96-well plates. The samples were placed inside a container whose temperature was maintained at 37°C. Experiments showed that incident fluence levels of 3 W/cm^2 provided effective PTT and PDT effect, demonstrating their potential in next generation medical therapy systems.

ÖZETÇE

Green Diode Pumping of Femtosecond Ti^{3+} :sapphire Lasers and the First Demonstration of 2.3- μm Laser Operation in Trivalent Thulium-doped KY_3F_{10} and BaY_2F_8 Fluoride Crystals

Abdullah Muti

Fizik, Doktora

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Bu tez elektromanyetik spektrumun yakın kızılötesi ve orta kızılötesi bölgelerinde yeni lazer mimarileri geliştirmeyi amaçlamaktadır. İlk bölüm yakın zamanda geliştirilmiş olan 520-nm lazer diyotları kullanılarak bir Ti^{3+} :safir lazerinin direk olarak bir yeşil diyot ile pompalanmasına odaklanmaktadır. Tezin ikinci kısmı Tm^{3+} iyonu katkılanmış yeni florür konaklarda 2.3 μm lazer operasyonunu araştırmaktadır. Dalgaboyu ayarlanabilir 2.3 μm lazer operasyonu, üç değerlikli Tm iyonu katkılanmış florür konaklar KY_3F_{10} ve BaY_2F_8 'te ilk kez gösterilmiştir. Ayrıca, Tm katkılı KY_3F_{10} lazerinde, grafen doyabilen soğurucu ile kip kilitlenmesi, 2.3 μm dalgaboyunda pikosaniye altı darbeler üretilerek gösterilmiştir. Tezin son kısmı çeşitli nanoparçacıkların fototermal ve fotodinamik tedavi potansiyellerinin değerlendirilmesi için 808 nm ve/veya 640 nm lazerlerini kullanan ev yapımı bir deneysel düzeneğin kuruluşunu anlatmaktadır.

Tezin ilk kısmında, 800 nm civarında çalışan, direk yeşil diyot pompalı bir Ti^{3+} :safir lazeri, bir kısa x şeklindeki kovuk ve bir genişletilmiş çoklu yansıma kovuğu yapısı kullanılarak incelenmiştir. İlk olarak kısa kovuk ve çoklu yansıma kovuğunun sürekli dalga güç performansı eniyileştirilmiştir. 520 nm diyotu ile Ti^{3+} : safir lazeri arasında en iyi kip örtüşmesini elde etmek için, ABCD matrisi tabanlı bir paraksiyal ışın yayılımı algoritması kullanılmıştır. Eniyileştirilmiş kısa kovuk 880 mW pompa gücü ve %3 çıkış aynası geçirgenliği ile 780 nm dalgaboyunda 90 mW güç üretmiştir. Kısa x şeklindeki kovuk daha sonra Kerr lens kip kilitli operasyon sırasındaki darbe tekrar frekansını 5.8 MHz'e düşürmek için bir çoklu yansıma kovuğu ile genişletilmiştir. Kip kilitli çoklu yansıma kovuklu Ti^{3+} :safir lazeri 860 mW pompa gücü ile 5.1 nJ darbe enerjisine sahip 95 fs uzunluğunda darbeler üretmiştir. Bu sonuçlar bugüne kadar tek diyotla pompalanmış bir Ti^{3+} :safir lazerinden elde edilmiş en yüksek darbe enerjisini göstermektedir.

Tezin ikinci kısmında, Tm katkılı florür kazanç ortamı KY_3F_{10} 'te 2.3 μm lazer ışınlamayı ilk kez gösterilmiştir. Deneylerde %8 katkılı bir Tm^{3+} : KY_3F_{10} kristali ev yapımı ve dalgaboyu ayarlanabilir bir Ti^{3+} :safir lazeri ile pompalanmıştır. Tm^{3+} : KY_3F_{10} lazerinin uyarılma spektrumu, dalgaboyu ayarlanması ve lazer güç performansı sürekli dalga rejiminde incelenmiştir. Tm^{3+} : KY_3F_{10} lazeri %1 geçirgenliğe sahip bir çıkış aynası ile tek ve çift pompalı durumlarda sırasıyla 31 ve 122 mW güç üretmiştir. Ek olarak, lazer çıkış dalgaboyu 2260 nm ile 2385 nm arasında 125 nm'lik bir aralıkta sürekli şekilde ayarlanmıştır. Ayrıca, üst lazer seviyesinin ($^3\text{H}_4$) yaşam süresi 16 μs olarak ölçülmüştür. Lazer eşik pompa değerleri kullanılarak emisyon arakesiti $(1.62 \pm 0.09) \times 10^{-24} \text{ m}^2$ olarak belirlenmiştir. Sürekli dalga lazer karakterizasyonundan sonra, kovuk boyunun arttırılması ve bir grafen doyabilen soğurucunun eklenmesiyle kip kilitli operasyon elde edilmiştir. Grafen kip kilitli Tm^{3+} : KY_3F_{10} lazeri 54 MHz darbe tekrar frekansında 2340 nm'de 739 fs uzunluğunda darbeler üretmiştir. Bu sonuçlar, Tm^{3+} : KY_3F_{10} kazanç ortamında 2.3 μm dalgaboyunda sürekli dalga ve grafen kip kilitli operasyonu

ilk kez deneysel olarak göstermektedir.

Tezin üçüncü kısmı Tm^{3+} katkılı BaY_2F_8 kristalinde 2.3 μm lazer ışınının ilk kez gösterilmesi deneylerine odaklanmaktadır. BaY_2F_8 kristali anizotropik olması sebebiyle iki pompa polarizasyonu (E//x ve E//y) incelenmiş ve iki durumda da 2290 nm’de lazer ışınımı elde edilmiştir. Daha sonra iki durum için de güç verimi ve uyarılma spektrumu ölçümleri yapılmıştır. E//x durumunda tek pompalı (çift pompalı) durumda 42 mW (100 mW) çıkış gücü elde edilmiştir. E//y durumunda çift pompalı durumda 43 mW çıkış gücü elde edilmiştir. Takip eden güç karakterizasyonları E//x durumu için yapılmıştır. Dalgaboyu ayarlanabilirliği 2233 nm ile 2385 nm arasındaki 152 nm’lik bir aralıkta elde edilmiştir. Ek olarak kazanç ortamının doygunluk yoğunluğu ve emilim arakesitinin belirlenebilmesi için emilim doygunluğu ölçümleri yapılmıştır. Üst lazer seviyesinin yaşam süresi 292 μs olarak ölçülmüştür. $Tm^{3+}:BaY_2F_8$ kazanç ortamı için elde edilen emisyon arakesiti $((0.66 \pm 0.06) \times 10^{-24} m^2)$ $Tm^{3+}:KY_3F_{10}$ ortamından $((1.62 \pm 0.09) \times 10^{-24} m^2)$ daha küçük bulunmuştur.

Tezin son kısmında, yakın kızılötesi bölgesindeki lazerlerin fototermal tedavi (PTT) ve fotodinamik tedavide (PDT) yeni ortaya çıkan uygulamalarını anlatmaktadır. Deneylerde, 640 nm ve/veya 808 nm ile ışınlanmış nanoparçacıkların PTT ve PDT potansiyellerinin değerlendirilmesi için bir ev yapımı düzenek inşa edilmiştir. 640 nm ve 808 nm lazer hüzmeleri, hem tek başlarına hem de beraber uygulanabilmeleri için bir dikroik ayna kullanılarak birleştirilmiştir. PTT ölçümleri sırasında, nanoparçacık çözeltilerinin sıcaklık artışları PTT verimlerinin belirlenebilmesi için zamana bağlı olarak kayıt edilmiştir. Ek olarak, PTT veriminin dalgaboyuna olan bağlılığını inceleyebilmek için bir dalgaboyu ayarlanabilir Ti^{3+} :safir lazeri kullanılmıştır. PTT ölçümleri, 96 kuyucuklu kutulara koyulmuş ve nanoparçacık enjekte edilmiş kanser hücreleri kültürleri, bakteri kültürleri ve bakteri biyofilmlerinin ışınlanması ile devam etmiştir. Örnekler sıcaklığı 37°C’de tutulan bir kutuya koyulmuştur. Deneyler göstermiştir ki 3W/cm² mertebesindeki ışık akıları verimli PTT ve PDT etkileri sağlayarak, PTT ve PDT’nin gelecek nesil tıbbi tedavi potansiyellerini göstermektedir.

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ABBREVIATIONS

CW	Continuous wave
KLM	Kerr lens mode locking
DPSS Laser	Diode pumped solid state laser
SESAM	Semiconductor saturable absorber mirror
w	Beam waist
R	Radius of curvature
MPC	Multipass cavity
r	Height of a ray measured from optical axis
θ	Angle between the ray and the optical axis
M_T	Ray tracing matrix
$q(z)$	Complex beam parameter
λ	Wavelength
n_0	Refractive index
ϕ	Angular displacement between the consecutive spots on MPC mirrors
n	Number of roundtrips inside the MPC
m	Number of semicircular arcs followed by the beam on one MPC mirror
d_{MPC}	Length of a q-preserving MPC extension
$\Delta\nu$	Spectral bandwidth
ν_{fsr}	Free spectral range
c	Speed of light in vacuum
d	Cavity length
M	Number of modes oscillating inside a cavity
ω_f	Angular frequency difference of the two neighboring modes
$E(t)$	Electric field
E_q	Amplitude of the electric field
$\phi_q(t)$	Phase of the q^{th} mode
K	Time-bandwidth product
τ_p	Pulse width
SAM	Self amplitude modulation

SBR	Saturable Bragg reflector
n_2	Nonlinear refractive index coefficient
L	Length of nonlinear medium
I	Intensity of a beam
SPM	Self phase modulation
GDD	Group delay dispersion
$\Phi_{\max}$	Maximum nonlinear phase shift
I_{peak}	Peak intensity of the pulse
D	GDD parameter
z_d	Characteristic dispersion length
Δx	Transition amount of the interferometer mirror
$g^2(t)$	Interferometric autocorrelation function
PTT	Photothermal therapy
PDT	Photodynamic therapy
HWP	Half-wave plate
PBS	Polarizing beam splitter
HR	High reflector
OC	Output coupler
M^2	M square parameter
RMS	Root-mean-squared
GTI	Gires-Tournois interferometer
FWHM	Full width at half maximum
W	Intracavity pulse energy
δ	Kerr nonlinearity coefficient
A_{eff}	Effective cross-sectional area
BTP	Birefringent tuning plate
σ_e	Stimulated emission cross section
GSA	Graphene saturable absorber
τ_f	Fluorescence lifetime
h	Planck's constant
w_p	Pump beam waist

w_l	Laser beam waist
P_{th}	Threshold pump power
ν_p	Pump photon frequency
η_p	Pump absorption
N_T	Effective ion concentration
η_a	Small-signal absorption
σ_a	Absorption cross section
d_g	Crystal length
P_s	Saturation power
A_p	Effective area of the pump beam
A	Saturated absorption
P_p	Incident pump power
DM	Dichroic mirror
SPION	Super paramagnetic iron oxide nanoparticle
ICG	Indocyanine green
APTMS	3-aminopropyltrimethoxysilane

Chapter 1

1 Introduction and Thesis Overview

This thesis focuses on the development of direct diode-pumped near infrared lasers, continuous wave (cw) and pulsed mid-infrared lasers with fluoride based host materials and finally development of an in-house experimental setup for investigating the potential of nanoparticles for photothermal and photodynamic therapy applications. In this introductory chapter, a brief theoretical background of the experimental methods which were crucial during the experimental work will be presented, following the review of historical developments in laser science and technology, with a particular emphasis on previous laser studies that inspired the experiments in this thesis.

1.1 *Laser science and technology revision*

The groundbreaking progress for the light-matter interactions in the past century is the invention of lasers. This invention did not only lead to new concepts in science and technology but also improved the approach to the existing ones. The works that revealed the nature of light and its interaction with matter by Newton [1], Young [2], Maxwell [3], Hertz [4], Planck [5] and Einstein [6] himself, finally led him to set the foundations of the stimulated emission theory [7]. Fabrikant suggested experiments for both investigation of stimulated emission and creation of population inversion in gas discharge in his 1940 paper [8]. Even before the publication of first population inversion paper, Maria Goeppert-Mayer theoretically investigated the possibility of an excitation caused by photons acting together that do not have enough energy individually [9]. This excitation mechanism was not practically possible until the invention of pulsed lasers. As can be seen, the emerging applications provided a high motivation toward developing a new light source with unique properties. The schematic demonstration of the three mechanisms that play an important role in laser action together with the multi-photon absorption is given in Figure 1.1. In 1951, Fabrikant filed a patent that contains methods for population inversion in gases together with plans for a light amplifier and experimental trials to obtain amplification with optical and gas discharge pumping [10]. Just three years later, Townes built the first maser, a device that amplifies microwave radiation through stimulated emission [11]. In 1964, Townes shared the Nobel Prize with Prokhorov and Basov, who also built their own maser prototype and published the maser idea at the same

time as Townes. After the invention of the maser, the next step was to obtain amplification through stimulated emission at optical wavelengths. This step was achieved by Maiman in 1960 with the operation of the first ruby laser [12]. In this first demonstration, a ruby crystal was used as a host for the Cr^{3+} ions and hence it is also the first solid state laser. Just like overcoming the threshold power for a laser, the invention of the first laser started a fast paced research trend in the area. In the same year, a uranium-doped CaF_2 laser was invented [13]. First neodymium laser and He-Ne gas laser was invented just the following year in 1961 [14, 15]. One year after in 1962, the first semiconductor laser was built [16]. The last addition to the material families was the dye laser which was first demonstrated in 1966 [17]. In seven years, lasers in every phase of matter were invented based on the 43 years of accumulation of information.

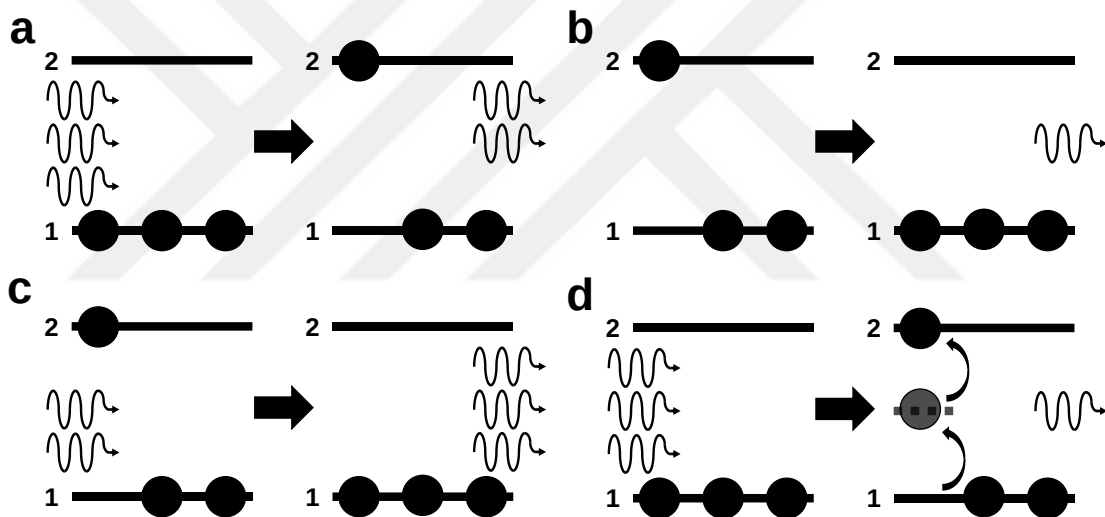


Figure 1.1 Schematic demonstration of the (a) absorption, (b) spontaneous emission, (c) stimulated emission, and (d) multi-photon absorption.

As mentioned at the beginning, invention and development of the lasers enhanced the methods used in technology. Lasers completely changed or increased the efficiency of the way to measure spatial dimensions such as distance, velocity, diameter, angular rotation, thickness and roughness. It also made the material processing faster, finer and economically more feasible. Furthermore, light in the form of laser became intense enough to interact more effectively with matter. This enabled advances in scientific fields like spectroscopy and microscopy. The properties that made lasers unique for approaches

in science and technology can be listed as *monochromaticity*, *coherence*, *directionality*, *brightness* and the *pulsed operation* capability. Below, each of these attributes is briefly introduced.

-Monochromaticity: Laser output has a narrow linewidth compared to thermal light which is the more commonly encountered form of light. This narrow linewidth feature is called monochromaticity and it plays a crucial role for applications such as holography and spectroscopy.

-Coherence: Coherence of a wave can be explained as the degree of similarity to a perfect wave. In terms of spatial coherence, a perfect wave has zero phase difference for two different point in space that lie on the wavefront. The phase conservation of a single point over a time interval is defined as the temporal coherence. Thus, coherent light obtained from lasers allows for the interferometric applications where light is divided into parts.

-Directionality: Having a low divergence angle due to the directional nature of the laser cavity. This allows the laser beam to remain spatially confined over a large range and hence to be used for applications such as alignment and angle tracking.

-Brightness: Brightness defines the amount of energy stored within a frequency bandwidth obtained from a certain amount of source area and sent through a solid angle. High brightness of lasers as compared to thermal sources, results from the monochromaticity and directionality of the lasers. This property of lasers enables material processing and long distance applications.

-Short pulse operation capability: Lasers with broad linewidths, especially solid state lasers, provides short pulses around the order of pico- or femtoseconds. The short pulses obtained from lasers make it possible to measure events occurring at time scales longer than the pulse duration and makes lasers a useful source for spectroscopy. Also, the short pulse operation provides sufficient peak powers to trigger nonlinear effects such as multi-photon excitation that lead to a new kind of microscopy called multi photon microscopy.

Exemplified by the first ruby laser, solid state lasers include all laser types apart from gas and liquid lasing media. This type of lasers employs optically activated ions doped inside the host material and these ions inside the host are excited optically. Commonly used

doping ions are transition metals and rare earth elements. Transition metals such as Ti, Cr, Fe and Co are among the widely used ones. A wider selection of ions belonging to rare earth elements to obtain lasing is available consisting of Nd, Yb, Tm, Ho, Er, Pr, Dy, Tb and Eu. The host materials can be single crystals, glasses or ceramics. Single crystal hosts provide good thermal and mechanical properties but poses a challenge in growth. Glass hosts, on the other hand, are easy to grow but they show weaker performance on the issues like mechanical strength and thermal management as compared to single crystals. In addition, ceramics are drawing increasing research attention as an intermediate phase between the single crystals and glass hosts. To date, cw and pulsed operation have been shown for all three material systems as hosts for numerous ions [18-20]. There are several families of host materials that possess favorable properties for certain wavelength ranges or applications. These families include garnets, fluorides, vanadates, tunstates, chalcogenides and Colquiriites among others. Over decades of laser development, some material systems have stood out due to their optimal operation. Among the garnet family, the $\text{Y}_3\text{Al}_5\text{O}_{12}$ (YAG) crystal has been shown to be used together with several number of rare earth ions such as Nd, Yb, Er, Tm and Ho over a wide range of wavelengths. However, YAlO_3 (YAP), vanadates, tunstates and fluorides are also widely used as hosts for rare earth elements. For the case of transition metals, optimal host materials show more diversity. The sapphire crystal was shown to be an ideal host for the Ti^{3+} ion, while chalcogenides and Colquiriites were widely used as hosts for Cr^{2+} and Cr^{3+} ions.

1.1.1 Ti^{3+} :sapphire laser

Just like lasers revolutionized the light based applications in science and technology, development of the Ti^{3+} :sapphire laser emerged as a game-changing source for almost every application in the near infrared wavelength range. The first Ti^{3+} :sapphire laser was reported by Peter Moulton in 12th International Quantum Electronics Conference in Munich in 1982 and later in 1986 [21]. Tunability range of Ti^{3+} :sapphire laser together with its good beam quality and high brightness, made it a useful pump source for investigation of new lasers. Due to its broad emission range, the Ti^{3+} :sapphire laser was used to generate pulses by using mode locking techniques such as saturable absorber mode locking and Kerr-lens mode locking (KLM) [22-25]. In time, with increased usage of specialized items and techniques for better dispersion control and higher quality broad

range mirrors, it became possible to obtain wider tuning range together with shorter pulses [26]. To date, research showed that, this laser is unique with its capability to be tuned from 650 to 1180 nm [27] and to generate 5-fs pulses [28]. Together with the Nobel winning chirped pulse amplification concept [29], Ti^{3+} :sapphire laser became a versatile lab equipment for scientific and technological areas such as spectroscopy [30], microscopy [31], laser research [32], metrology [33] and even nuclear fusion research [34].

Although the Ti^{3+} :sapphire gain medium has many advantages, there are certain limitations that prevent its widespread use. Due to its short upper-state lifetime and high saturation power, Ti^{3+} :sapphire laser requires strongly focused high intensity pump with high quality beam shape. The absorption peak of Ti^{3+} :sapphire is around 490 nm. Since high power laser diodes around this wavelength are not present yet, the pump sources with high brightness and high quality features are rather expensive. Even though the first demonstration of the Ti^{3+} :sapphire laser was done with xenon flashlamp, inefficient and expensive argon ion lasers operating at 514 nm were used for optical pumping [27, 35]. Frequency doubled diode pumped solid state (DPSS) lasers operating around 532 nm emerged as a more efficient alternative to argon ion lasers [36]. In order to reduce the cost of the pumping systems there is a growing interest in the direct diode pumping schemes. Currently, diodes operating around 450 nm can provide up to 4 W of pump power. However, the beam shape of these blue diodes are not ideal and needs conditioning before the use as a pump source for Ti^{3+} :sapphire. Recently, green laser diodes operating around 520 nm received a great deal of attention as possible sources for Ti^{3+} :sapphire pumping. The operating wavelengths are closer to the peak absorption wavelength than both DPSS lasers and blue diodes. Also their quantum defect is lower than that of the blue diodes. The output power levels of the green diodes have reached around 2W, about half of what is available from blue diodes.

Direct diode pumping of a cw Ti^{3+} :sapphire laser was first demonstrated by Roth et al. in 2009 [37]. In this work, a GaN based laser diode which operates around 450 nm and delivering 1 W of pump power was used as the pump laser. The output power of the cw Ti^{3+} :sapphire was 19 mW which seems to be low but initiated the research effort towards low-cost Ti^{3+} :sapphire lasers. Mode locked operation of a direct diode-pumped Ti^{3+} :sapphire was obtained with a saturable Bragg reflector two years later again by Roth

et al. [38]. In this first demonstration of mode-locked operation, 114-fs pulses with an average power of 13 mW were observed. Kerr-lens mode-locked operation was obtained by employing 2 of 1.2 W laser diodes operating at 445 nm. The resulting pulse durations were comparable to those obtained with DPSS laser pumped Ti^{3+} :sapphire lasers [39]. As a result of the enhancement of the power performance and the increase in the number of the blue pump diodes, Ti^{3+} :sapphire lasers yielded higher output powers and shorter pulses [40]. These developments led to the use of direct diode pumped Ti^{3+} :sapphire lasers in multi photon microscopy applications for the first time [41]. The demonstration of first AlInGaN based high power laser diodes operating around 520 nm [42] quickly led to the first green diode pumped Ti^{3+} :sapphire laser with mode locked operation by Sawai et al. [43]. In this first study, 62-fs pulses with 23.5 mW of output power were obtained with a pump power of 1W. Mode locking was obtained with a semiconductor saturable absorber mirror (SESAM). As in the case of the blue diodes, power scaling studies were conducted along with Kerr lens mode locking trials by increasing the number of pump diodes [44]. Pulses as short as 39 fs with an output power of 350 mW were obtained by the use of two 1.5-W pump diodes operating at 520 nm. After the introduction of the green laser diodes, they were used alongside with the blue diodes to demonstrate another important application of the Ti^{3+} :sapphire laser. An ultrafast regenerative amplifier was built with a Kerr-lens mode-locked green diode pumped Ti^{3+} :sapphire and blue diode pumped amplifier [45]. Power levels reaching up to 2.9 watts for diode operating at 450 nm, made it possible to obtain pulses with multi-nanojoule pulse energy which is useful for multiphoton microscopy applications [46]. In this particular paper, SESAM mode locked 82-fs pulses with 5-nJ pulse energy were obtained with two blue diodes, each delivering 2.9 W of pump power. The work on direct green diode pumped Ti^{3+} :sapphire laser that was done as a part of this thesis also reports sub-100-fs pulses with 5.1 nJ of pulse energy. However, in our case, only one green laser diode delivering 1 W of pump power was used instead of 5.8 W of pump power, due to the use of a q-preserving multi-pass cavity extension [47]. Even though the increase in the power levels of blue diodes as compared to green diodes was faster, green diodes are still popular and being used alongside with blue diodes [48-56].

1.1.2 Tm^{3+} lasers

The discovery of the element thulium dates back to 1879. During the investigation for the elements that gave the different colors to erbia (Er_2O_3), Swedish chemist Per Teodore Cleve found out there were two new elements in the mixture [57]. These two elements, which have been used together in laser science for a long time, were named holmium (Ho) and thulium (Tm). The atomic number of Tm is 69 and it is a member of the lanthanide series in the periodic table. The electronic structure of the Tm element is $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 4f^{13} 5s^2 5p^6 5d^0 6s^2$ and the practical version is $(Xe) 4f^{13} 5d^0 6s^2$. The general electronic structure for a rare earth element only differs in the number of electrons in the 4f shell. As can be understood from the short electronic configuration of Tm, rare earth elements use their two electrons in the 6s shell and 1 electron in the 4f shell for ionic bonding. Thulium ions are represented by Tm^{3+} due to this triply ionized configuration. In general, transitions of the Tm^{3+} which make it interesting for laser research, occur among the states of the 4f shell. These 4f shell transitions are mainly caused by Coulomb interaction. The fully filled 5s and 5d shells generate a screening effect and reduce the electron-photon coupling, hence narrowing down the absorption lines.

The first laser operation obtained from Tm ion was reported at very early times of the laser history, in 1965 [58]. Even the acronym “LASER” was not widely used at that time and the action was described as “optically pumped solid-state optical maser”. During this first demonstration of a Tm laser, the host material was YAG. Both cryogenic (77K) and room temperature operation was shown by the use of a tungsten lamp as the pump source. The operating wavelength of the laser was around 1.8 μm and 2 μm corresponding to the $^3F_4 \rightarrow ^3H_6$ transition. Ten years after this first demonstration, another lasing operation of Tm ion was demonstrated by using one of the transitions among the aforementioned states caused by 4f electrons [59]. In this work, the operating wavelength was around 2.3 μm and resulted from the $^3H_4 \rightarrow ^3H_5$ transition. Host materials were YAG and YAP. The $^3H_4 \rightarrow ^3H_5$ transition yielding the 2.3 μm laser operation has been further investigated in numerous host materials [60]. Also, spectroscopic studies were conducted to understand and optimize this emission [61]. In 2017, the research interest on this laser line was again renewed with the demonstration of the first Kerr lens mode locked operation [62]. Following this study, the research effort shifted towards obtaining cw and pulsed

operation at 2.3 μm . Different host materials that were used for 2 μm emission of Tm ion, reemerged as direct candidates to be investigated for 2.3 μm operation. In addition to these host possibilities, new pumping schemes were also demonstrated for pumping of Tm ion [63]. The studies conducted for this thesis are about the host materials research. Operation around 2.3 μm was realized for the first time in KY_3F_{10} and BaY_2F_8 crystals, the two hosts that were only demonstrated for 2 micron lasing of Tm [64, 65]. Mode locked operation was further obtained for $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser with a graphene saturable absorber [66].

Following the historic and literature survey, the experimental methods that were used during the studies for this thesis will be explained in the following section. In particular, the ABCD matrix method, mode locking and the characterization measurements for cw and pulsed operation will be discussed.

1.2 Experimental

The tools and techniques that were used to design the laser cavity, obtain, optimize and characterize the cw and pulsed operation of lasers can be grouped under three main sections. The first one of these sections explains the application of the ABCD or ray matrix for main cavity design together with the optimization of the laser operation. Although, ABCD matrix method is based on geometrical optics, which excludes the wave nature of light, the outcoming matrix can be used to trace the important electromagnetic beam parameters such as beam waist (w) and radius of curvature (R). These two parameters are traced in combination inside another parameter called q -parameter which plays a crucial role for designing multipass-cavity (MPC) extension. The MPC can be briefly defined as the organization of mirrors in order to obtain extension of the optical path while keeping the overall addition as tightly packed as possible. The second section is composed of pulse generation technique called mode locking and in particular passive mode locking. Two different passive mode locking methods used during this thesis work, namely Kerr-lens and saturable absorber mode locking will be explained. The final section consists of the characterization measurements for both cw and pulsed operation.

1.2.1 ABCD Matrix Method and q -preserving

The ABCD matrix method is built on the definition of a ray which is composed of its two parameters. These two parameters are its height measured from the optical axis (r) and

the angle between the ray and the optical axis (θ). The representation of the ray is given as a vector;

$$\begin{pmatrix} r \\ \theta \end{pmatrix}. \quad (1.1)$$

As the ray propagates, this ray vector transforms and the matrix that operates on this vector to obtain the transformation is called the ray tracing matrix or ABCD matrix. The transformation can be shown as;

$$\begin{pmatrix} r_2 \\ \theta_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r_1 \\ \theta_1 \end{pmatrix}, \quad (1.2)$$

where the indices 1 and 2 describe the ray, before and after the propagation, respectively. There are basic optical elements such as free space displacement, curved dielectric interface and curved reflector. These basic elements can be used to obtain more complex systems that transform the ray, for example, a thin lens. Due to the linear nature of these matrices, systems containing different elements in tandem can be represented by a cumulative transformation matrix. This cumulative matrix is composed of the multiplication of each different element inside the system. The transformation of a ray through a number of different elements can be calculated as

$$\begin{pmatrix} r_2 \\ \theta_2 \end{pmatrix} = M_{T_n} M_{T_{n-1}} M_{T_{n-2}} \dots M_{T_1} \begin{pmatrix} r_1 \\ \theta_1 \end{pmatrix} = M_T \begin{pmatrix} r_1 \\ \theta_1 \end{pmatrix}. \quad (1.3)$$

One important remark can be to apply the matrices in the correct order. As expected, the matrix for the first element should be applied to the ray first. The overall matrix can be checked by calculating the determinant which should be unity for systems with the same refractive index at the beginning and at the end of the optical system.

The simple approach of ABCD matrix method also includes information about the stability of an optical resonator. The stability of an optical resonator requires the confinement of the ray after an indefinite number of round trips. The stability condition is related to the trace of the transfer matrix as follows

$$\left| \frac{A+D}{2} \right| \leq 1. \quad (1.4)$$

Until now, the Gaussian nature of light was not taken into account. The properties like having a Gaussian field profile and spherical equiphase surface instead of a constant distribution and plane equiphase surface are excluded. However, these properties should be traced when the behavior of a Gaussian beam inside a resonator needs to be determined. The Gaussian beam solutions of the wave equation in a homogeneous media contains the complex beam parameter $q(z)$ which can be expressed as

$$\frac{1}{q(z)} = \frac{1}{R(z)} - i \frac{\lambda}{n_0 \pi w^2(z)}, \quad (1.5)$$

where $R(z)$ is the radius of curvature, $w(z)$ is the beam spot size function, λ is the wavelength and n_0 is the refractive index. Radius of curvature function describes the radius of the circular equiphase surfaces of the Gaussian beam. Beam waist can be explained as the radial distance at which the electric field reduces to $1/e$ of its maximum value in the transverse plane. Tracing the beam parameter $q(z)$ inside a resonator is important for designing the optical resonator. The usefulness of the ABCD matrix arises here, because the transformation of the q -parameter through a paraxial optical system is related to the matrix obtained with the ray picture as

$$q_f = \frac{Aq_i + B}{Cq_i + D}, \quad (1.6)$$

where indices i and f represent initial and final values, respectively. That means that the evolution of the Gaussian beam parameters, namely $R(z)$ and $w(z)$, can be traced with the use of ABCD matrix.

In the scope of this thesis, ABCD matrix method was employed to trace the pump beam and laser beam inside the gain crystal. These two parameters together with other related parameters such as refractive index, threshold pump power, upper state lifetime, pump absorption and total losses of the cavity are used to determine the emission cross section of different gain media. Another key point where the ABCD matrix was employed in the thesis is the addition of the MPC extension to the short x-shaped cavity. The aim here is to keep the q -parameter of the beam at the point of the high reflector of an x-shaped cavity the same after one roundtrip inside the MPC extension. This helps to maintain the beam parameters of the short cavity while the pulse energy scales up due to the increased cavity

length. The extension also allows to control the dispersion in the cavity by providing enough space to insert dispersion control mirrors.

The design of the q-preserving MPC extension based on the ABCD matrix method can be summarized as follows. The ABCD matrix obtained after one roundtrip inside MPC extension is;

$$M_T = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \quad (1.7)$$

and this matrix satisfies the stability inequality. After n roundtrips inside the extension, the overall transformation matrix becomes;

$$M_T^n = \begin{pmatrix} \frac{A-D}{2} \frac{\sin(n\phi)}{\sin(\phi)} + \cos(n\phi) & B \frac{\sin(n\phi)}{\sin(\phi)} \\ C \frac{\sin(n\phi)}{\sin(\phi)} & \frac{D-A}{2} \frac{\sin(n\phi)}{\sin(\phi)} + \cos(n\phi) \end{pmatrix}. \quad (1.8)$$

If this cumulative matrix is equal to the unity matrix, the equality between the q-parameter before and the q-parameter after the MPC extension can be achieved [67]. The unity matrix requires that the angle ϕ which corresponds to the angular displacement between the consecutive spots on the mirrors should be equal to;

$$\phi = \frac{m\pi}{n} \quad (1.9)$$

where both m and n are integers. The integers n and m represent the number of roundtrips inside the MPC and number of semicircular arcs that are followed by the beam on one end mirror before leaving the extension, respectively. Furthermore, the specific example of the MPC used in this thesis is a flat-curved MPC which means that the MPC extension is composed of one curved and one flat mirror. Together with this constraint, another important design rule of the MPC related to its length can be obtained. The length of a q-preserving MPC extension with one curved mirror of radius of curvature of R and a second flat mirror is calculated to be [68];

$$d_{MPC} = \frac{R}{2} \left(1 - \cos \left(\frac{m\pi}{n} \right) \right). \quad (1.10)$$

1.2.2 Mode locking

Ultrashort laser pulses provide a unique way to measure the fastest events in science and technology. The family of methods to obtain ultrafast pulses is called mode locking. Mode locking is based on the generation of longitudinal modes oscillating with the same phase inside a cavity. This equiphased behavior can be obtained with insertion of both active and passive modulating elements into the laser or employing nonlinear processes such as Kerr lensing. In order to obtain a large number of longitudinal modes, a gain material with a broad spectral bandwidth ($\Delta\nu$) is required. These longitudinal modes are separated by a frequency spacing which is also called free spectral range. The free spectral range is given by

$$\nu_{fsr} = \frac{c}{2d}, \quad (1.11)$$

where c is the speed of light and d is the cavity length. When M modes are oscillating together and the angular frequency difference of two neighboring modes is

$$\omega_F = 2\pi\nu_{fsr} = \frac{\pi c}{d} \quad (1.12)$$

the net electric field due to these oscillating modes is represented by

$$E(t) = \sum_{q=0}^{M-1} E_q \exp(i(\omega_0 + q\omega_F)t + i\phi_q(t)) \quad (1.13)$$

where q is an integer, ω_0 is a reference angular frequency, E_q and ϕ_q are the amplitude and the phase of the q^{th} mode, respectively. As mentioned earlier, mode locking will be obtained, if a modulating element could force all M modes to oscillate with the same phase. The net electric field together with equal phase and equal amplitude for all modes results in [69]

$$E(t) = E_0 \exp(i\omega_0 t) \frac{\sin\left(\frac{M\omega_F t}{2}\right)}{\sin\left(\frac{\omega_F t}{2}\right)}. \quad (1.14)$$

The output power of the laser at any given time is proportional to $|E(t)|^2$. As can be understood from the equation above, the number of locked modes affects both the pulse

width and the peak power of the pulses arriving with a repetition frequency equal to the free spectral range. The pulse width decreases and the peak power of the pulses increases with the increase in the number of locked modes. However, the pulse width has its own fundamental limit apart from the phase distortions caused by dispersion and nonlinear effects. A pulse with the shortest width allowed by the spectral bandwidth along with no phase distortions is called a transform-limited pulse. For a transform-limited pulse, the shortest possible pulse width allowed by a certain spectral bandwidth can be described by a constant K which is called the time-bandwidth product and obeys the relation [69]

$$\Delta\nu\tau_p = K \quad (1.15)$$

where τ_p is the pulse width. K is related to the pulse profile and has the specific values of 0.441 and 0.315 for Gaussian and hyperbolic secant-squared pulse shapes, respectively.

As mentioned above, in order to obtain mode locking, there are active and passive mode locking techniques. In active mode locking, a modulator, with a modulation frequency equal to the free spectral range of the cavity, is inserted into the cavity to generate the pulsed operation. These modulators are electronically controlled so that the generated pulses with the active mode locking are on nanosecond or picosecond range. However, in passive mode locking, the modulation is provided by the much faster recovery times of the passive element such as a saturable absorber. Hence, pulse durations obtained with passive mode locking are on the order of picoseconds and femtoseconds. The pulsed operations investigated in this thesis are obtained with passive mode locking techniques. Thus, saturable absorber mode locking and Kerr lens mode locking will be explained in detail.

In passive mode locking, the necessary modulation needed to obtain mode locking is provided by the nonlinear effects. The loss or the gain modulation required for mode locking is obtained through the saturation of the absorber. This is called self amplitude modulation (SAM). The interplay between the loss saturation and the gain saturation generates a net gain window. The pulse is generated during this net gain window. There are two different passive mode locker types which are named according to the recovery time of the saturation in comparison to the pulse duration. The saturable absorber with a recovery time longer than the generated pulse is called a slow saturable absorber. In this case, the net gain window starts with the decrease in the loss by the absorber saturation

and ends with the gain saturation. Correspondingly, the fast saturable absorber has the recovery time similar to the generated pulse width. Thus, the opening and closing of the gain window is controlled by the absorber saturation. Due to the fast saturable absorber behavior generated by the crystal itself, Kerr lens mode locking can be taken as a good example for fast saturable absorber action. During the studies performed in this thesis, graphene saturable absorber and Kerr lens mode locking were employed to obtain pulsed behavior. Hence, in the following subchapters, these two mode locking methods will be explained.

Saturable absorber mode locking

A saturable absorber can be basically described as an element with intensity dependent reflectivity/absorption to generate the loss modulation required for mode locking. Since the high intensity pulses experience smaller loss, the pulsed operation becomes more favorable as compared to cw operation. The widely used saturable absorbers consist of a Bragg type of layered structure made out of two semiconductor materials with different refractive indices and a saturable absorber layer. In literature, saturable absorbers with similar architecture can be found under two different names which are semiconductor saturable absorber mirrors (SESAM) and saturable Bragg reflector (SBR) [70, 71]. The saturable absorber part is generally a quantum well structure with a bandgap tailored according to the operation wavelength. The photons with enough energy, transfer the electrons in the valance band to the conduction band of the absorber. For low intensity, the conduction band can provide enough final states for the incoming valance band electrons and incoming photons keep being absorbed. On the other hand, for high intensity, the final states in the conduction band are full and the states in the valance band are empty. Thus, the absorber is saturated and the absorption decreases. After the recovery time the electrons in the conduction band recombine and the saturable absorber becomes ready for the next pulse. There are several different properties that define the performance of a saturable absorber. These properties are impulse recovery time, modulation depth, non-saturable loss, saturation fluence, and spectral bandwidth.

-Recovery time: The time required for the absorber to return to its non-saturated state.

-Modulation depth: The difference in loss for the cases of unsaturated and saturated states.

-Non-saturable loss: The amount of loss that cannot be reduced further during the saturation.

-Saturation fluence: The amount of energy per unit area required to reduce the loss of the absorber to half of its small-signal value.

-Spectral bandwidth: The wavelength range that the properties above stay constant and the saturable absorber provides mode locking.

Although the semiconductor based saturable absorbers are widely used, the fabrication process is still complicated due to the use of methods such as molecular beam epitaxy. Also, they need to be specially designed and fabricated to provide the required spectral bandwidth. Due to this complication, the research for material systems with less complicated fabrication steps continues. One example for these material systems is graphene. Since graphene has no bandgap and its loss of around 2.3% is constant over a wide wavelength range, it can be used as a saturable absorber for this wavelength range [72]. There are several works that used graphene as a saturable absorber [73-76]. The pulsed operation obtained with graphene saturable absorbers ranges from 750 nm [73] to around 3 μm [77]. This thesis also includes a mode locking study that employs a graphene saturable absorber inserted into a $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser for the first time to obtain pulsed operation around 2.3 μm [66].

Kerr lens mode locking

In Kerr lens mode locking (KLM), self focusing caused by the Kerr lensing is the main effect that generates mode locking. The Kerr effect can be briefly explained as the nonlinear dependence of the refractive index on the intensity of the light. The refractive index with the nonlinear contribution can be expressed as

$$n = n_0 + n_2 I, \quad (1.16)$$

where n_0 is the refractive index for low intensity, n_2 is the nonlinear refractive index coefficient and I is the intensity of the incoming beam. Self focusing is a result of the positive nonlinear refractive index. When a beam with a Gaussian distribution travels through a medium with positive nonlinear refractive index, the high intensity part of the beam experiences higher refractive index. This higher refractive index generates a lensing effect which in turn increases the intensity and hence the experienced refractive index becomes even more. Together with apertures that inhibits the cw operation, Kerr lensing

favors the mode locked operation. There are two types of apertures, which are hard and soft apertures, used to obtain KLM. Hard aperture KLM is obtained by the insertion of an actual aperture into the cavity. The low intensity parts of the circulating beam are exposed to larger losses and the high intensity mode locked pulses become more and more favorable by each transmission through the cavity. The size and position of the aperture is critical in this case of hard-aperture KLM. On the other hand, soft aperture KLM does not require an actual aperture. The aperture behavior is provided by the arrangement of the pump and the laser beams. A laser beam, slightly larger than the pump beam, experiences higher gain when it overlaps better with the pump beam when affected by the Kerr lensing. This better overlap makes the high intensity mode locked operation more preferable for the laser.

In order to obtain mode locking, Kerr lens effect works alongside with self phase modulation (SPM) compensated by negative group delay dispersion (GDD) for pulse formation. SPM is a phase shift arising due to the time-dependent change in the refractive index caused by positive n_2 . The maximum nonlinear phase shift can be expressed as

$$\Phi_{\max} = \frac{2\pi}{\lambda} n_2 I_{\text{peak}} L \quad (1.17)$$

where L is the length of the nonlinear medium and I_{peak} is the peak intensity of the pulse. The corresponding frequency shift for a Gaussian pulse can be shown as [69]

$$\Delta\omega = 4 \ln 2 \frac{\Phi_{\max}}{T_{1/2}} \exp[-2\alpha T^2] \frac{T}{T_{1/2}} \quad (1.18)$$

where $T_{1/2}$ is the initial pulse duration. As can be understood from the formula given above, the leading edge of the pulse ($T < 0$) becomes red shifted and the trailing edge of the pulse ($T > 0$) becomes blue shifted when affected by SPM.

The other effect that plays an important role on pulse formation is the GDD. GDD is related to the second order derivative of the acquired phase with respect to the angular frequency. The GDD parameter D can be calculated as follows for a known wavelength dependence of refractive index

$$D = L \frac{\lambda^3}{2\pi c^2} \frac{d^2 n}{d\lambda^2}. \quad (1.19)$$

This second order dispersion also provides a frequency shift to the propagating pulse. The frequency shift induced by the dispersion can be expressed as [69]

$$\Delta\omega = \frac{(4\ln 2)\text{sgn}(D)(z/z_d)}{1+(z/z_d)^2} \frac{T}{T_{1/2}} \quad (1.20)$$

For the negative dispersion case ($D < 0$), blue shift occurs on the leading edge ($T < 0$) and red shift occurs on the trailing edge ($T > 0$). When compared to the SPM case, the frequency shifts have opposite signs. This compensating interplay among SPM and negative GDD sets the ground for solitary pulse formation.

In this thesis, Kerr lens mode locking method is employed to obtain sub-100 fs pulses from a direct green diode pumped MPC Ti^{3+} :sapphire laser.

1.2.3 Laser characterization

There are several characterization measurements to understand and optimize the lasing behavior. Cw and pulsed operation measurements are the two types of measurements needed to fully characterize the laser operation. The cw measurements include power efficiency, lasing threshold, and optical spectrum measurements. On the other hand, pulsed operation characterization measurements consist of radio frequency (RF) spectrum measurements, autocorrelation measurements and again optical spectrum measurements of broadened spectrum. Each of these measurements will be explained briefly together with a sample measurement result.

-Power efficiency measurements: This measurement gives the relation between the pump power and the output power of the laser. The input pump power is varied and the corresponding output power is recorded. Both input pump power and output laser power are measured with a powermeter. In Figure 1.2a, a sample power efficiency measurement can be seen.

-Lasing threshold measurements: Threshold pump power measurement is similar to efficiency measurements. It is done to find out the minimum pump power required to obtain laser operation. An example of the threshold pump power measurement is given in Figure 1.2b. This measurement is also used for different output coupler transmissions to determine the loss of the cavity by using the Findlay-Clay analysis [78].

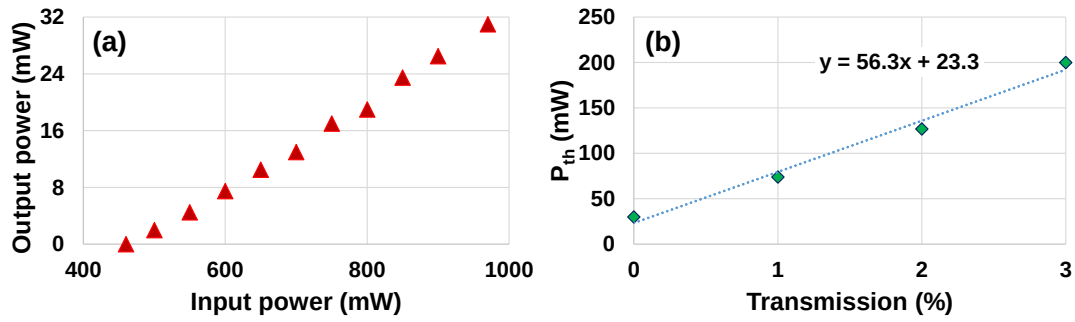


Figure 1.2 (a) Sample power efficiency and (b) threshold pump power measurement.

-Optical spectrum measurements: The output wavelength of a laser is measured by using spectrometers. If the pump laser is tunable, these spectrometers are also used to measure the wavelength of the pump laser. Optical spectrum measurements are also done during the mode locked operation. The aim of this measurement is to find out the spectral broadening reached with mode locked operation. This broadening amount is used to control if the pulses are transform limited by using time-bandwidth product. Sample cw and mode-locked spectrum measurements are given in Figure 1.3a and b, respectively.

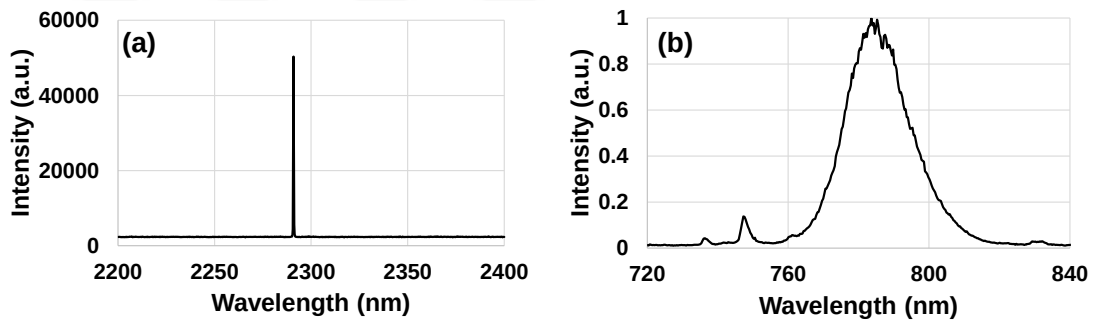


Figure 1.3 Continuous wave (a) and mode-locked spectrum (b) measurement examples.

-RF spectrum measurements: During mode locked operation, the pulses arrive at a repetition rate related to the length of the cavity. The cavity lengths ranging around meters to tens of meters correspond to MHz repetition rates. These repetition rates fall into the radio frequency range. RF spectrum measurements are done to check if the pulses are arriving on a narrow repetition rate range. This contains information about the quality of the mode locking. In Figure 1.4, an illustrative RF spectrum measurement can be seen.

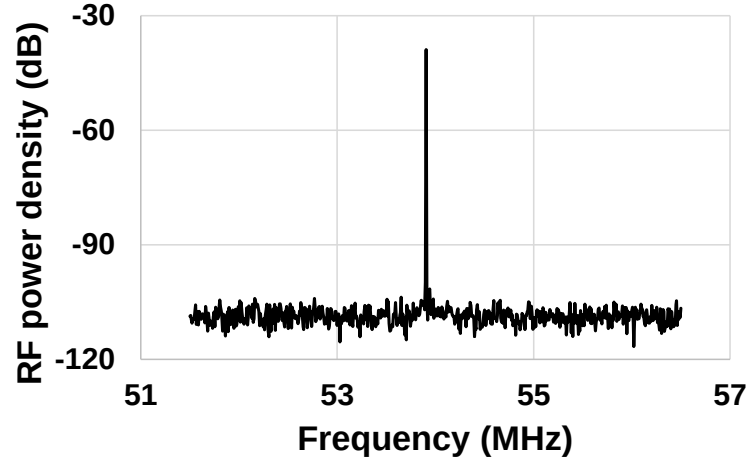


Figure 1.4 Representative RF spectrum measurement.

-Autocorrelation measurements: Autocorrelation method is used to measure the duration of ultrashort pulses based on delay-dependent interference. In order to measure the pulses obtained during this thesis study, Michelson interferometer based autocorrelators were employed. First, the mode-locked output of the laser is split into two by using a beam splitter. There is a fixed mirror on one arm and a movable mirror on the second arm. This movable mirror generates a path difference between the two split beams. Then, the two beams reflected from these mirrors are combined by the beam splitter and sent to a nonlinear element. This nonlinear element is generally a second harmonic generation (SHG) crystal. The signal generated by the SHG crystal is sent to a sensitive detector after filtering the nonconverted part of the signal. Another nonlinear element is a two-photon detector. This type of detector acts as both the signal generating nonlinear element and the detector itself.

As mentioned above, the movable mirror of the interferometer generates a time delay of $\tau = 2\Delta x/c$ between the split beams. Here, Δx is the amount of transition of the mirror, and c is the speed of light. The transition distances ranging between millimeters to micrometers correspond to delays in picoseconds and femtoseconds. During the pulsed operation characterization studies done for this thesis, intensity autocorrelation was used. The interferometric autocorrelation function is given as

$$g^2(\tau) = \int_{-\infty}^{+\infty} \left| (E(t)e^{i\omega t} + E(t-\tau)e^{i\omega(t-\tau)})^2 \right|^2. \quad (1.21)$$

This interferometric autocorrelation expression yields a ratio of 8 to 1 between the maximum of the signal and the background when the mode locked operation is achieved as can be seen in the sample autocorrelation trace of a mode-locked pulse given in Figure 1.5.

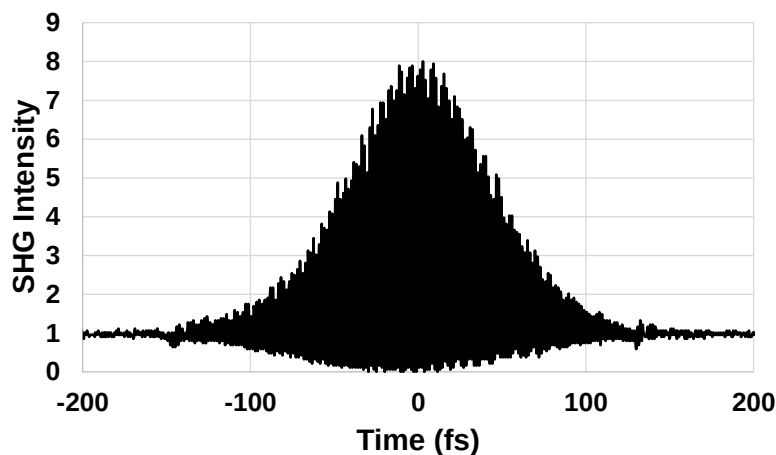


Figure 1.5 A sample autocorrelation trace of a mode-locked laser.

1.3 What is new in this thesis work?

This thesis contains a near infrared laser study yielding the highest pulse energy to date, obtained with a single green diode pumped MPC Ti^{3+} :sapphire laser. In this study, sub-100 femtosecond pulses with a pulse energy of 5.1 nJ were observed. This pulsed operation was obtained with a single green diode delivering 1-W of pump power. Furthermore, this is the first time an MPC Ti^{3+} :sapphire laser is pumped with a green diode laser.

In terms of mid-infrared lasers, this thesis provides the first-time demonstration of 2.3 μm operation of Tm^{3+} ion in both KY_3F_{10} and BaY_2F_8 crystals. The tunable laser operation is obtained for both lasers around 2.3 μm . In addition to cw operation, a graphene saturable absorber was inserted into the Tm^{3+} : KY_3F_{10} laser to obtain mode locking for the first time at 2.3 μm .

Finally, during the studies for this thesis, a setup for the characterization of photothermal therapy (PTT) and photodynamic therapy (PDT) performance of nanoparticles was constructed. In this setup, the cancer cell cultures and bacteria biofilms were irradiated

with two different lasers at 808 and 640 nm. The system allows for both individual and simultaneous irradiation of the two different wavelengths at 37°C. The system also includes an infrared camera so that the temperature of the cell cultures can be measured during the irradiation.

1.4 Overview of the remaining chapters

In the following chapters, the experimental results of the mode locking studies for the single green diode pumped KLM MPC Ti^{3+} :sapphire will be given in detail. The details consist of the beam conditioning studies on the pump laser and the pulse characterization of the KLM MPC Ti^{3+} :sapphire laser. Following that chapter, the studies yielding the first time cw and graphene saturable absorber mode locked laser operation of Tm^{3+} : KY_3F_{10} laser at 2.3 μm will be given. Characterization measurements such as excitation spectrum and tunability measurements together with power efficiency measurements will be provided as a part of the cw characterization. Furthermore, the pulse characterization obtained with a graphene saturable absorber will be given. After that, the experimental results regarding the first time laser operation of Tm^{3+} : BaY_2F_8 at 2.3 μm will be shown. In this case, the cw characterization is done for two different crystal axes due to the monoclinic nature of this crystal. In the last chapter, the construction of a home-made setup will be described for the characterization of the PTT and PDT performance of laser irradiated nanoparticles on cancer cell cultures and bacteria biofilms. The design steps and the novel features of the setup will be explained in detail.

Chapter 2

2 Green-diode-pumped Kerr-lens-mode-locked multipass-cavity

Ti^{3+} :sapphire laser

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2.1 Introduction

In recent years, development of cost-effective, diode-pumped solid-state lasers operating in the 700-800 nm spectral region has triggered a great deal of interest. These lasers have been utilized in numerous medical and technological applications, including optical coherence tomography [79], multiphoton microscopy [41, 46, 80, 81], spectroscopy [30], and material processing [82, 83]. One approach has utilized AlGaInP-based red laser diodes as pump sources and gain media from the Colquiriite family, which includes Cr^{3+} :LiSAF, Cr^{3+} :LiCAF, and Cr^{3+} :LiSGaF [84, 85]. Red diode-pumped Colquiriite lasers with high slope efficiency and low lasing thresholds have been successfully demonstrated in both continuous-wave (cw) and mode-locked regimes [84-86]. In addition, red-diode-pumped operation of alexandrite lasers has also been demonstrated near 750 nm [87-90]. More recently, advances in high-power green and blue laser diodes have enabled the direct diode pumping of Ti^{3+} :sapphire lasers [37-41, 43, 44, 46, 91, 92]. When compared with Colquiriite or Alexandrite gain media, the Ti^{3+} :sapphire gain medium offers additional advantages of broader tunability, negligible excited-state absorption, and reduced thermal effects [21, 84]. Direct diode-pumped operation of Ti^{3+} :sapphire lasers was first achieved by using GaN-based pump diodes near 452 nm [37]. To date, cw and mode-locked operations of diode-pumped Ti^{3+} :sapphire lasers have been demonstrated by using both blue and green pump diodes. In the mode locking experiments reported by Backus et al., as high as 1.85 nJ of pulse energy was obtained by using a single 4-W pump diode at 465 nm [92]. Furthermore, a more powerful pumping arrangement with two 2.9-W, 450-nm pump diodes, was utilized to generate 5-nJ pulses [46]. Recent studies have also shown that, green AlInGaIn-based laser diodes can be used to excite Ti^{3+} :sapphire lasers with high efficiency near the conventional pumping wavelength of 532 nm [43, 44, 93]. In particular, frequency comb generation was demonstrated with a femtosecond Ti^{3+} :sapphire laser which was diode pumped at 520 nm and generated pulse energies as high as 1.16 nJ [93]. A thorough literature review is provided below in Table 1.

Table 2.1 Literature review of directly diode pumped Ti^{3+} :sapphire lasers.

λ_{pump} (nm)	P_{pump} (W)	Mode	P_{avg} (mW)	E_{pulse} (nJ)	τ_p (fs)	Reference
452	1	CW	19	-	-	[37]
452	1	SBR	13	0.1	142	[38]
445	2×1	KLM	34	-	15	[39]
452 454	2×1	SBR	101	0.8	111	[40]
445	2×2	KLM	105 70	1 0.7	50 15	[94]
518	1	SESAM	23.5	0.25	62	[43]
520	2×1.5	KLM	450	1.1	58	[44]
450	2×2.9	SESAM	460 350	5 3.8	82 65	[46]
465	4	KLM	173 145	2.2 1.9	15 13	[92]
520	1	KLM	30	5.1	95	Study in this thesis

In this chapter of the thesis, the description of the operation of an extended-cavity Ti^{3+} :sapphire laser, directly diode-pumped at 520 nm with one, 1-W AlInGaN diode is given. With 880 mW of incident pump power, as high as 90 mW of output power was obtained from the short cavity during cw operation. After adding a q-preserving multipass cavity and GTI mirrors for dispersion control, Kerr-lens mode-locked operation of the laser was initiated and 95-fs pulses at 776 nm with a pulse repetition rate of 5.78 MHz were obtained. The resulting energy and peak power of the pulses were 5.1 nJ and 53 kW, respectively. According to literature, this represents the highest pulse energy directly obtained from a mode-locked, single-diode-pumped Ti^{3+} :sapphire laser to date.

2.2 Experimental

Figure 2.1 shows the experimental arrangement of the single-diode-pumped, x-cavity Ti^{3+} :sapphire laser. In the experiments, a Brewster-cut, 2.3-mm-long Ti^{3+} :sapphire crystal with a figure of merit of 51 was used as the gain medium. The crystal was wrapped in indium foil and held inside a copper holder which was maintained at 22°C by water cooling. Initially, a standard x-cavity was built and end pumped with a single, 1-W, 520-nm diode laser (Nichia NDG7K75T). The output beam of the green diode laser had different beam parameters for slow and fast axes. In particular, the divergence angle of the fast axis (46.7°) was about 4 times larger than that for the slow axis (11°). In order to couple the pump beam into the crystal, an aspheric collimating lens (L1, $f=4$ mm), a telescope with a magnification of 4 (L2 with $f=25$ mm and L3 with $f=100$ mm) and an input focusing lens (L4, $f=50$ mm) were used. Here, L2 and L3 were cylindrical lenses, providing magnification only for the slow axis. A half-wave plate (HWP) together with a polarizing beam splitter (PBS) were used in order to vary the input pump power while keeping the diode current constant. The short x-cavity consisted of a pair of curved high reflectors (C1 and C2, each with group delay dispersion (GDD) $= -50$ fs² and $R=50$ mm), a flat end high reflector (HR) and an output coupler (OC) with 3% transmission.

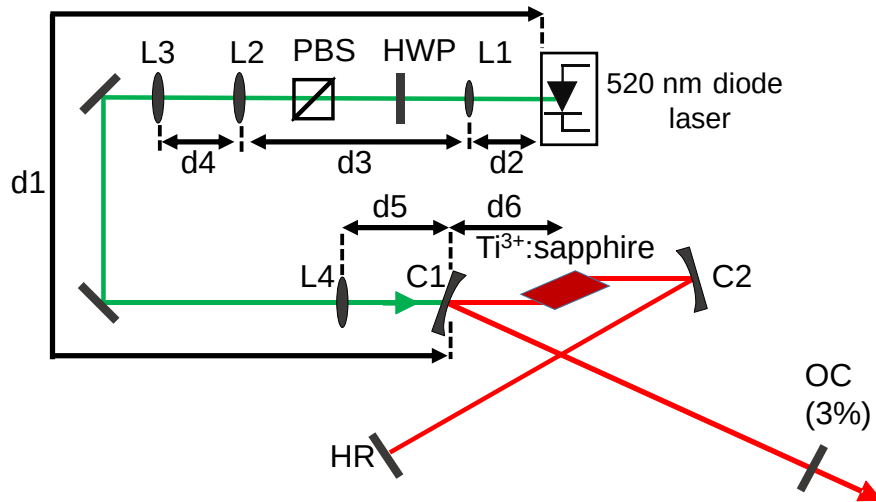


Figure 2.1 Experimental setup of the single diode-pumped, x-cavity, Ti^{3+} :sapphire laser.

To determine an efficient pumping geometry, first an approximate beam propagation algorithm, based on the standard ABCD matrix method, was used and applied to each axis of

the diode beam separately. The M^2 parameters for the slow and fast axes of the diode beam were taken as 5.5 and 2.5, respectively. This algorithm was used to determine the telescope position (d_3 in Figure 2.1) and the telescope lens separation (d_4 in Figure 2.1), which minimize the root-mean-squared (rms) spotsize inside the Ti^{3+} :sapphire crystal. Here, the values of d_1 , d_2 , and d_6 were kept fixed at 120 cm, 4.5 mm, and 2.5 cm, respectively. The input lens (L_4) position d_5 was varied to bring the waist location to the center of the crystal for the fast axis. For this position of L_4 , the optimum values of d_3 and d_4 which minimize the rms spotsize were determined while keeping the waist location of the slow axis at the center of the crystal. The optimum values of d_3 and d_4 were determined to be 30 cm and 12.6 cm, respectively. In the experimental setup, the position of the lens L_2 was kept fixed at the calculated value. In order to refine the optimum positions of L_1 and L_3 , d_2 and d_4 were varied in order to maximize the fluorescence power at the position of the output coupler (OC). For each relative value of d_2 , the fluorescence power was measured as a function of d_4 . Figure 2.2 shows the measured fluorescence power as a function of the telescope separation (d_4) and the relative position of collimating lens (L_1). The highest measured fluorescence power was obtained at the d_4 value of around 12.5 cm, in good agreement with the modelling. In the experiments the best power performance was also obtained at this pumping geometry.

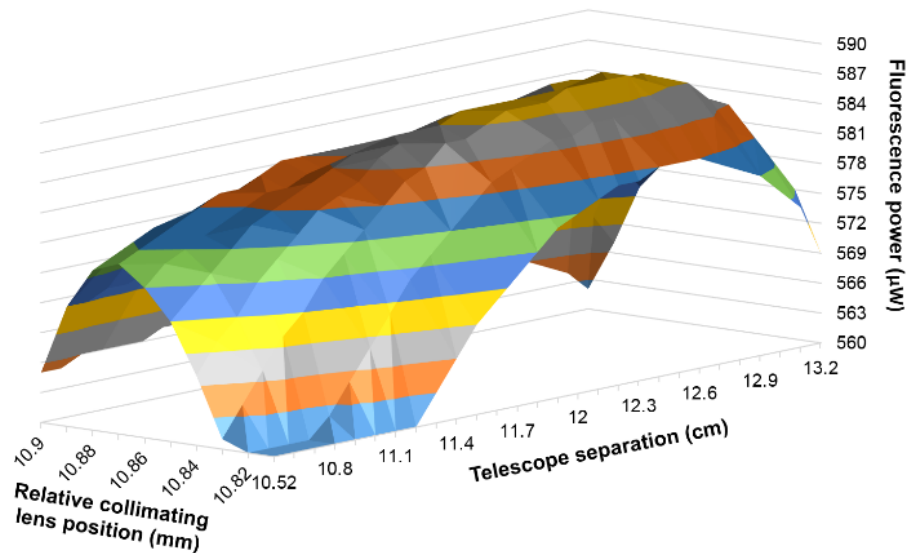


Figure 2.2 Variation of the fluorescence power measured on the output coupler arm as a function of the telescope lens separation (d_4 in Figure 2.1) and the relative position of the aspheric collimating lens.

After optimizing the power performance of the short x-cavity, a q-preserving multipass cavity (MPC) extension was added to reduce the pulse repetition rate [68]. The MPC extension is consisted of a curved (M3, $R=2000$ mm) and a flat (M4) high reflector, each with a rectangular notch to enable the injection and the extraction of the circulating beam. The flat-curved MPC becomes q-preserving at the specific values of the mirror separation d_{MPC} given by

$$d_{\text{MPC}} = \frac{R}{2} \left(1 - \cos \left(\frac{m\pi}{n} \right) \right), \quad (2.1)$$

where R is the radius of curvature of the curved MPC mirror, n is the number of roundtrips, and m is the number of semicircular arcs completed by the circulating beam [68]. In our specific MPC design m and n were chosen as 6 and 11, giving a mirror separation of 114 cm. Finally, to make the MPC configuration q-preserving, the missing roundtrip due to the notches was compensated by using a curved retro-reflector (C3, $R=1000$ mm) at a distance of 114 cm from M4. The total round-trip optical path length of the composite cavity was 51.9 m, corresponding to a pulse repetition frequency of 5.78 MHz. The schematic representation of the diode pumped MPC Ti^{3+} :sapphire laser is given in Figure 2.3.

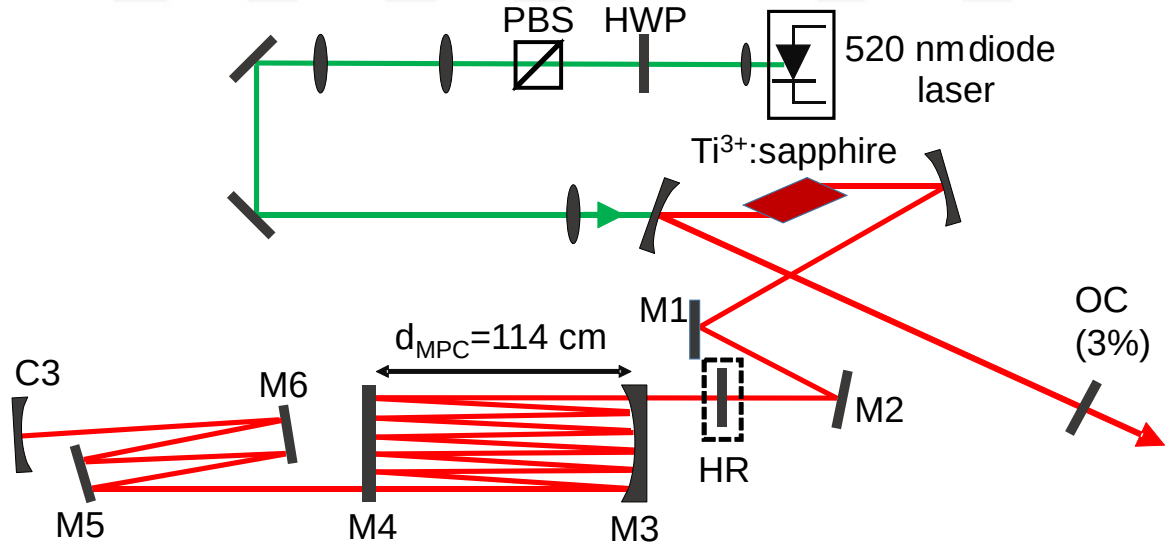


Figure 2.3 Experimental setup of the green-diode-pumped KLM MPC Ti^{3+} :sapphire laser.

The extended cavity contained two flat steering mirrors (M1 with $\text{GDD} = -60 \text{ fs}^2$ and M2 with $\text{GDD} = -45 \text{ fs}^2$ per bounce) before M3. Two additional flat GTI mirrors (M5 and M6, each with

GDD=-500 fs² per bounce) were also included in the cavity to provide additional negative dispersion to support solitary pulses. Two different configurations of the extended cavity were constructed with the same MPC design but with different number of GTI bounces to investigate different mode-locking operating points. The first configuration (not shown in Figure 2.3) had six GTI bounces per roundtrip, giving a total roundtrip GDD of -2100 fs². The second configuration (shown in Figure 2.3) contained 8 GTI bounces with a net roundtrip GDD of -3100 fs².

2.3 Results and Discussion

Power efficiency measurements were performed for both the short x-cavity and the extended resonator containing the MPC. For the x-cavity, the power efficiency measurements were done with 3 and 6% output coupler transmissions. The power efficiency measurements for two different OC transmission with loss estimation is given in Figure 2.4a and b. As shown in Figure 2.4a, the short cavity produced a maximum output power of 90 mW at 780 nm during cw operation with 880 mW of incident pump power (measured before L4). The measured power slope efficiency was 15%. In addition, by measuring the threshold pump power of the short cavity for output couplers with different transmission (0%, 3%, and 6%), the roundtrip loss was determined to be 1.8%. With the 3% output coupler the incident threshold pump power increased from 250 mW to 380 mW when the cavity was extended. The resulting roundtrip loss due to the cavity extension (MPC, steering mirrors, and GTI mirrors) was estimated to be 2.5%. At the maximum incident pump power of 860 mW, the extended cavity produced 44 mW of output power with a power efficiency of 9%. The comparison of the efficiency curves of x-cavity and MPC is given in Figure 2.4c.

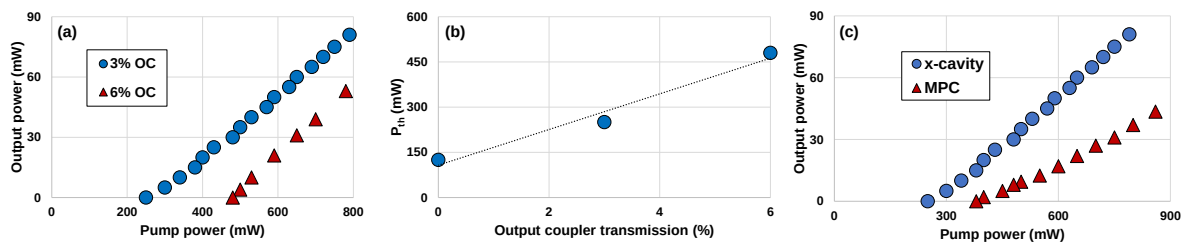


Figure 2.4 Continuous-wave power efficiency data for the (a) short x-cavity for 3% and 6 % output coupler transmission, (b) cavity loss estimation and (c) power efficiency of the extended cavity containing the MPC in comparison with x-cavity.

In the mode locking experiments, cavity focusing around the gain crystal was optimized and the output coupler mirror was translated to generate a stable mode-locked pulse train. In order to characterize the mode-locked operation of the cavity, the interferometric autocorrelation, optical spectrum, pulse train, and the RF spectrum of the generated pulses were measured. During the initial experiments, the first extended cavity configuration with six GTI bounces per roundtrip was used. The interferometric autocorrelation measurement yielding 106-fs pulses by the assumption of sech^2 pulse profile and the corresponding optical spectrum are shown in Figure 2.5a and b. The pulse train of the obtained pulses with a 172.4 ns period is shown in Figure 2.5c. The RF measurements resulted the contrast against the noise floor as 63 dB at the fundamental beat note of 5.8 MHz as given in Figure 2.5d. In summary, with 750 mW of incident pump power, 4.1-nJ, 106-fs pulses were generated at 778 nm [95].

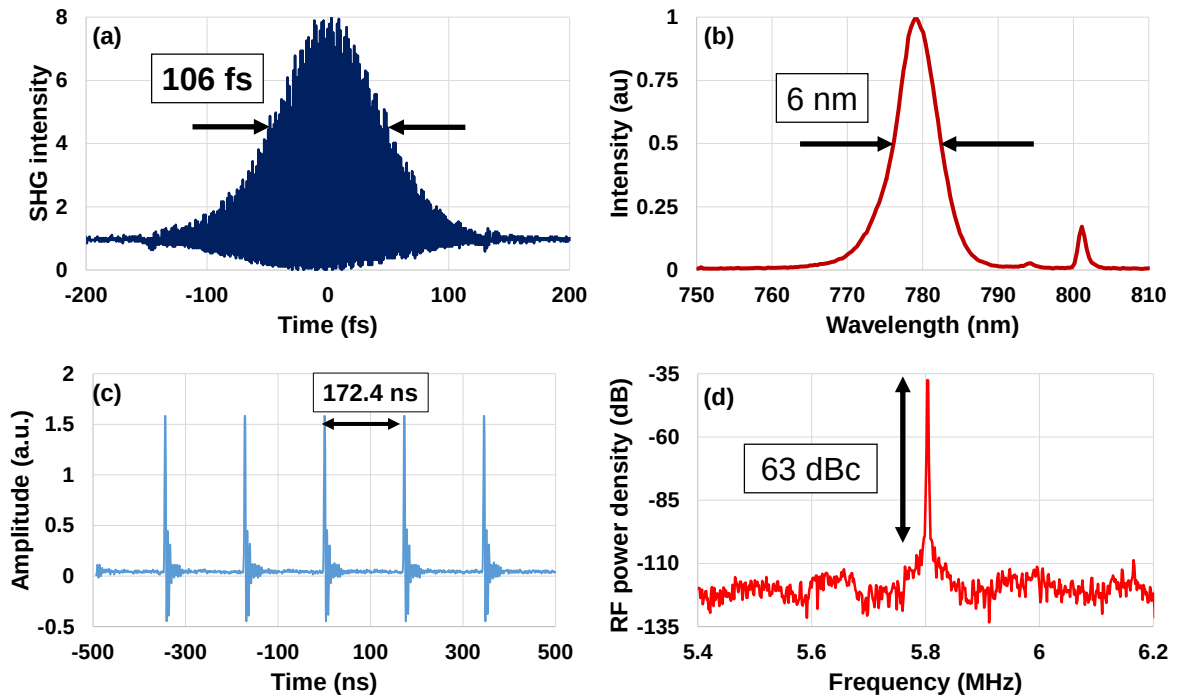


Figure 2.5 Measured interferometric autocorrelation (a), mode-locked optical spectrum (b), pulse train (c), and RF spectrum (d) for the characterization of the 4-nJ pulses of the green-diode-pumped KLM MPC Ti^{3+} :sapphire laser.

To obtain further energy scaling, the diode pump power was increased to 860 mW and the second extended cavity configuration with eight GTI bounces was used. Figure 2.6 and Figure 2.7 show the spectral and temporal characteristics of the pulses obtained at the highest achievable pulse energy. The interferometric autocorrelation trace of the pulses is shown in Figure 2.6a. By assuming a sech^2 intensity profile, the pulse duration (full width at half maximum, FWHM) was determined to be 95 fs. The corresponding optical spectrum shown in Figure 2.6b had a width (FWHM) of 7.5 nm, giving a time bandwidth product of 0.355. This is in good agreement with the theoretical value of 0.315 for sech^2 pulses.

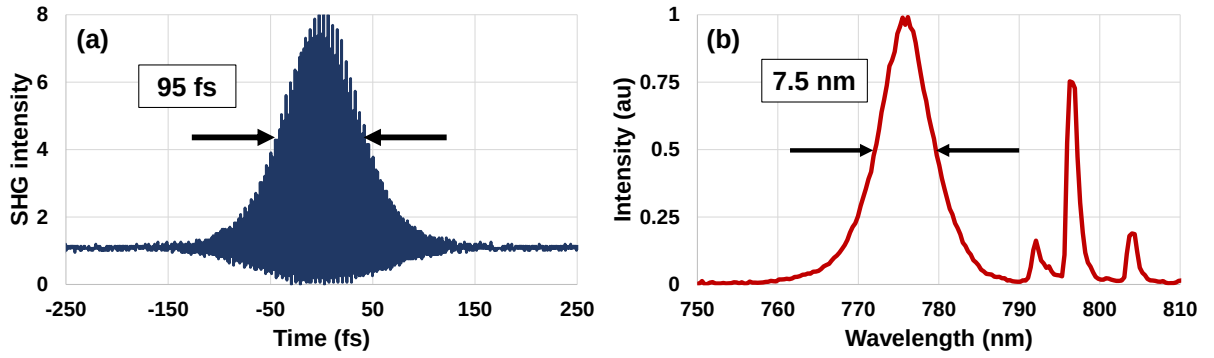


Figure 2.6 (a) Measured interferometric autocorrelation and (b) optical spectrum of the pulses generated with the green-diode-pumped Kerr-lens mode-locked MPC Ti^{3+} :sapphire laser.

Figure 2.7a shows the pulse train of the KLM MPC Ti^{3+} :sapphire laser. The period of the pulse train was 173 ns, corresponding to a pulse repetition frequency of 5.78 MHz. A further note is that there is no Q-switching instabilities were observed at longer time scales. The RF measurements indicated that the fundamental beat note at 5.78 MHz was 72 dBc above the noise level as can be seen in Figure 2.7b. At the pump power of 860 mW, a maximum output power of 30 mW was obtained during mode-locked operation, corresponding to 5.1 nJ of pulse energy and 53 kW of peak power.

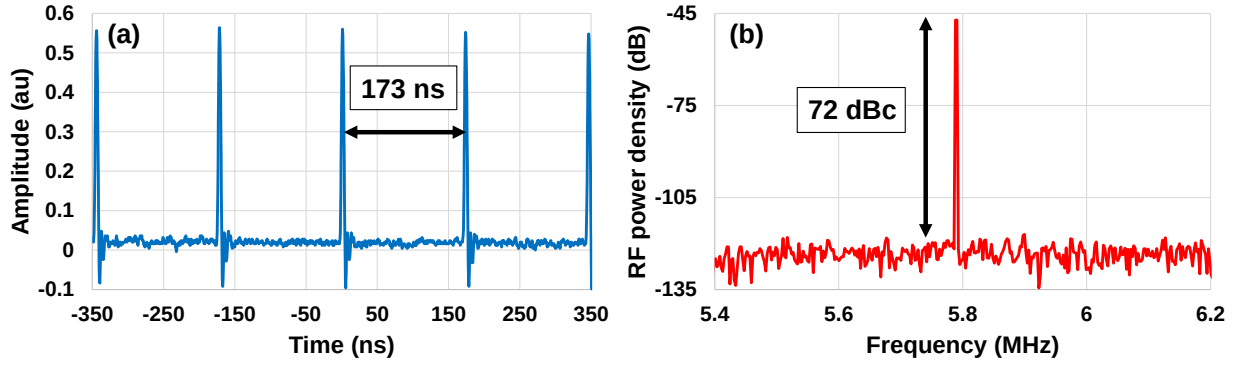


Figure 2.7 (a) Pulse train and (b) radio frequency (RF) spectrum of the pulses generated with the diode-pumped Kerr-lens mode-locked MPC Ti³⁺:sapphire laser. At the pulse repetition rate of 5.78 MHz, the fundamental beat note was 72 dBc above the noise level.

By using the operating parameters of the mode-locked MPC Ti³⁺:sapphire laser, the roundtrip GDD (D) needed to support 5.1-nJ, 95-fs pulses was estimated from [96, 97]

$$W = \frac{4|D|}{\delta\tau}, \quad (2.2)$$

where W is the intracavity pulse energy, δ is the Kerr nonlinearity coefficient, and $\tau = \tau_p/1.76$ (τ_p = FWHM pulse duration). Here, δ is given by

$$\delta = \frac{2\pi}{\lambda} \frac{2n_2 L}{A_{eff}}, \quad (2.3)$$

where n_2 is the nonlinear refractive index, L is the length of the medium, and A_{eff} ($A_{eff} = \pi w_{rms}^2$, w_{rms} = rms spotsize inside the Kerr medium, n_0 = refractive index of the medium) is the effective cross-sectional area of the beam inside the Kerr medium. From the ABCD matrix analysis of the cavity, w_{rms} was estimated to be 17 μm . By using the output parameters of the mode-locked MPC Ti³⁺:sapphire laser ($W=173$ nJ, $\tau_p = 95$ fs) and by taking n_2 and L as 3.2×10^{-20} m²/W [84] and 2.3 mm, D was calculated from soliton-area theorem as -2912 fs² which is close to the estimated value of -3100 fs².

2.4 Summary

In conclusion, nearly transform limited 95-fs pulses with 30 mW of mode-locked output power, corresponding to 5.1 nJ of pulse energy and 53 kW of peak power at 776 nm from a single diode-pumped multipass-cavity Kerr-Lens mode-locked Ti³⁺:sapphire laser were

generated. According to the literature, this represents the highest pulse energy directly generated from a Ti^{3+} :sapphire laser by using a single 1W pump diode to date. Based on the observation, further energy scaling should be possible by using more powerful pump diodes. Furthermore, with better distribution of the negative dispersion coming from all mirrors instead of just the GTI mirrors, will provide shorter pulses due to the lack of bandwidth limitations caused by the GTI mirrors. The studies explained in this chapter were accepted as an oral presentation at Advanced Solid State Lasers Conference and published in Laser Physics letters [47, 95].



Chapter 3

3 Continuous wave and Graphene Mode-locked $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ Laser

†This chapter is adapted with permission from [66] and [123] © The Optical Society.

3.1 Introduction

In addition to the widely explored 2 μm transition of the Tm^{3+} ion, another long-known and important laser transition occurs near 2.3 μm between the $^3\text{H}_4$ and $^3\text{H}_5$ levels, following excitation near 800 nm. By using readily available 800 nm diodes, 2.3 μm thulium lasers can be built in various regimes of operation for many potential applications in the mid-infrared (mid- IR), including vibrational spectroscopy [98], x-ray/high harmonic generation [99], and atmospheric gas sensing [100]. In addition, the fourth biological window covering the spectral region from 2100 to 2300 nm [101] can benefit from 2.3 μm lasers in various biomedical applications, such as blood glucose level measurement [102]. Another attractive potential application of pulsed 2.3 μm lasers involves the pumping of long-wavelength ZnGeP_2 (ZGP) type optical parametric converters, since the absorption of ZGP drops sharply above 2.1 μm [103]. Previous studies focused on the spectroscopic characterization of the 2.3 μm emission in different Tm crystalline hosts including YAG [59, 60], YAlO_3 [59, 104], LuAG [60, 105, 106], and LiYF_4 [60, 107-109], and various regimes of laser operation were investigated [62, 110-116]. Upconversion pumping has been further shown to generate efficient laser output in $\text{Tm}^{3+}:\text{YLF}$ with pump wavelengths above 800 nm [63, 117]. Among potential hosts for 2.3 μm thulium lasers, crystals belonging to the fluoride family were shown to possess numerous attractive features. In particular, the maximum phonon energy of the fluoride hosts is considerably lower than those in oxides, reducing the strength of unwanted nonradiative decay processes and extending the transparency range of the host into the mid-IR region. In comparison with other low phonon energy hosts like chlorides, bromides, and sulfides, fluorides further exhibit better thermal and chemical properties [61]. In the particular case of $\text{Tm}^{3+}:\text{YLF}$, broad, smooth tuning could be demonstrated in the 2200–2460 nm wavelength range, during continuous-wave (cw) operation [107], further underlying the importance of this class of gain media for mid-IR femtosecond pulse generation. Recent experiments further demonstrated passively Q-switched and mode-locked operation of 2.3 μm $\text{Tm}^{3+}:\text{YLF}$ lasers, resulting in the generation of pulses as short as 514 fs at 2303 nm [62, 116]. An alternative scheme for the initiation of pulsed operation involves the use of monolayer graphene, which

has been shown to operate as a mode locker and passive Q switch in lasers over an ultrabroad wavelength range from 750 to 2930 nm [73, 77], leading to the direct generation of ultrashort pulses as short as 19 fs [118]. Another potentially important member of the fluoride family is the cubic (optically isotropic) potassium yttrium fluoride (KY_3F_{10}) crystal, which has been investigated as a host for laser-active ions such as Pr^{3+} , Ho^{3+} , and Tm^{3+} [64, 119, 120]. In the case of Tm^{3+} doped KY_3F_{10} , only 1.85 μm lasing was reported up until this study [64]. With its potential of accommodating higher concentration of lanthanide ions compared with other fluoride crystals [121], the ordered $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ crystal is also promising for mid-IR lasing near 2.3 μm .

In this part of the chapter, the first-time lasing of $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ crystal together with the first time stable mode-locked operation of $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser near 2.3 μm by using a graphene saturable absorber (GSA) will be explained. A $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ crystal with 8 at.% thulium doping was end pumped with a narrow-linewidth, tunable, cw $\text{Ti}^{3+}:\text{sapphire}$ laser. By using 1 W of incident pump power, we obtained 31 and 122 mW of cw output power in single-end and double-end pumping configurations, respectively, with an output coupling of 1%. Excitation efficiencies were examined for pump wavelengths from 765 to 806 nm. Two major absorption peaks were determined at 773 and 778 nm, and two additional weaker bands were observed at 796 and 802 nm. Tunability of the laser over a bandwidth of 125 nm was demonstrated by use of a quartz birefringent tuning plate (BTP). Additionally, the lifetime of $^3\text{H}_4$ level was measured as 16 μs . Based on the lasing threshold data, the emission cross section (σ_e) was determined to be $(1.62 \pm 0.09) \times 10^{-24} \text{ m}^2$. Furthermore, with the addition of a cavity extension and double-end pumping to scale up the pulse energy, the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser delivered 739 fs pulses near 2340 nm at a repetition rate of 54 MHz, corresponding to 1.2 nJ of pulse energy and 1.6 kW of peak power.

3.2 Experimental

The schematic of the cw $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser with its $\text{Ti}^{3+}:\text{sapphire}$ pump source is given in Figure 3.1. The $\text{Ti}^{3+}:\text{sapphire}$ laser was built as a tunable and narrow-line laser source with a FWHM linewidth of 0.09 nm to enable efficient excitation of the Tm ions, which have narrow absorption bands. A 20-mm Brewster-cut $\text{Ti}^{3+}:\text{sapphire}$ crystal with a FOM > 280 was end pumped with a 5-W green pump laser (OPUS, MPC6000) through a converging lens (L1, $f=100\text{mm}$). The $\text{Ti}^{3+}:\text{sapphire}$ laser cavity was composed of two curved mirrors (C1 and C2, ROC=100 mm), two cascaded Brewster-cut SF14 prisms (P1 and P2), a flat high reflector

(HR1), and an output coupler with 15% transmission (OC1). The $\text{Ti}^{3+}:\text{sapphire}$ laser delivered up to 1 W of input power at 778 nm after the half-wave plate (HWP) and the polarizing beam splitter (PBS) combination, which was used to continuously vary the pump power. The pump beam was focused into the Brewster-cut, 2-mm-long, 8-at.-% Tm^{3+} -doped KY_3F_{10} crystal with a converging lens (L2, $f = 50$ mm). The estimated pump beam waist inside the crystal was $7 \mu\text{m}$. The single-pass pump absorption was 26%, 30%, 13%, and 18% at wavelengths of 773, 778, 796, and 802 nm respectively. The astigmatically compensated x-shaped cavity of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser consisted of 2 curved mirrors (C3 and C4, $\text{ROC}=50$ mm), a flat high reflector (HR2, shown in dashed rectangle in Figure 3.1), and an output coupler with 1% transmission (OC2). There was also a third curved mirror (C5, $\text{ROC}=75$ mm) after C4 to enable double pumping of the crystal. The length of the x-cavity was 152 cm. The reflectivity range of all high reflectors was above $2.2 \mu\text{m}$, so as to suppress the potential lasing of $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ at $1.9 \mu\text{m}$ due to the $^3\text{F}_4 \rightarrow ^3\text{H}_6$ transition.

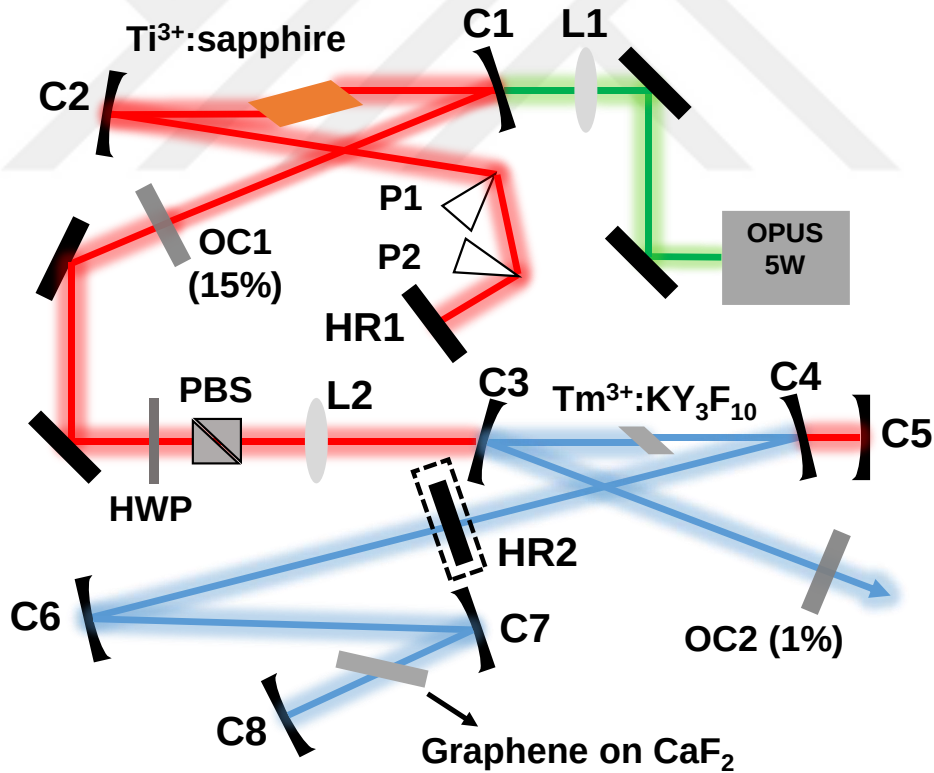


Figure 3.1 Schematic illustration of tunable, narrow-line $\text{Ti}^{3+}:\text{sapphire}$ pumped extended cavity of $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser. The mirror shown inside dashed rectangle represents the position of x-cavity HR mirror.

To increase the intracavity pulse energy during mode-locking experiments, the HR2 mirror is removed and this arm of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser resonator was extended. Shown in Figure 3.1, the mirror arrangements provided q -preserving extension [68] of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ lasers, as a result of which the beam parameters remained nearly the same inside the gain medium, as those of the short x cavity's. In the case of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser, the cavity extension included a large-radius curved mirror (C6, ROC=1 m) and an additional pair of small-radius curved mirrors (C7 and C8, ROC=75 mm). The total length of the mode-locked $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser was 2.77 m. The mirrors C7 and C8 were used to obtain an additional waist at the location of the GSA. The GSA was placed at Brewster incidence near the waist between C7 and C8. In the experiments, we used a monolayer GSA synthesized by chemical vapor deposition and transferred onto a 2-mm-thick CaF_2 substrate. The CaF_2 substrate had a high transparency near 2.3 μm and resulted stable mode-locking performance.

3.3 Results and Discussion

In the first part of the cw characterization, the excitation spectrum of the cw $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser was measured. The wavelength of the $\text{Ti}^{3+}:\text{sapphire}$ laser was varied with 1 nm increments, and for each pump wavelength, both the output power of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser and the $\text{Ti}^{3+}:\text{sapphire}$ laser were measured. In Figure 3.2a, the excitation spectrum of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser and the output power variation of the $\text{Ti}^{3+}:\text{sapphire}$ laser can be seen. There are two optimum pump bands with nearly equal pumping efficiency, centered near 773 and 778 nm. Overall, 2.3 μm lasing transition in $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ could be excited with pump wavelengths in the 765–806 nm range, with two additional but weaker pump bands centered near 796 and 802 nm. With respect to the optimum band at 778 nm, the pumping efficiencies of the 796 nm and 802 nm pumping were around 1/10 and 1/3, respectively. The measured excitation spectrum closely follows the absorption spectrum of the gain medium, shown in Figure 3.2b.

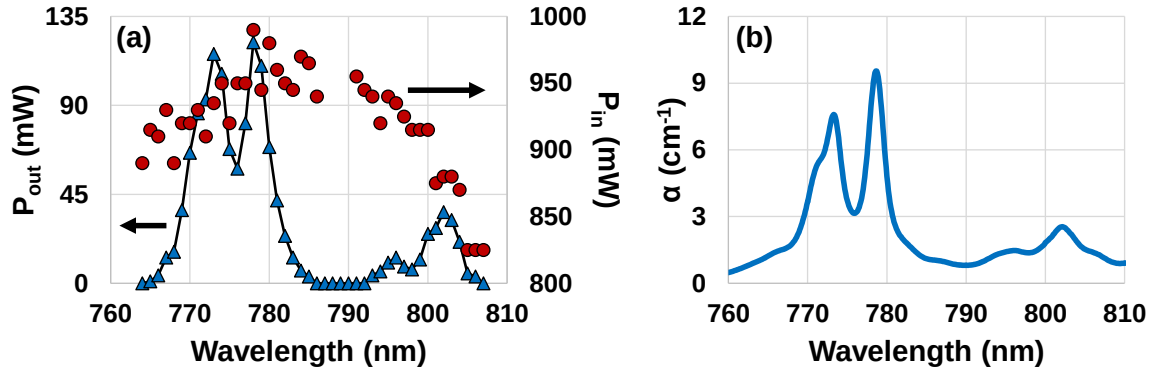


Figure 3.2 (a) Excitation spectrum of the $2.3 \mu\text{m}$ $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser (triangles) and the variation of the input pump power over the same wavelength range (circles). (b) Measured differential absorption coefficient of the 8 at.% $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ crystal.

In the second set of experiments, the tunability of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser was investigated near $2.3 \mu\text{m}$. Here, a 1.5-mm-long quartz BTP was inserted into the high reflector (HR2) arm of the x-cavity. The output coupler transmission was 1%. The output power of the laser was then measured as a function of the output wavelength at 5 nm intervals. The pump power at 778 nm was 990 mW. The resulting tuning curve can be seen in Figure 3.3. The maximum output power of 80 mW was obtained at 2345 nm, and lasing action could be obtained over a wavelength range of 125 nm from 2260 to 2385 nm.

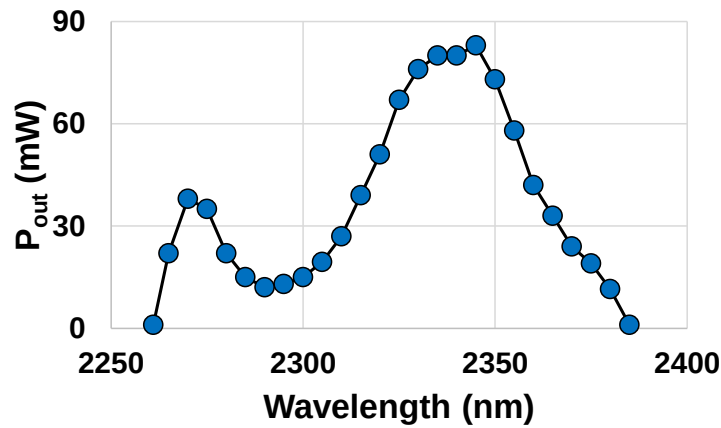


Figure 3.3 Tuning curve of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser around $2.3 \mu\text{m}$. The input pump power was 990 mW at 778 nm.

The third set of the experiments consisted of power efficiency measurements. With around 1W of input power, power efficiency curves were recorded for three different output coupler

transmissions of 1%, 2%, and 3% in both single-end and double-end pumping configurations. For the output coupler with 3% transmission, lasing could be obtained only with the double-end pumping configuration. In the double-end pumping regime, the incident threshold pump power was measured to be 340 mW, 470 mW, and 725 mW for the output coupler transmissions of 1%, 2%, and 3%, respectively (Figure 3.4d). By doing a linear least squares fitting to the experimental threshold data, the loss of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ crystal was estimated to be 0.65%, based on the Findlay–Clay analysis [27]. Power efficiency curves can be seen in Figure 3.4.a, b, and c. With 1% output coupler, the maximum laser output power was measured to be 31 mW in single-pumping configuration with 970 mW of input power. Double pumping resulted in as much as 122 mW of output power for the same output coupler. The power slope efficiencies for the single-end pumped and double-end pumped resonator were determined to be 6% and 18%, respectively. For the 2% output coupler, the single-end pumped cavity produced 7 mW output power with 5.5% power slope efficiency with 960 mW of input power. Here, the output power and power slope efficiency increased to 114 mW and 24% with the double-end pumping. Finally, 18% efficiency and 44 mW of output power were obtained with the 3% output coupler when the input power was 970 mW.

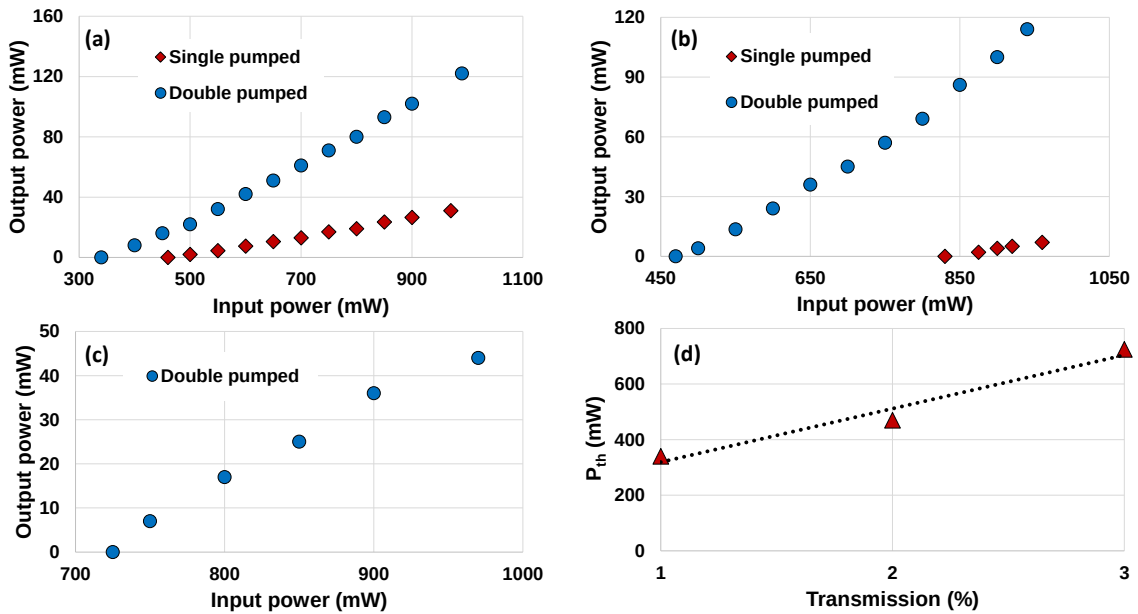


Figure 3.4 Continuous-wave efficiency curves of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser at 2343 nm with a (a) 1%, (b) 2%, and (c) 3% output coupler transmissions for both single-end pumping (diamonds) and double-end pumping (circles). (d) Measured incident threshold pump power as a function of the output coupler transmission in the double pumping regime.

To measure the fluorescence lifetime of the ³H₄ upper laser level, we used a photoluminescence spectrometer (FLS 1000, Edinburgh Instruments). The Tm³⁺:KY₃F₁₀ crystal was excited with a Xe flashlamp. We recorded the fluorescence decay of the ³H₄ level to the ground ³H₆ level with a photomultiplier tube. By making a single exponential fit to the measured data, the fluorescence lifetime was determined as 16 μs. Figure 3.5 shows the time-resolved decay of the ³H₄ level at the wavelength of 808 nm, following pulsed excitation with the Xe flashlamp at the wavelength of 685 nm to the higher lying ³F₂ and ³F₃ levels, with subsequent fast nonradiative relaxation to ³H₄.

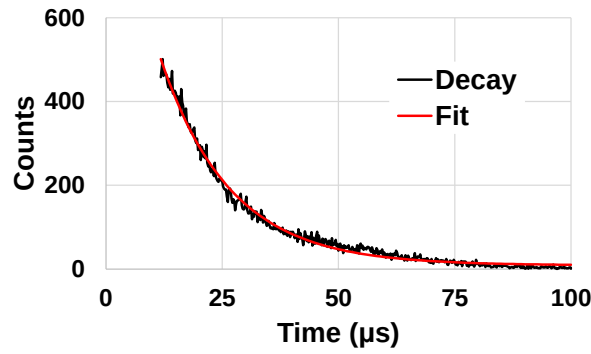


Figure 3.5 Measured room-temperature time-resolved fluorescence decay of the ³H₄ level for the 8 at. % Tm³⁺:KY₃F₁₀ crystal.

The lasing threshold and fluorescence lifetime ($\tau_f=16$ μs) data can be used to estimate the emission cross section (σ_e) of the Tm³⁺:KY₃F₁₀ gain medium at 2343 nm by using the equation

$$\sigma_e = \frac{\pi h \nu_p n (w_p^2 + w_l^2)}{4 P_{th} \tau_f \eta_p} (T + L). \quad (3.1)$$

In Equation 3.1, h is Planck's constant, w_p is the root-mean-squared (rms) pump beam spot size ($w_p=14$ μm), w_l is the rms laser spot size ($w_l=27.5$ μm), P_{th} is the incident threshold pump power, ν_p is the pump photon frequency ($\nu_p=364$ THz), η_p is the pump absorption (30%), and L accounts for the total round trip loss of the resonator [122]. By analyzing two of threshold data taken with two different output couplers, σ_e value was determined to be $(1.62 \pm 0.09) \times 10^{-24}$ m².

After the investigation of the cw power performance of Tm³⁺:KY₃F₁₀ laser, the experiments continued with mode locking trials. As given above, double-end pumping resulted in the generation of 122 mW of cw output power from the short-cavity Tm³⁺:KY₃F₁₀ laser using a

1% output coupler with 1 W of incident pump power at 778 nm. The output power of the extended $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser containing the additional mirrors and the GSA [see Figure 3.1] dropped to 64 mW. The insertion loss of the GSA on CaF_2 sample was determined in an earlier study to be 4.2% [75]. Reference [75] further provides additional information about the nonlinear optical properties of the GSA on the CaF_2 sample.

After the GSA was placed at the waist location of the extended cavity, mode locking could be initiated by translating the output coupler. In the mode-locking experiments of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser a GSA transferred onto CaF_2 was used. Stable mode-locked operation required purging of the extended cavity with dry N_2 to keep the relative humidity below 20%. The mode-locked output power of 64 mW was obtained at 2340 nm, with 1W of incident pump power during double-end pumping. Figure 3.6a shows the interferometric autocorrelation trace of the generated pulses, where the FWHM pulse duration was determined to be 739 fs by assuming a sech^2 profile. The mode-locked spectrum shown in Figure 3.6b had a FWHM of 9.6 nm, giving a time-bandwidth product of 0.39. The spikes appearing in the mode-locked spectrum displayed in Figure 3.6b are due to the residual absorption in the atmosphere and coincide with the atmospheric absorption lines shown in Figure 3.6d. Figures 3.6c and 3.6e show the radio frequency (RF) spectrum and pulse train of the generated pulses from the graphene mode-locked $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser. The RF spectrum shows that the fundamental tone of the resonator at the repetition frequency of 54 MHz was at least 67 dB above the noise floor. The pulse train was measured with a fast, extended-range InGaAs detector. At longer timescales, no Q-switching instabilities were observed as can be seen in Figure 3.6f. All mode-locking data shown in Figure 3.6 were recorded at the incident pump power of 1 W. The corresponding pulse energy and peak power were 1.2 nJ and 1.6 kW, respectively.

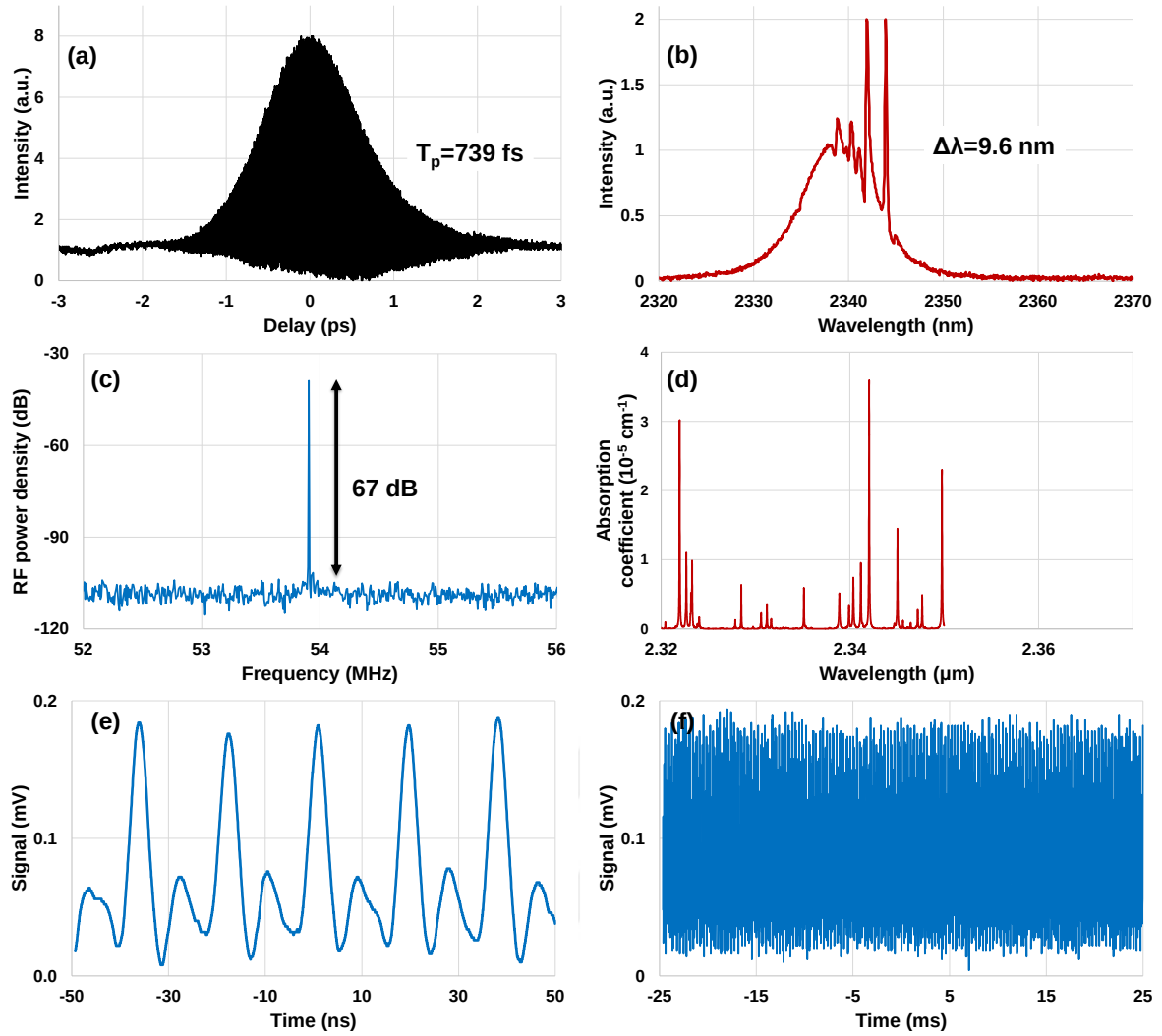


Figure 3.6 Measured (a) interferometric autocorrelation trace and (b) optical spectrum of the pulses generated with the graphene mode-locked $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser at 2340 nm. (c) Measured RF spectrum of the graphene mode-locked $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$. (d) Atmospheric absorption lines in the 2280–2350 nm wavelength range for the relative humidity level of 50%. Measured pulse train of mode locked $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser at 2340 nm for short (e) and long (f) time scales.

3.4 Summary

In conclusion, the first-time lasing and GSA mode-locked operation of a $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser near 2.3 μm was demonstrated. With the available pump power of 1 W, as high as 122 mW of cw output power was obtained. In the excitation spectrum measurements of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ crystal, four excitation bands were identified with the two strongest bands being centered near 773 and 778 nm. Wavelength-tunability measurements with a BTP gave a tuning range of

125 nm. We also measured the lifetime of the $^3\text{H}_4$ level and determined the emission cross section of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ gain medium as $(1.62 \pm 0.09) \times 10^{-24} \text{ m}^2$. With the broad tuning bandwidth of 125 nm, the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser has the potential to become a versatile ultrafast laser source in the mid-IR range if the humidity problem was properly addressed.

In pulsed operation characterization of $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$, the laser was double-end pumped with a cw $\text{Ti}^{3+}:\text{sapphire}$ laser near 780 nm. With 1 W of pump power, the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser generated 739 fs pulses at a pulse repetition rate of 54 MHz. As high as 64 mW of average output power was obtained from the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ lasers at the maximum available pump power. This corresponds to output pulse energy of 1.2 nJ for the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser. The challenge with the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser was the need to purge the extended cavity to reduce the atmospheric absorption lines that coincided with the pulse spectrum. This may cause challenges in building longer cavities for pulse energy scaling or in obtaining shorter pulses. The experimental results regarding the cw and GSA mode-locked operation of $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser explained in this chapter were accepted as a poster presentation in Advanced Solid State Lasers Conference and published as two separate journal articles in Optics Letters [66, 123, 124].

Chapter 4

4 Tunable continuous-wave laser operation of $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ near 2.3 μm

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4.1 Introduction

Following optical excitation to the $^3\text{H}_4$ level, the trivalent thulium (Tm^{3+})-doped active media exhibit two broadly tunable laser emission bands centered near 2 and 2.3 μm . Both laser emissions fall within the mid-infrared range and can be used in many potential applications including blood glucose measurements [102], spectroscopy [98], and coherent high harmonic generation [99], among others. In the particular case of the 2.3- μm Tm^{3+} lasers, developments have recently taken place in search of new host materials as well as investigation of pulsed regimes of operation and upconversion pumping schemes. Recently reported hosts for 2.3- μm Tm^{3+} lasers include YAP [125], KY_3F_{10} [123, 126], and tellurite glass [127, 128]. Efficient excitation of the $^3\text{H}_4$ level based on upconversion energy transfer mechanisms has been demonstrated in YLiF_4 (YLF) [63, 117] and KY_3F_{10} [126, 129] crystals. Furthermore, different regimes of pulsed operation, including passive Q switching [116], saturable absorber mode locking [66, 130], and Kerr lens mode locking [62] were employed to generate pulses in the microsecond and sub-picosecond time scales.

Among potential fluoride hosts for 2.3- μm Tm^{3+} lasers, the long-known monoclinic crystal BaY_2F_8 possesses numerous favorable spectroscopic characteristics, including a wide transparency range from 200 nm up to the long-wavelength absorption edge near 9 μm and a low phonon energy of less than 400 cm^{-1} [131]. These features can enable low-loss lasing in the mid-infrared and reduce the strength of unwanted multi-photon non-radiative decay processes. In fact, the BaY_2F_8 crystal has been successfully employed as a host for 2- μm Tm^{3+} lasers, where broadly tunable continuous-wave and pulsed laser operation were reported in numerous studies [132-135].

In this chapter of the thesis, the first time tunable laser operation of the 3 at.% $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ crystal near 2.3 μm will be explained. A narrow-linewidth, tunable $\text{Ti}^{3+}:\text{sapphire}$ laser was used to measure the excitation spectra for E//x and E//y pumping in the 760–810 nm range, as well as the absorption saturation, power efficiency, tuning, and lasing threshold data. Fluorescence decay curves of the $^3\text{F}_4$ and $^3\text{H}_4$ levels were further measured. Absorption

saturation and lasing threshold data were used along with the lifetime data to determine the absorption and stimulated emission cross sections. Double-end, E//x pumping at 779 nm yielded 100 mW of output power at 2290 nm with 920 mW of incident pump power.

4.2 Experimental

A schematic of the tunable, continuous-wave 2.3- μm $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ laser is shown in Figure 4.1. A homemade, tunable $\text{Ti}^{3+}:\text{sapphire}$ pump laser with an M^2 close to one was employed to end pump the x-configured $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ resonator. The linewidth of the pump laser was maintained below 0.09 nm to have good spectral overlap with the narrow absorption bands of the Tm^{3+} ion in the 760–790 nm range. The detailed layout and operating parameters of the $\text{Ti}^{3+}:\text{sapphire}$ laser can be found in the previous chapter. In the experiments, the $\text{Ti}^{3+}:\text{sapphire}$ pump laser was operated at maximum output power, and the incident power before the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ crystal could be continuously varied by using a half-wave plate (HWP in Figure 4.1) and a polarizing beam splitter (PBS). Up to a maximum incident pump power of 920 mW was available at 779 nm after the PBS. A converging lens (L2, $f=50$ mm) was used to focus the pump beam to an estimated waist size of $9\ \mu\text{m} \times 13.5\ \mu\text{m}$ inside the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ crystal. The BaY_2F_8 crystal was a rectangular piece with dimensions of $6\ \text{mm} \times 5.8\ \text{mm} \times 4\ \text{mm}$, oriented along the x, y, and z axes, respectively, and was doped with 3 at. % Tm^{3+} , corresponding to an effective Tm^{3+} ion concentration of $N_T = 3.82 \times 10^{26}\ \text{m}^{-3}$. The Tm^{3+} doped BaY_2F_8 single crystal was grown by employing the Czochralski method as described in detail in Ref. [134]. The x-shaped $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ cavity had a total length of 152 cm and included a flat end high reflector (HR), a flat output coupler (OC), and a pair of highly reflecting curved mirrors (C3 and C4, radius of curvature $\text{ROC}=50\text{mm}$). Each cavity arm was folded by approximately 10 degrees. A third highly reflecting curved mirror (C5, $\text{ROC}=75\text{mm}$) was used to allow double-end pumping of the Brewster oriented Tm^{3+} doped BaY_2F_8 crystal and to increase total pump absorption. Since the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ medium can also produce laser radiation near 2 μm due to stimulated emission between the $^3\text{F}_4$ and $^3\text{H}_6$ levels, the cavity mirrors C3, C4, and HR had a high reflectivity coating above 2.2 μm to prevent 2- μm lasing of the gain medium.

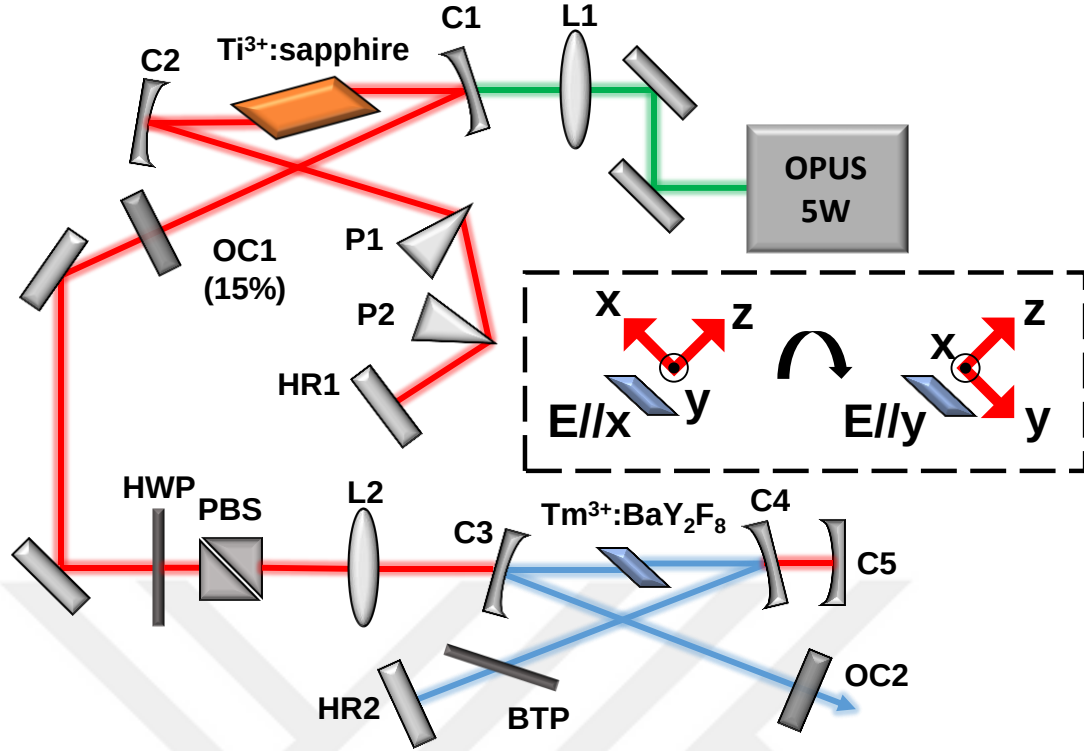


Figure 4.1 Schematic of the continuous-wave 2.3- μm $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ laser and the crystal orientations during E//x and E//y pumping together with tunable, narrow-linewidth $\text{Ti}^{3+}:\text{sapphire}$ pump laser.

4.3 Results and discussion

In the experiments, lasing was obtained near 2.3 μm for both E//x and E//y pumping orientations (see insets in Figure 4.1). Here, E//x (E//y) pumping refers to the case where the crystal y (x) axis is perpendicular to the plane of incidence containing the pump electric field and the crystal x (y) axis. To go from E//y to E//x pumping, the crystal was rotated by 90 degrees. In the first set of measurements, the excitation spectrum was recorded for both E//x and E//y orientations to determine the optimum pumping wavelengths. For both cases, the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ laser was operated at the free running wavelength of 2290 nm without the intracavity birefringent tuning plate (BTP in Figure 4.1) and the variation in the cw output power was measured as a function of the pump wavelength. The OC had a transmission of 1%. Here, the pump wavelength was varied in steps of 1 nm and the incident pump power was also recorded at each pump wavelength. Double-end pumping was further employed for both pumping configurations. Figure 4.2a shows the measured excitation spectrum for E//y pumping configuration and the variation in the pump power between 760 and 790 nm. The

two optimum pump bands at 777 and 788 nm were measured to be equally efficient. The excitation spectrum for E//y pumping was in qualitative agreement with the absorption spectrum of the crystal shown in Figure 4.2c. Similarly, the measured excitation spectrum and the pump power variation for E//x are shown in Figure 4.2b. Again, the excitation spectrum agrees well with the absorption spectrum in Figure 4.2d.

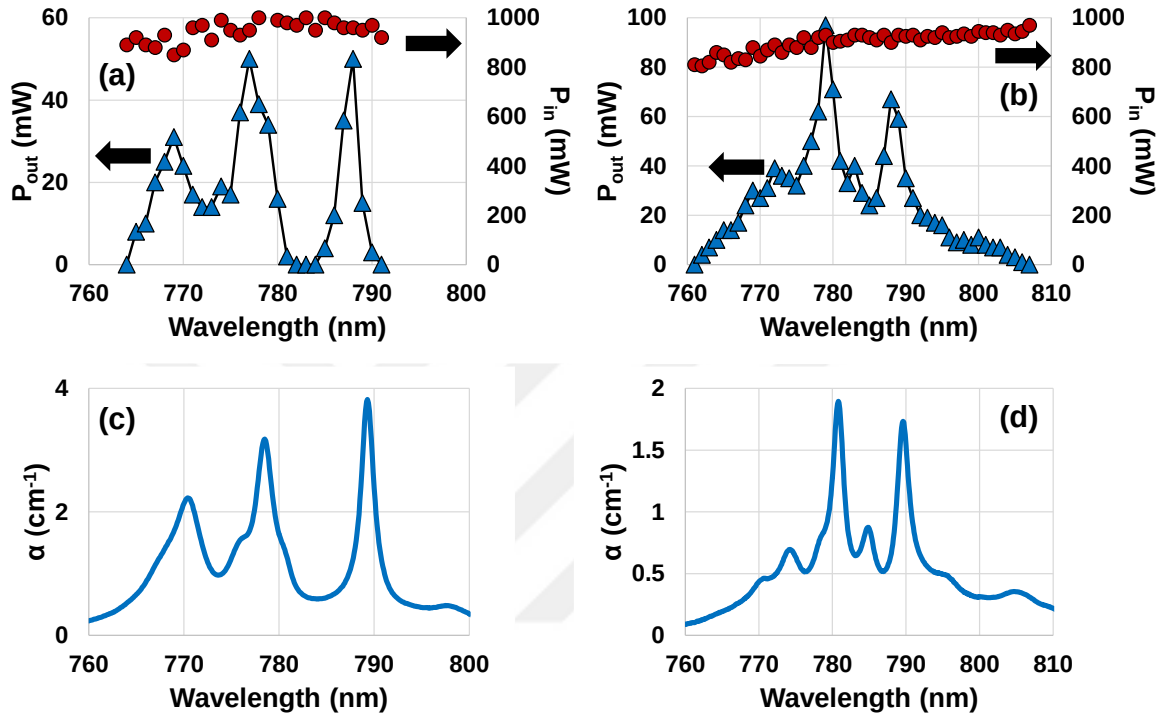


Figure 4.2 Measured excitation spectrum of the $2.3\text{-}\mu\text{m}$ $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ laser (triangles) for (a) E//y and (b) E//x pumping configuration and corresponding variation of the input pump power over the same wavelength range (circles). Measured small-signal absorption coefficient of the 3 at.% $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ crystal for (c) E//y and (d) E//x orientation.

Among the excitation cases considered, the most efficient pump wavelength was determined to be at 779 nm for E//x pumping. There is a second, somewhat weaker pump line at 788 nm, again for E//x (see Figure 4.2b). Overall, better power efficiency was obtained for the case of E//x pumping despite the fact that the small-signal absorption coefficient was higher for E//y [see Figures 4.2c and 4.2d]. This was mainly because the effective pump absorption was lower for E//y due to a larger amount of absorption saturation at the pumping intensities used in this experiment. The remaining power characterization experiments were therefore conducted for the E//x pumping configuration.

Tunability of the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ laser was next explored near $2.3\ \mu\text{m}$ by using the 1% OC and the E//x double-end pumping configuration. Here, a 2.6-mm-long quartz BTP was inserted into the HR arm of the x-cavity at Brewster incidence. The output wavelength of the laser was varied in 5-nm increments, and the corresponding output power was measured. The input pump power was 920 mW at 779 nm. The measured tuning curve is displayed in Figure 4.3. The highest output power of 53 mW was obtained at 2290 nm. The laser was continuously tunable from 2233 to 2385 nm.

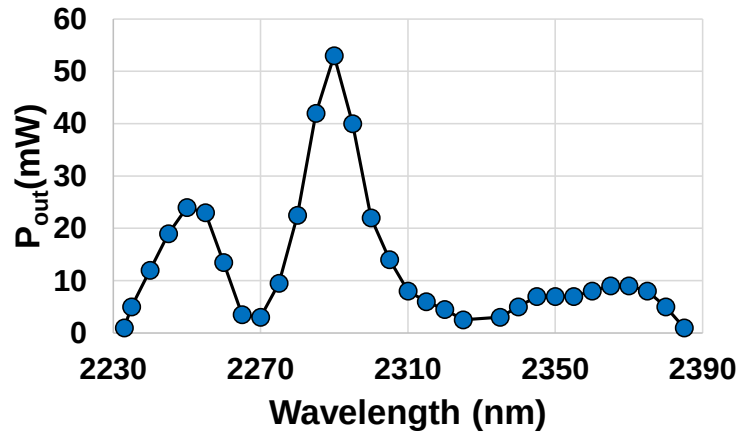


Figure 4.3 Measured variation of the output power of the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ laser as a function of the output wavelength near $2.3\ \mu\text{m}$. The input pump power is 920 mW at 779 nm.

Prior to the cw efficiency measurements, the absorption saturation behavior of the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ medium was investigated for E//x pumping. The pump beam waist location was adjusted to maximize the crystal transmission, and the variation of the crystal transmission was measured as a function of the input power at 779 nm as shown in Figure 4.4. A thin-length absorption saturation model was then used to obtain the best fit with the experimental data, by using the small-signal absorption η_a [$\eta_a = 1 - \exp(-\sigma_a N_T d_g)$, σ_a = absorption cross section, N_T = total ion density, and d_g = crystal length] and the saturation power P_s [$P_s = (h\nu_p / \sigma_a \tau_f) A_p$, $h\nu_p$ = pump photon energy, τ_f = lifetime of the level, and A_p = effective area of the pump beam] as fitting parameters, as described in Ref. [136]. The saturated absorption A was assumed to have the form $A = (\eta_a / (1 + P_p / P_s))$, where P_p is the incident pump power [136]. A_p and N_T were taken as $3.7 \times 10^{-9}\ \text{m}^2$ and $3.82 \times 10^{26}\ \text{m}^{-3}$, respectively. The best fit to the experimental data shown in Figure 4.4 was obtained for $\eta_a = 0.65$ and $P_s = 0.282\ \text{W}$, yielding σ_a values of $0.57 \times 10^{-20}\ \text{cm}^2$ and $0.17 \times 10^{-20}\ \text{cm}^2$, with an average of $0.37 \times 10^{-20}\ \text{cm}^2$.

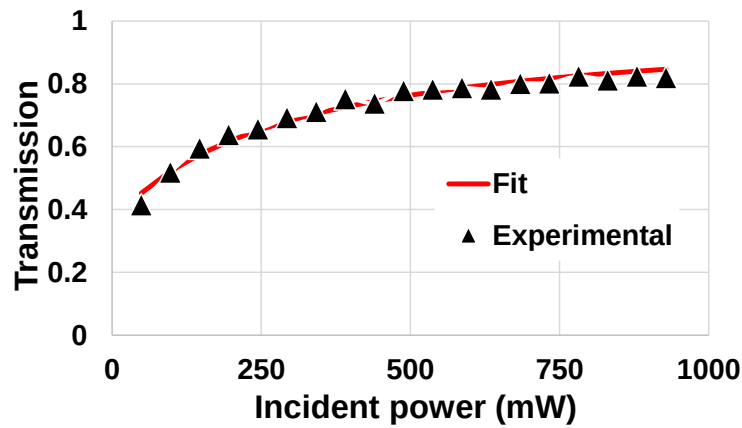


Figure 4.4 Measured and fit variation of the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ transmission at 779 nm as a function of the input pump power.

The power efficiency curves shown in Figure 4.5 were taken for single-end and double-end E//x pumping with three flat OCs having 1, 2, and 3% transmission. With the 3% OC, lasing could be obtained only during double-end pumping. As can be seen in Figure 4.5a the highest output power of 42 (100) mW was obtained with the 1% OC during single- (double-) end pumping. Here, the slope efficiency with respect to incident pump power was 5.5% (12%) for single- (double-) end pumping. For the case of 2% OC given in Figure 4.5b, the highest output power was recorded as 74 mW and 24 mW for double- and single-end pumping, respectively. The corresponding slope efficiencies were 11% for double-end and 4% for single-end pumping. The laser generated 18 mW of output power and 5% slope efficiency with 3% OC in double-end pumping scheme shown in Figure 4.5c. By taking the average pump absorption as 25%, we further estimated the slope efficiency with respect to the absorbed pump power as 22% for the 1% OC during single-end pumping. Based on the Findlay–Clay analysis of the lasing threshold data given in Figure 4.5d, the passive loss of the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ laser was further estimated to be 0.5% [78, 137].

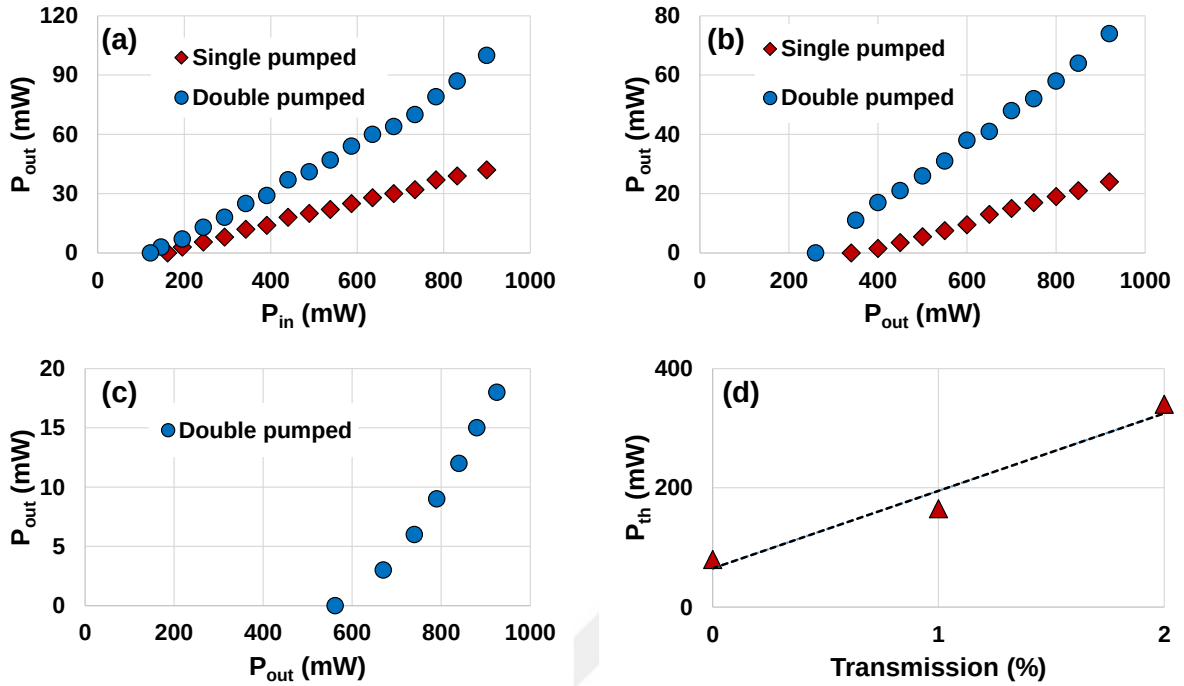


Figure 4.5 Continuous-wave efficiency curves of the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ laser at 2290 nm for single-end and double-end pumping configuration with OC transmissions of (a) 1%, (b) 2%, and (c) 3%. (d) Measured threshold pump power values for 0, 1, and 2% OC transmissions in single-end pumping.

The output spectrum and the beam profiles at the highest output power for single-end and double-end pumped configuration are further shown in the Figure 4.6a,b and Figure 4.6c,d, respectively. The output beam remained nearly diffraction limited for single-end and double-end pumping cases with an M^2 value of 1.1.

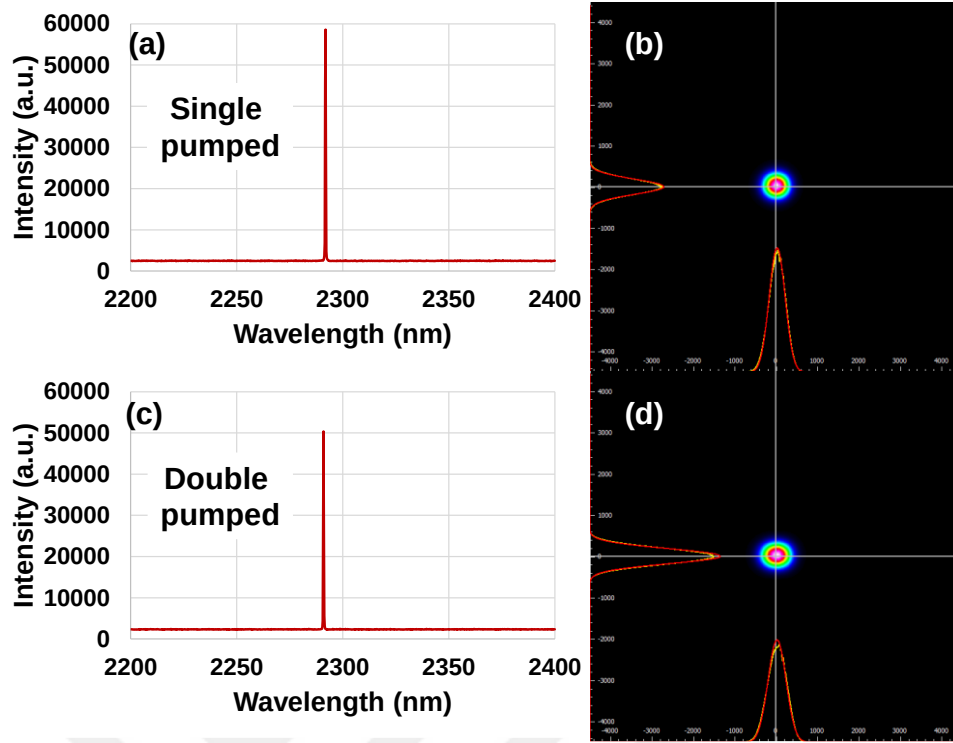


Figure 4.6 Measured cw spectrum and beam profiles of 2.3 μm $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ laser for single-end pumped, (a), (b) and double-end pumped (c), (d) configuration.

The measured room-temperature fluorescence decay curves of the $^3\text{F}_4$ and $^3\text{H}_4$ levels are shown in Figure 4.7a and 4.7b, respectively, for the 3 at.% thulium-doped BaY_2F_8 crystal. The measurements were performed by using the method described in Ref. [123]. A single exponential fit to the measured data of the $^3\text{F}_4$ level [Figure 4.7a] yielded a decay time of 19 ms. For the $^3\text{H}_4$ level, due to the non-exponential nature of the decay, the integral method described in Ref. [138] was used, and the lifetime τ_f was determined to be 292 μs .

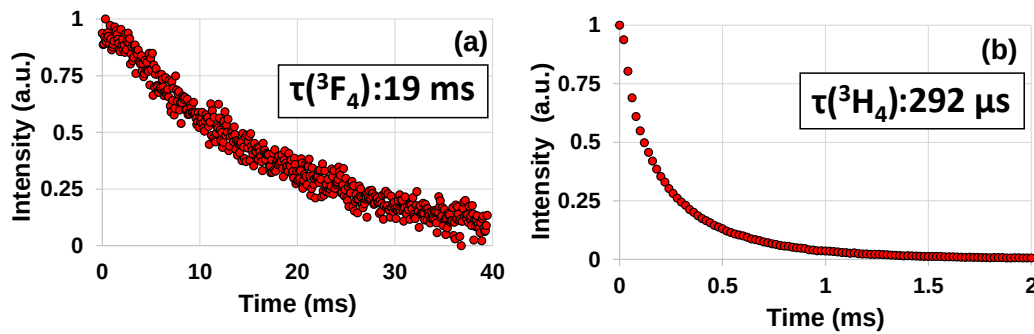


Figure 4.7 Measured room temperature time-resolved fluorescence decay of the (a) $^3\text{F}_4$ and (b) $^3\text{H}_4$ levels for the 3 at.% $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ crystal.

The lasing threshold and fluorescence lifetime ($\tau_f = 292 \mu\text{s}$) data were then used to determine the emission cross section (σ_e) of the $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ gain medium at 2290 nm from

$$\sigma_e = \frac{\pi h \nu_p n (w_p^2 + w_l^2)}{4 P_{th} \tau_f \eta_p} (T + L) . \quad (4.1)$$

Here, in addition to the parameters previously defined, w_p and w_l are the perpendicular root-mean-squared (rms) spot sizes of the pump ($w_p = 29 \mu\text{m}$) and laser ($w_l = 37 \mu\text{m}$) beams, respectively, P_{th} is the incident threshold pump power, η_p is the effective pump absorption (25%) near the threshold pump power, and L is the total roundtrip loss of the resonator [122]. The refractive index n in Equation 4.1 was included to account for the ellipticity of the beams as in Ref. [122]. Analyzing three sets of threshold data taken with three different OCs during single-end pumping, σ_e was determined to be $(0.66 \pm 0.06) \times 10^{-24} \text{ m}^2$. This σ_e value is about 2.5 times smaller than the value we obtained for $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ which is $(1.62 \pm 0.09) \times 10^{-24} \text{ m}^2$.

4.4 Summary

In conclusion, tunable continuous-wave lasing was demonstrated with a 3 at.% $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ crystal between 2233 and 2385 nm by employing 800-nm pumping. The optimum excitation wavelength was determined to be 779 nm for E//x pumping configuration. Based on the analysis of the lasing threshold data, the stimulated emission cross section at 2290 nm was determined to be $(0.66 \pm 0.06) \times 10^{-24} \text{ m}^2$. Since absorption saturation reduces the effective pump absorption, we foresee that use of longer crystals and higher pump powers should enable watt-level operation. The experimental results explained above are published in Optics Letters [139].

Chapter 5

5 Construction of the experimental setup for photothermal and photodynamic therapy

5.1 Introduction

The photothermal therapy (PTT) and the photodynamic therapy (PDT) are two therapeutic methods that employ light to induce death of unwanted cells. In PTT, the effect that generates decrease in cell viability is the temperature rise above 46°C. On the other hand, in PDT, the singlet oxygen generation is the mechanism that reduces the number of alive cells. In the PTT, the amount of energy that needed to be transferred to the nanoparticles are high as compared to the PDT. This is due to the fact that in the PTT there has to be a temperature rise of a bulk material. However, in PDT, the energy levels are much lower since only an excitation of an oxygen molecule takes place.

In addition to the laser studies in the near infrared and mid infrared range that took place in the rest of the thesis, a setup for the evaluation of PTT and PDT potential of laser irradiated nanoparticles is built to conduct a study on an emerging application. This setup consisted of two lasers operating in the visible and near infrared range. Two types of measurements were done with this setup which are solution and cell culture irradiation measurements. In order to evaluate the PTT or the PDT performance of the nanoparticles, at first the solution experiments were done. In PTT experiments, a solution containing a certain concentration of nanoparticles was put inside a cuvette, either polystyrene or quartz, and irradiated with laser. During irradiation, the temperature rise of the solution was monitored by using a thermocouple. In the PDT case, the sample inside the cuvette was irradiated and then the solution is checked for singlet oxygen generation.

After the solution experiments, the concentration with the highest performance that shows low levels of toxicity was used for cell culture experiments. The cell cultures were placed in 96-well plates. Each well was irradiated with laser for time intervals specific to the type of the therapy. The usual time interval for the PTT is around 10 minutes. This time interval was determined by the previous experiments. In the case of the PDT, the time intervals were ranging from half a minute to 5 minutes depending on the laser power.

In this part of the thesis, the construction and details of the setup for determining the photothermal heating of nanoparticles in solutions together with irradiation setup for cell cultures hosting nanoparticles for PTT and PDT will be explained. Furthermore, sample experimental data taken with the setup will be provided and the published results will be summarized.

5.2 Experimental

In the course of the experiments, the setup was evolved several times. The latest configuration of the setup will be explained in this chapter. There are two types of measurements that can be performed with the setup. First kind of measurements are the solution measurements in which the solutions of nanoparticles were irradiated and the temperature increase in the solution was measured by the help of a k-type thermocouple. During these measurements, the laser beam is sent through a telescope consisted of two lenses with focal length of 4 mm and 50 mm to adjust the spot size. The solutions of nanoparticles were placed inside a quartz or polystyrene cuvette and the thermocouple was dipped in the solution as far as possible from the beam in the solution. The cuvette was insulated with glass slides from the metal holder. In Figure 5.1, a picture of the solution experiment setup is given.

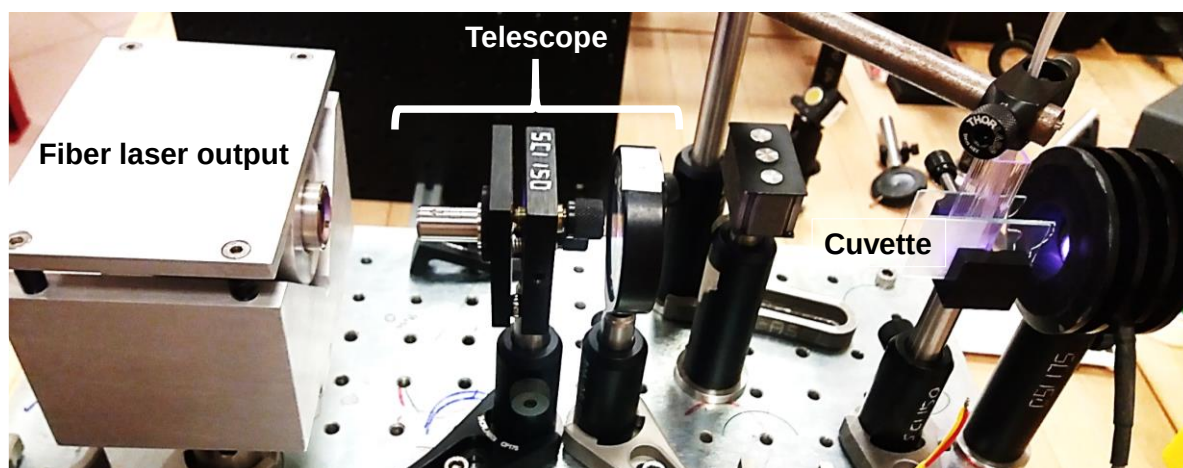


Figure 5.1 The picture of the solution measurement setup consisted of fiber laser output and the telescope.

The schematic representation of the cell culture irradiation setup used during the experiments is shown in Figure 5.2. The setup consists of two lasers operating at 640 nm and 808 nm which makes it capable of both simultaneous and individual irradiation. The output of the 640 nm diode was first coupled to a fiber and collimated with a telescope (consisting of lenses L1 and L2, with $f_1 = 4$ mm and $f_2 = 50$ mm). After the telescope the beam was transferred onto a dichroic mirror (DM) with a corner mirror (M1). The DM was a longpass dichroic mirror with a cut-on wavelength of 650 nm. The fiber bundle-coupled output of the other diode laser operating at 808 nm was also collimated with a second telescope (consisting of lenses L3 and L4, with $f_3 = 4$ mm and $f_4 = 50$ mm) before passing through the DM. In order to irradiate the 96-well plates, the two beams combined with the DM were reflected upwards with another corner mirror (M2). The well diameter of the 96-well plates used for the in vitro experiments was 7 mm. Therefore, the two telescope arrangements of two different lasers were used to match the spot size of each laser beams to this diameter. The experimental setup also consisted of a plexiglass box in which all the samples were placed during irradiation. The temperature inside this box was maintained at 37°C by using a closed-loop heater. The system also included an infrared camera to monitor the temperature increase during cell culture irradiation experiments. However, the plexiglass is not transparent at infrared (IR) wavelengths ranging from 8 μ m to 10 μ m radiated from an object at temperatures of 37 °C and above. Thus, in order to obtain correct reading with the infrared camera, a circular hole was punched on top of the plexiglass box. For the same reason, a GaAs wafer was used instead of the polystyrene well-plate cover due to the fact that the GaAs wafer has a flat transmission up to 12 μ m. The infrared camera was also calibrated to take the transmission of the GaAs wafer into account to perform temperature measurements.

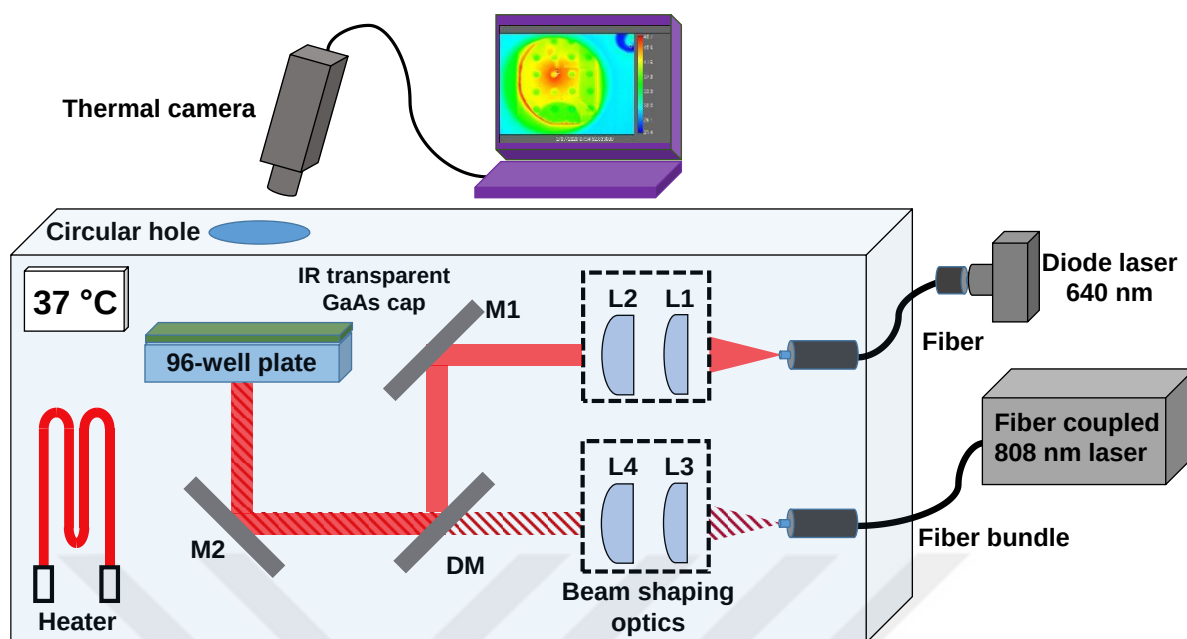


Figure 5.2 Schematic illustration of cell culture irradiation setup placed inside the homemade temperature controlled box with the infrared camera.

5.3 Sample measurement results

As explained above, two types of measurements were performed in order to evaluate the PTT and PDT performance of nanoparticles. During solution measurements, solutions with different concentrations were tested. A sample measurements with 3 different concentrations is given in Figure 5.3a. Furthermore, solution measurements were also done in a cyclic manner in order to control the stability of the particles. Multiple heating and cooling cycles were measured on the same sample. In Figure 5.3b, a sample stability measurement can be seen.

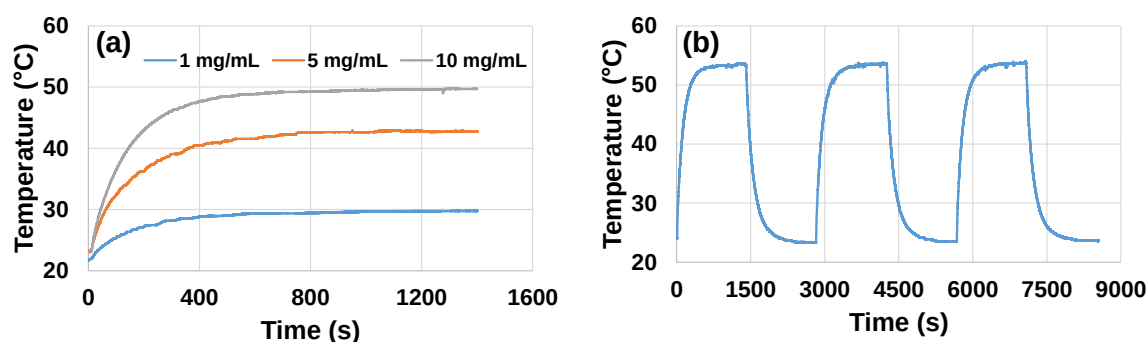


Figure 5.3 (a) Sample solution measurement results with three different concentrations and (b) a sample stability measurement performed with three heating and cooling cycles.

In cell irradiation experiments, samples were tested with several kits that yields the cell viability. During these experiments, there were two control sets. One of the control sets was composed of wells with nanoparticles but they were not irradiated in order to see that if the nanoparticles kill the cells without laser irradiation. The second control set was laser control wells. There were no nanoparticles in these wells but they were irradiated to see if the laser irradiation reduces the cell viability without nanoparticles. In Figure 5.4, a sample cell irradiation experiment result that shows the cell viability in both control wells and wells with nanoparticles of different concentrations is given.

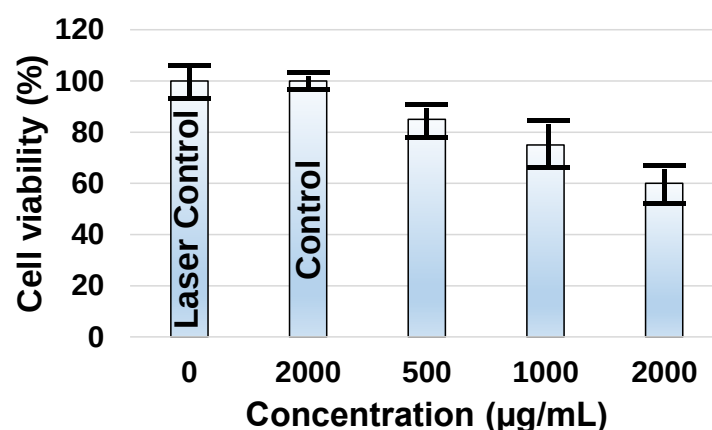


Figure 5.4 Sample cell viability results of control wells and three different concentrations of nanoparticles.

5.4 Summary

Together with this homemade setup, solution characterization of super paramagnetic iron oxide nanoparticles (SPION) in the 730 nm to 840 nm wavelength range and cell culture measurements yielding 20% cell viability for HeLa cell line were achieved. These results were published in Photochemical and Photobiological Sciences [140]. Furthermore, in another study, cell culture experiments were performed with indocyanine green (ICG) loaded 3-aminopropyltrimethoxysilane (APTMS) coated cationic SPIONs. ICG is a well-known PDT agent which has fluorescence in the near-infrared region. The loading of this PDT agent to the PTT inducing SPIONs, allowed to obtain dual therapy in cell cultures. Cell viability below 10% was achieved for both MCF7 and HT29 cell lines. This study was published in Journal of Photochemistry and Photobiology, B: Biology [141]. In addition to the aforementioned SPION studies, Ag₂S-Glutathione quantum dots were also investigated by using the setup. Cell proliferation values around 10% and 40 % were achieved for the MCF7 and HT29 cell lines respectively during the experiments. These outputs were also published in New Journal of Chemistry [142]. Apart from the cancer research, the setup was also employed in the studies including the antibiotics resistant bacteria study. In this study, the ICG loaded APTMS SPIONs were used again for dual therapy effect on *E. coli*, *K. pneumoniae*, *P. aeruginosa* and *S. epidermidis* in planktonic cells and biofilms. During the experiments, log reduction of around 10 to 12 was obtained in planktonic bacteria cells and 3 to 7 log reduction was obtained in bacteria biofilms. These results were published in Biomaterials Science [143]. As can be seen, the setup shows a promising performance of the experimental studies for a wide variety of emerging research areas requiring visible and near infrared laser irradiation. The setup can also be upgraded with mid infrared lasers that were explained in the previous chapters to start new research in the newly discovered biological windows [101].

Chapter 6

6 Conclusions

In this thesis, the development of direct diode-pumped near infrared lasers around 800 nm, continuous wave and pulsed mid-infrared $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ and $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ lasers around 2.3 μm and finally the construction of a homemade experimental setup for the evaluation of the potential of nanoparticles for photothermal and photodynamic therapy applications are the main focus. In particular, the experimental results of the mode locking studies for the single green diode pumped KLM MPC $\text{Ti}^{3+}:\text{sapphire}$, the studies yielding the first time cw and GSA mode locked operation of $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser at 2.3 μm , the experimental results regarding the first time laser operation of $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ near 2.3 μm and the construction of a home-made setup for the characterization of the PTT and PDT performance of laser irradiated nanoparticles on cancer cell cultures and bacteria biofilms were discussed.

First, the operation of an extended-cavity $\text{Ti}^{3+}:\text{sapphire}$ laser, directly diode-pumped at 520 nm with one, 1-W AlInGaN diode was described. As high as 90 mW of output power was obtained with 880 mW of incident pump power from the short cavity during cw operation. The addition of a q-preserving multipass cavity and GTI mirrors for dispersion control, allowed the Kerr-lens mode-locked operation of the laser yielding nearly transform limited 95-fs pulses at 776 nm with a pulse repetition rate of 5.78 MHz. The resulting pulse energy was 5.1 nJ and the peak power of the pulses was 53 kW. This represents the highest pulse energy to date, directly obtained from a mode-locked, single-diode-pumped $\text{Ti}^{3+}:\text{sapphire}$ laser [47]. There is not a fundamental limit for energy scaling as far as we could see, so that energy scaling should be possible by using more powerful pump diodes. Furthermore, shorter pulses can be achieved by using mirrors with negative dispersion providing coatings instead of the GTI mirrors. This will allow better dispersion control and remove the bandwidth limitations caused by the GTI mirrors.

Second, both the first-time cw operation of a $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser and the first time stable mode-locked operation of $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser near 2.3 μm by using a graphene saturable absorber were described. A 8 at.% $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ crystal was end pumped with a narrow-linewidth, tunable, cw $\text{Ti}^{3+}:\text{sapphire}$ laser. As high as 31 and 122 mW of cw output power in single- and double-end pumping configurations, respectively, with an output coupling of 1% and 1 W of incident pump power. Pump wavelength excitation efficiencies were examined between 765

to 806 nm. Two major absorption peaks were determined at 773 and 778 nm, and two additional weaker bands were observed at 796 and 802 nm. A 125-nm tunability range was demonstrated by using a quartz birefringent tuning plate (BTP). In addition, the lifetime of $^3\text{H}_4$ level was measured as 16 μs . The emission cross section (σ_e) was determined to be $(1.62 \pm 0.09) \times 10^{-24} \text{ m}^2$ with calculation based on lasing threshold data. Furthermore, 739 fs pulses with average output power of 64 mW near 2340 nm at a repetition rate of 54 MHz, corresponding to 1.2 nJ of pulse energy and 1.6 kW of peak power were obtained from the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser by the help of a cavity extension and double-end pumping to scale up the pulse energy [66, 123]. The stable mode locked operation of the $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ laser required purging of the extended cavity to reduce the atmospheric absorption lines that coincided with the pulse spectrum. This might pose a challenge against building longer cavities for pulse energy scaling or in obtaining shorter pulses.

Then, the first time tunable continuous-wave lasing with a 3 at.% $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ crystal between 2233 and 2385 nm by employing 800-nm pumping was described [139]. The optimum excitation wavelengths for E//x and E//y pumping were determined by using a narrow-linewidth, tunable $\text{Ti}^{3+}:\text{sapphire}$ laser in the 760–810 nm range. The absorption saturation, power efficiency, tuning, and lasing threshold data were further measured. Fluorescence decay curves of the $^3\text{F}_4$ and $^3\text{H}_4$ levels were measured to determine the lifetimes of the corresponding levels. Absorption saturation and lasing threshold data were used along with the lifetime data to determine the absorption and stimulated emission cross sections. The stimulated emission cross section at 2290 nm was determined to be $(0.66 \pm 0.06) \times 10^{-24} \text{ m}^2$. As high as 100 mW of output power at 2290 nm was obtained from the laser in E//x configuration with double-end pumping at 779 nm with 920 mW of incident pump power. Due to the reduction of the effective pump absorption caused by absorption saturation, the watt-level operation might only be possible by the use of longer crystals and higher pump powers.

Finally, the construction of the homemade setup designed for determining the photothermal heating of nanoparticles in solutions together with irradiation setup for cell cultures was explained and sample experimental data taken with the setup was shown. The results obtained with the experiments on the setup including the PTT effect of SPIONs on HeLa cell line [140], combined effect of the PDT and PTT generated by ICG loaded APTMS SPIONs on MCF7 and HT29 cell lines together with bacteria in the planktonic and biofilm form were explained [141, 143]. The PTT effect on MCF7 and HT29 cell lines were further investigated with the Ag_2S -Glutathione quantum dots [142].

BIBLIOGRAPHY

1. I. Newton, *Opticks: or, a treatise of the reflections, refractions, inflexions and colours of light. Also two treatises of the species and magnitude of curvilinear figures.* (London, 1704).
2. T. Young, "The Bakerian Lecture. Experiments and calculations relative to physical optics," *Philosophical Transactions of the Royal Society* **94**, 1-16 (1804).
3. J. C. Maxwell, "A dynamical theory of the electromagnetic field," *Philosophical Transactions of the Royal Society of London* **155**, 459-512 (1865).
4. H. Hertz, "Ueber einen Einfluss des ultravioletten Lichtes auf die electrische Entladung," *Annalen der Physik* **267**, 983-100 (1887).
5. M. Planck, "Ueber das Gesetz der Energieverteilung im Normalspektrum," *Annalen der Physik* **309**, 553-563 (1901).
6. A. Einstein, "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt," *Annalen der Physik* **17**, 132-148 (1905).
7. A. Einstein, "Zur Quantentheorie der Strahlung," *Physikalische Zeitschrift* **18**, 121-128 (1917).
8. V. A. Fabrikant, "The emission mechanism of a gas discharge," in *Trudy (Proceedings) of VEI (the All-Soviet-Union Electro-Technical Institute), Electronic and Ion Devices*, 1940), 236-296.
9. M. Goeppert-Mayer, "Über Elementarakte mit zwei Quantensprüngen," *Annals of Physics* **9**, 273-295 (1931).
10. V. A. Fabrikant, "Materials of Soviet Patent application N576749," (1951-1964).
11. J. P. Gordon, H. J. Zeiger, and C. H. Townes, "The Maser---New Type of Microwave Amplifier, Frequency Standard, and Spectrometer," *Physical Review* **99**, 1264-1274 (1955).
12. T. H. Maiman, "Stimulated optical radiation in ruby," *Nature* **187**, 493-494 (1960).
13. P. P. Sorokin and M. J. Stevenson, "Stimulated Infrared Emission from Trivalent Uranium," *Physical Review Letters* **5**, 557-559 (1960).
14. L. F. Johnson and K. Nassau, "Infrared Fluorescence and Stimulated Emission of Nd^{+3} in CaWO_4 ," *Proc. Inst. Radio Engrs.* **49**, 1704-1706 (1961).
15. A. Javan, W. R. Bennett Jr, and D. R. Herriott, "Population inversion and continuous optical maser oscillation in a gas discharge containing a He-Ne mixture," *Physical Review Letters* **6**, 106 (1961).
16. R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson, "Coherent Light Emission From GaAs Junctions," *Physical Review Letters* **9**, 366-368 (1962).
17. P. P. Sorokin and J. R. Lankard, "Stimulated Emission Observed from an Organic Dye, Chloro-aluminum Phthalocyanine," *IBM J. Res. Develop.* **10**, 162-163 (1966).
18. A. Ikesue and Y. L. Aung, "Ceramic laser materials," *Nature Photonics* **2**, 721-727 (2008).
19. A. A. Kaminskii, "Laser crystals and ceramics: recent advances," *Laser & Photon. Rev.* **1**, 93-177 (2007).
20. J. H. Campbell, J. S. Hayden, and A. Marker, "High-Power Solid-State Lasers: a Laser Glass Perspective," *Int. J. Appl. Glass. Sci.* **2**, 3-29 (2011).
21. P. F. Moulton, "Spectroscopic and Laser Characteristics of $\text{Ti-Al}_2\text{O}_3$," *J. Opt. Soc. Am. B.* **3**, 125-133 (1986).
22. D. H. Sutter, G. Steinmeyer, L. Gallmann, N. Matuschek, F. Morier-Genoud, U. Keller, V. Scheuer, G. Angelow, and T. Tschudi, "Semiconductor saturable-absorber mirror-assisted Kerr-lens mode-locked Ti : sapphire laser producing pulses in the two-cycle regime," *Opt Lett* **24**, 631-633 (1999).

23. U. Morgner, F. X. Kartner, S. H. Cho, Y. Chen, H. A. Haus, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, and T. Tschudi, "Sub-two-cycle pulses from a Kerr-lens mode-locked Ti : sapphire laser," *Opt. Lett.* **24**, 411-413 (1999).
24. I. H. Baek, H. W. Lee, S. Bae, B. H. Hong, Y. H. Ahn, D.-I. Yeom, and F. Rotermund, "Efficient Mode-Locking of Sub-70-fs Ti:Sapphire Laser by Graphene Saturable Absorber," *Appl. Phys. Express* **5**, 032701 (2012).
25. I. H. Baek, S. Y. Choi, H. W. Lee, W. B. Cho, V. Petrov, A. Agnesi, V. Pasiskevicius, D. I. Yeom, K. Kim, and F. Rotermund, "Single-walled carbon nanotube saturable absorber assisted high-power mode-locking of a Ti:sapphire laser," *Opt. Express* **19**, 7833-7838 (2011).
26. A. Stingl, M. Lenzner, C. Spielmann, F. Krausz, and R. Szipocs, "Sub-10-fs mirror-dispersion-controlled Ti:sapphire laser," *Opt. Lett.* **20**(1995).
27. J. Šulc and H. Jelínková, "5 - Solid-state lasers for medical applications," in *Lasers for Medical Applications*, H. Jelínková, ed. (Woodhead Publishing, 2013), pp. 127-176.
28. R. Ell, U. Morgner, F. X. Kartner, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, T. Tschudi, M. J. Lederer, A. Boiko, and B. Luther-Davies, "Generation of 5-fs pulses and octave-spanning spectra directly from a Ti : sapphire laser," *Opt. Lett.* **26**, 373-375 (2001).
29. D. Strickland and G. Mourou, "Compression of Amplified Chirped Optical Pulses," *Optics Communications* **55**, 447-449 (1985).
30. D. W. McCamant, P. Kukura, S. Yoon, and R. A. Mathies, "Femtosecond broadband stimulated Raman spectroscopy: Apparatus and methods," *Rev. Sci. Instrum.* **75**, 4971-4980 (2004).
31. W. R. Zipfel, R. M. Williams, and W. W. Webb, "Nonlinear magic: multiphoton microscopy in the biosciences," *Nature Biotechnology* **21**, 1368-1376 (2003).
32. R. C. Stoneman and L. Esterowitz, "Efficient, broadly tunable, laser-pumped Tm:YAG and Tm:YSGG cw lasers," *Opt. Lett.* **15**, 486-488 (1990).
33. D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis," *Science* **288**, 635-639 (2000).
34. J. Zweiback, R. A. Smith, T. E. Cowan, G. Hays, K. B. Wharton, V. P. Yanovsky, and T. Ditmire, "Nuclear fusion driven by Coulomb explosions of large deuterium clusters," *Physical Review Letters* **84**, 2634-2637 (2000).
35. P. Albers, E. Stark, and G. Huber, "Continuous-Wave Laser Operation and Quantum Efficiency of Titanium-Doped Sapphire," *J. Opt. Soc. Am. B* **3**, 134-139 (1986).
36. J. M. Eggleston, L. G. DeShazer, and K. W. Kangas, "Characteristics and kinetics of laser-pumped Ti:Sapphire oscillators," *IEEE Journal of Quantum Electronics* **24**, 1009-1015 (1988).
37. P. W. Roth, A. J. Maclean, D. Burns, and A. J. Kemp, "Directly diode-laser-pumped Ti:sapphire laser," *Opt. Lett.* **34**, 3334-3336 (2009).
38. P. W. Roth, A. J. Maclean, D. Burns, and A. J. Kemp, "Direct diode-laser pumping of a mode-locked Ti:sapphire laser," *Opt. Lett.* **36**, 304-306 (2011).
39. C. G. Durfee, T. Storz, J. Garlick, S. Hill, J. A. Squier, M. Kirchner, G. Taft, K. Shea, H. Kapteyn, M. Murnane, and S. Backus, "Direct diode-pumped Kerr-lens mode-locked Ti:sapphire laser," *Opt. Express* **20**, 13677-13683 (2012).
40. P. W. Roth, D. Burns, and A. J. Kemp, "Power scaling of a directly diode-laser-pumped Ti:sapphire laser," *Opt. Express* **20**, 20629-20634 (2012).
41. M. D. Young, S. Backus, C. Durfee, and J. Squier, "Multiphoton imaging with a direct-diode pumped femtosecond Ti:sapphire laser," *Journal of Microscopy* **249**, 83-86

- (2013).
42. S. Masui, T. Miyoshi, T. Yanamoto, and S. Nagahama, "1 W AlInGaN based green laser diodes," in *2013 Conference on Lasers and Electro-Optics Pacific Rim (CLEOPR)*, 2013), 1-2.
 43. S. Sawai, A. Hosaka, H. Kawauchi, K. Hirosawa, and F. Kannari, "Demonstration of a Ti:sapphire mode-locked laser pumped directly with a green diode laser," *Appl. Phys. Express* **7**(2014).
 44. K. Gurel, V. J. Wittwer, M. Hoffmann, C. J. Saraceno, S. Hakobyan, B. Resan, A. Rohrbacher, K. Weingarten, S. Schilt, and T. Sudmeyer, "Green-diode-pumped femtosecond Ti:Sapphire laser with up to 450 mW average power," *Opt. Express* **23**, 30043-30048 (2015).
 45. S. Backus, M. Kirchner, R. Lemons, D. Schmidt, C. Durfee, M. Murnane, and H. Kapteyn, "Direct diode pumped Ti:sapphire ultrafast regenerative amplifier system," *Opt. Express* **25**, 3666-3674 (2017).
 46. A. Rohrbacher, O. E. Olarte, V. Villamaina, P. Loza-Alvarez, and B. Resan, "Multiphoton imaging with blue-diode-pumped SESAM-modelocked Ti: sapphire oscillator generating 5 nJ 82 fs pulses," *Opt. Express* **25**, 10677-10684 (2017).
 47. A. Muti, A. Kocabas, and A. Sennaroglu, "5-nJ Femtosecond Ti³⁺:sapphire laser pumped with a single 1 W green diode," *Laser Phys. Lett.* **15**(2018).
 48. N. Sugiyama, H. Tanaka, and F. Kannari, "Mode-locked Ti: sapphire laser oscillators pumped by wavelength-multiplexed laser diodes," *Jpn. J. Appl. Phys.* **57**(2018).
 49. J. C. E. Coyle, A. J. Kemp, J. M. Hopkins, and A. A. Lagatsky, "Ultrafast diode-pumped Ti: sapphire laser with broad tunability," *Opt. Express* **26**, 6826-6832 (2018).
 50. D. A. Kopylov, M. N. Esaulkov, I. I. Kuritsyn, A. O. Mavritskiy, B. E. Perminov, A. V. Konyashchenko, T. V. Murzina, and A. I. Maydykovskiy, "Kerr-lens mode-locked Ti:Sapphire laser pumped by a single laser diode," *Laser Phys. Lett.* **15**(2018).
 51. H. Liu, G. Y. Wang, K. Yang, R. Z. Kang, W. L. Tian, D. C. Zhang, J. F. Zhu, H. N. Han, and Z. Y. Wei, "Diode-pumped Kerr-lens mode-locked Ti: sapphire laser with broad wavelength tunability," *Chinese Phys. B* **28**(2019).
 52. P. F. Moulton, J. G. Cederberg, K. T. Stevens, G. Foundos, M. Koselja, and J. Preclikova, "Optimized InGaN-diode pumping of Ti:sapphire crystals," *Opt. Mater. Express* **9**, 2131-2146 (2019).
 53. P. Castro-Marin, T. Mitchell, J. H. Sun, and D. T. Reid, "Characterization of a carrier-envelope-offset-stabilized blue- and green-diode-pumped Ti:sapphire frequency comb," *Opt. Lett.* **44**, 5270-5273 (2019).
 54. T. T. Yang, T. I. Yang, R. Soundararajan, P. H. S. Yeh, C. Y. Kuo, S. L. Huang, and S. Donati, "Widely Tunable, 25-mW Power, Ti:sapphire Crystal-Fiber Laser," *IEEE Photonic. Tech. L* **31**, 1921-1924 (2019).
 55. V. Sonnenschein, M. Ohashi, H. Tomita, and T. Iguchi, "A direct diode pumped continuous-wave Ti:sapphire laser as seed of a pulsed amplifier for high-resolution resonance ionization spectroscopy," *Nucl. Instrum. Meth. B* **463**, 512-514 (2020).
 56. Z. W. Miao, H. J. Yu, J. Y. Zhang, S. Z. Zou, P. F. Zhao, B. J. Lou, and X. C. Lin, "Watt-Level CW Ti: Sapphire Oscillator Directly Pumped With Green Laser Diodes Module," *IEEE Photonic Tech L* **32**, 247-250 (2020).
 57. C. James, "THULIUM I.1," *Journal of the American Chemical Society* **33**, 1332-1344 (1911).
 58. L. F. Johnson, J. E. Geusic, and L. G. Van Uitert, "Coherent oscillations from Tm³⁺, Ho³⁺, Yb³⁺ and Er³⁺ ions in yttrium aluminum garnet," *Applied Physics Letters* **7**, 127 (1965).

59. J. Caird, L. DeShazer, and J. Nella, "Characteristics of room-temperature 2.3- μm laser emission from Tm^{3+} in YAG and YAlO_3 ," *IEEE Journal of Quantum Electronics* **11**, 874-881 (1975).
60. V. Sudesh and J. A. Piper, "Spectroscopy, Modeling, and Laser Operation of Thulium Crystals at 2.3 μm ," *IEEE Journal of Quantum Electronics* **QE-36**, 879-884 (2000).
61. A. Braud, S. Girard, J. L. Doualan, M. Thuau, R. Moncorge, and A. M. Tkachuk, "Energy-transfer processes in $\text{Yb} : \text{Tm}$ -doped KY_3F_{10} , LiYF_4 , and BaY_2F_8 single crystals for laser operation at 1.5 and 2.3 μm ," *Phys. Rev. B* **61**, 5280-5292 (2000).
62. F. Canbaz, I. Yorulmaz, and A. Sennaroglu, "Kerr-lens mode-locked 2.3- μm $\text{Tm}^{3+}:\text{YLF}$ laser as a source of femtosecond pulses in the mid-infrared," *Opt. Lett.* **42**, 3964-3967 (2017).
63. L. Guillemot, P. Loiko, R. Soulard, A. Braud, J. L. Doualan, A. Hideur, R. Moncorge, and P. Camy, "Thulium laser at $\sim 2.3 \mu\text{m}$ based on upconversion pumping," *Opt. Lett.* **44**, 4071-4074 (2019).
64. A. Braud, P. Y. Tigreat, J. L. Doualan, and R. Moncorge, "Spectroscopy and cw operation of a 1.85 μm $\text{Tm} : \text{KY}_3\text{F}_{10}$ laser," *Appl. Phys. B-Lasers O* **72**, 909-912 (2001).
65. G. Galzerano, F. Cornacchia, D. Parisi, A. Toncelli, and M. Tonelli, "Widely tunable 1.94- μm $\text{Tm} : \text{BaY}_2\text{F}_8$ laser," *Opt. Lett.* **30**, 854-856 (2005).
66. A. Muti, F. Canbaz, M. Tonelli, J. E. Bae, F. Rotermund, V. Petrov, and A. Sennaroglu, "Graphene mode-locked operation of $\text{Tm}^{3+}:\text{YLiF}_4$ and $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ lasers near 2.3 μm ," *Opt. Lett.* **45**, 656-659 (2020).
67. A. Sennaroglu and J. G. Fujimoto, "Design criteria for Herriott-type multi-pass cavities for ultrashort pulse lasers," *Opt. Express* **11**, 1106-1113 (2003).
68. A. Sennaroglu, A. M. Kowalewicz, E. P. Ippen, and J. G. Fujimoto, "Compact femtosecond lasers based on novel multipass cavities," *IEEE Journal of Quantum Electronics* **40**, 519-528 (2004).
69. A. Sennaroglu, *Photonics and Laser Engineering: Principles, Devices, and Applications* (McGraw Hill, New York, 2010).
70. U. Keller, K. J. Weingarten, F. X. Kartner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. A. d. Au, "Semiconductor saturable absorber mirrors (SESAM's) for femtosecond to nanosecond pulse generation in solid-state lasers," *IEEE Journal of Selected Topics in Quantum Electronics* **2**, 435-453 (1996).
71. S. Tsuda, W. H. Knox, S. T. Cundiff, W. Y. Jan, and J. E. Cunningham, "Mode-locking ultrafast solid-state lasers with saturable Bragg reflectors," *IEEE Journal of Selected Topics in Quantum Electronics* **2**, 454-464 (1996).
72. R. R. Nair, P. Blake, A. N. Grigorenko, K. S. Novoselov, T. J. Booth, T. Stauber, N. M. R. Peres, and A. K. Geim, "Fine structure constant defines visual transparency of graphene," *Science* **320**, 1308-1308 (2008).
73. C. Cihan, C. Kocabas, U. Demirbas, and A. Sennaroglu, "Graphene mode-locked femtosecond Alexandrite laser," *Opt. Lett.* **43**, 3969-3972 (2018).
74. A. A. Lagatsky, Z. Sun, T. S. Kulmala, R. S. Sundaram, S. Milana, F. Torrisi, O. L. Antipov, Y. Lee, J. H. Ahn, C. T. A. Brown, W. Sibbett, and A. C. Ferrari, "2 μm solid-state laser mode-locked by single-layer graphene," *Applied Physics Letters* **102**(2013).
75. M. N. Cizmeciyan, J. W. Kim, S. Bae, B. H. Hong, F. Rotermund, and A. Sennaroglu, "Graphene mode-locked femtosecond $\text{Cr}:\text{ZnSe}$ laser at 2500 nm," *Opt. Lett.* **38**, 341-343 (2013).
76. S. D. D. Cafiso, E. Ugolotti, A. Schmidt, V. Petrov, U. Griebner, A. Agnesi, W. B.

- Cho, B. H. Jung, F. Rotermund, S. Bae, B. H. Hong, G. Reali, and F. Pirzio, "Sub-100-fs Cr:YAG laser mode-locked by monolayer graphene saturable absorber," *Opt. Lett.* **38**, 1745-1747 (2013).
77. G. W. Zhu, X. S. Zhu, K. Balakrishnan, R. A. Norwood, and N. Peyghambarian, "Fe²⁺:ZnSe and graphene Q-switched singly Ho³⁺-doped ZBLAN fiber lasers at 3 μ m," *Opt. Mater. Express* **3**, 1365-1377 (2013).
 78. D. Findlay and R. A. Clay, "The measurement of internal losses in 4-level lasers," *Physics Letters* **20**, 277-278 (1966).
 79. D. Huang, E. Swanson, C. Lin, J. Schuman, W. Stinson, W. Chang, M. Hee, T. Flotte, K. Gregory, C. Puliafito, and a. et, "Optical coherence tomography," *Science* **254**, 1178-1181 (1991).
 80. W. R. Zipfel, R. M. Williams, and W. W. Webb, "Nonlinear magic: multiphoton microscopy in the biosciences," *Nat Biotech* **21**, 1369-1377 (2003).
 81. S. Sakadžić, U. Demirbas, T. R. Mempel, A. Moore, S. Ruvinskaya, D. A. Boas, A. Sennaroglu, F. X. Kartner, and J. G. Fujimoto, "Multi-photon microscopy with a low-cost and highly efficient Cr:LiCAF laser," *Opt. Express* **16**, 20848-20863 (2008).
 82. X. Liu, D. Du, and G. Mourou, "Laser ablation and micromachining with ultrashort laser pulses," *IEEE J. Quantum Elect.* **33**, 1706-1716 (1997).
 83. R. R. Gattass and E. Mazur, "Femtosecond laser micromachining in transparent materials," *Nature Photonics* **2**, 219-225 (2008).
 84. U. Demirbas, D. Li, J. R. Birge, A. Sennaroglu, G. S. Petrich, L. A. Kolodziejski, F. X. Kartner, and J. G. Fujimoto, "Low-cost, single-mode diode-pumped Cr:Colquiriite lasers," *Opt. Express* **17**, 14374-14388 (2009).
 85. U. Demirbas, G. S. Petrich, D. Li, A. Sennaroglu, L. A. Kolodziejski, F. X. Kartner, and J. G. Fujimoto, "Femtosecond tuning of Cr:colquiriite lasers with AlGaAs-based saturable Bragg reflectors," *J. Opt. Soc. Am. B* **28**, 986-993 (2011).
 86. U. Demirbas, A. Sennaroglu, F. X. Kaertner, and J. G. Fujimoto, "Highly efficient, low-cost femtosecond Cr³⁺: LiCAF laser pumped by single-mode diodes," *Opt. Lett.* **33**, 590-592 (2008).
 87. E. Beyatli, I. Baali, B. Sumpf, G. Erbert, A. Leitenstorfer, A. Sennaroglu, and U. Demirbas, "Tapered diode-pumped continuous-wave alexandrite laser," *J. Opt. Soc. Am. B* **30**, 3184-3192 (2013).
 88. I. Yorulmaz, E. Beyatli, A. Kurt, A. Sennaroglu, and U. Demirbas, "Efficient and low-threshold Alexandrite laser pumped by a single-mode diode," *Opt. Mater. Express* **4**, 776-789 (2014).
 89. A. Teppitaksak, A. Minassian, G. M. Thomas, and M. J. Damzen, "High efficiency > 26 W diode end-pumped Alexandrite laser," *Opt. Express* **22**, 16386-16392 (2014).
 90. G. M. Thomas, A. Minassian, X. Sheng, and M. J. Damzen, "Diode-pumped Alexandrite lasers in Q-switched and cavity-dumped Q-switched operation," *Opt. Express* **24**, 27212-27224 (2016).
 91. R. Sawada, H. Tanaka, N. Sugiyama, and F. Kannari, "Wavelength-multiplexed pumping with 478-and 520-nm indium gallium nitride laser diodes for Ti:sapphire laser," *Appl. Optics* **56**, 1654-1661 (2017).
 92. S. Backus, M. Kirchner, C. Durfee, M. Murnane, and H. Kapteyn, "Direct diode-pumped Kerr Lens 13 fs Ti:sapphire ultrafast oscillator using a single blue laser diode," *Opt. Express* **25**, 12469-12477 (2017).
 93. K. Gurel, V. J. Wittwer, S. Hakobyan, S. Schilt, and T. Sudmeyer, "Carrier envelope offset frequency detection and stabilization of a diode-pumped mode-locked Ti:sapphire laser," *Opt. Lett.* **42**, 1035-1038 (2017).

94. M. D. Young, S. Backus, C. Durfee, and J. Squier, "Multiphoton imaging with a direct-diode pumped femtosecond Ti: sapphire laser," *Journal of microscopy* **249**, 83-86 (2013).
95. A. Muti, A. Kocabas, and A. Sennaroglu, "Generation of 4-nJ Pulses from a Diode-Pumped Femtosecond Ti³⁺:sapphire Laser," in *Laser Congress 2017 (ASSL, LAC)*, OSA Technical Digest (online) (Optical Society of America, 2017), ATu1A.5.
96. H. A. Haus, "Mode-locking of lasers," *IEEE Journal of Selected Topics in Quantum Electronics* **6**, 1173-1185 (2000).
97. M. N. Cizmeciyan, H. Cankaya, A. Kurt, and A. Sennaroglu, "Operation of femtosecond Kerr-lens mode-locked Cr:ZnSe lasers with different dispersion compensation methods," *Appl. Phys. B-Lasers O* **106**, 887-892 (2012).
98. A. A. Lanin, A. A. Voronin, A. B. Fedotov, and A. M. Zheltikov, "Time-domain spectroscopy in the mid-infrared," *Nature* **4**, 6670 (2014).
99. Z. Chang, A. Rundquist, H. Wang, M. M. Murnane, and H. C. Kapteyn, "Generation of coherent soft X rays at 2.7 nm using high harmonics," *Physical Review Letters* **79**, 2967 (1997).
100. G. J. Koch, B. W. Barnes, M. Petros, J. Y. Beyon, F. Amzajerdian, J. R. Yu, R. E. Davis, S. Ismail, S. Vay, M. J. Kavaya, and U. N. Singh, "Coherent differential absorption lidar measurements of CO₂," *Appl. Optics* **43**, 5092-5099 (2004).
101. L. Y. Shi, L. A. Sordillo, A. Rodriguez-Contreras, and R. Alfano, "Transmission in near-infrared optical windows for deep brain imaging," *J. Biophotonics* **9**, 38-43 (2016).
102. J. Yadav, A. Rani, V. Singh, and B. M. Murari, "Prospects and limitations of non-invasive blood glucose monitoring using near-infrared spectroscopy," *Biomed. Signal Proces.* **18**, 214-227 (2015).
103. T. Kanai, P. Malevich, S. S. Kangaparambil, K. Ishida, M. Mizui, K. Yamanouchi, H. Hoogland, R. Holzwarth, A. Pugzlys, and A. Baltuska, "Parametric amplification of 100 fs mid-infrared pulses in ZnGeP₂ driven by a Ho:YAG chirped-pulse amplifier," *Opt Lett* **42**, 683-686 (2017).
104. L. Hobrock, L. DeShazer, W. Krupke, G. Keig, and D. Witter, "Four-level operation of Tm: Cr: YAlO₃ laser at 2.35 μm ," *IEEE Journal of Quantum Electronics* **8**, 533-534 (1972).
105. H. Kalaycioglu, A. Sennaroglu, A. Kurt, and G. Ozen, "Spectroscopic analysis of Tm³⁺: LuAG," *Journal of Physics: Condensed Matter* **19**, - (2007).
106. N. P. Barnes, E. D. Filer, F. L. Naranjo, W. J. Rodriguez, and M. R. Kokta, "Spectroscopic and lasing properties of Ho:Tm:LuAG," *Opt. Lett.* **18**, 708-710 (1993).
107. J. F. Pinto and L. Esterowitz, "Tm³⁺:YLF laser continuously tunable between 2.20 and 2.46 μm ," *Opt. Lett.* **19**, 883-885 (1994).
108. B. M. Walsh, N. P. Barnes, and B. D. Bartolo, "Branching ratios, cross sections, and radiative lifetimes of rare earth ions in solids: Application to Tm³⁺ and Ho³⁺ ions in LiYF₄," *J. Appl. Phys.* **83**, 2772-2787 (1998).
109. I. Yorulmaz and A. Sennaroglu, "Low-Threshold Diode-Pumped 2.3- μm Tm³⁺: YLF Lasers," *IEEE Journal of Selected Topics in Quantum Electronics* **24**(2018).
110. T. J. Kane and T. S. Kubo, "Diode-Pumped Single-Frequency Lasers and Q-Switched Laser Using Tm:YAG and Tm,Ho:YAG," in *Advanced Solid-State Lasers*, (OSA, 1990),
111. E. Beyath, S. Naghizadeh, A. Kurt, and A. Sennaroglu, "Low-cost low-threshold diode end-pumped Tm:YAG laser at 2.016 μm ," *Applied Physics B* **109**, 221-225 (2012).
112. C. Luan, K. Yang, J. Zhao, S. Zhao, T. Li, H. Zhang, J. He, L. Song, T. Dekorsy, M.

- Guina, and L. Zheng, "Diode-pumped mode-locked Tm:LuAG laser at 2 μm based on GaSb-SESAM," *Opt. Lett.* **42**, 839-842 (2017).
113. T. Feng, K. Yang, J. Zhao, S. Zhao, W. Qiao, T. Li, T. Dekorsy, J. He, L. Zheng, Q. Wang, X. Xu, L. Su, and J. Xu, "1.21 W passively mode-locked Tm:LuAG laser," *Opt. Express* **23**, 11819-11825 (2015).
114. A. C. Sullivan, G. J. Wagner, D. Gwin, R. C. Stoneman, and A. I. R. Malm, "High power Q-switched Tm:YAlO₃ lasers," in *Technical Digest of Advanced Solid State Photonics*, (OSA, 2005), WA7.
115. J. Liu, Y. G. Wang, Z. S. Qu, L. H. Zheng, L. B. Su, and J. Xu, "Graphene oxide absorber for 2 μm passive mode-locking Tm:YAlO₃ laser," *Laser Phys. Lett.* **9**, 15-19 (2012).
116. F. Canbaz, I. Yorulmaz, and A. Sennaroglu, "2.3- μm Tm³⁺:YLF laser passively Q-switched with a Cr²⁺:ZnSe saturable absorber," *Opt. Lett.* **42**, 1656-1659 (2017).
117. R. S. P. Loiko, L. Guillemot, G. Brasse, J. L. Doualan, A. Braud, A. Tyazhev, A. Hideur, F. Druon, P. Camy, "Efficient Tm:LiYF₄ Lasers at $\sim 2.3 \mu\text{m}$: Effect of Energy-Transfer Upconversion," *IEEE Journal of Quantum Electronics* **55**, 1-12 (2019).
118. F. Canbaz, N. Kakenov, C. Kocabas, U. Demirbas, and A. Sennaroglu, "Generation of sub-20-fs pulses from a graphene mode-locked laser," *Opt. Express* **25**, 2834-2839 (2017).
119. M. Schellhorn, D. Parisi, S. Veronesi, G. Bolognesi, M. Eichhorn, and M. Tonelli, "In-band pumped Ho³⁺:KY₃F₁₀ 2 μm laser," *Opt. Lett.* **38**, 504-506 (2013).
120. P. Camy, J. L. Doualan, R. Moncorge, J. Bengoechea, and U. Weichmann, "Diode-pumped Pr³⁺: KY(3)F(10) red laser," *Opt. Lett.* **32**, 1462-1464 (2007).
121. M. Diaf, A. Braud, C. Labbe, J. Doualan, S. Girard, J. Margerie, R. Moncorge, and M. Thuau, "Synthesis and spectroscopic studies of Tm³⁺-doped KY₃F₁₀ single crystals," *Can. J. Phys.* **77**, 693-697 (1999).
122. P. F. Moulton, "An Investigation of the Co:MgF₂ Laser System," *IEEE Journal of Quantum Electronics* **21**, 1582-1595 (1985).
123. A. Muti, M. Tonelli, V. Petrov, and A. Sennaroglu, "Continuous-wave mid-infrared laser operation of Tm³⁺:KY₃F₁₀ at 2.3 μm ," *Opt. Lett.* **44**, 3242-3245 (2019).
124. A. Muti, M. Tonelli, J. E. Bae, F. Rotermund, V. Petrov, and A. Sennaroglu, "Continuous-Wave and Graphene Mode-Locked Operation of a Tm³⁺:KY₃F₁₀ Laser at 2.3 μm ," in *Laser Congress 2019 (ASSL, LAC, LS&C)*, (OSA Technical Digest (Optical Society of America, 2019)).
125. L. Guillemot, P. Loiko, A. Braud, J. L. Doualan, A. Hideur, M. Koselja, R. Moncorge, and P. Camy, "Continuous-wave Tm:YAlO₃ laser at $\sim 2.3 \mu\text{m}$," *Opt. Lett.* **44**, 5077-5080 (2019).
126. L. Guillemot, P. Loiko, R. Souldard, A. Braud, J.-L. Doualan, A. Hideur, and P. Camy, "Close look on cubic Tm:KY₃F₁₀ crystal for highly efficient lasing on the 3H₄ $\rightarrow$ 3H₅ transition," *Opt. Express* **28**, 3451-3463 (2020).
127. B. I. Denker, V. V. Dorofeev, B. I. Galagan, V. V. Koltashev, S. E. Motorin, V. G. Plotnichenko, and S. E. Sverchkov, "2.3 μm laser action in Tm³⁺-doped tellurite glass fiber," *Laser Phys. Lett.* **16**(2019).
128. B. Denker, V. Dorofeev, B. Galagan, Y. Korostelin, V. Kozlovsky, S. Motorin, and S. Sverchkov, "Short pulse formation in a 2.3 μm Tm-doped tellurite glass laser by an Fe²⁺:ZnS saturable absorber," *Laser Phys. Lett.* **15**(2018).
129. Y. Morova, M. Tonelli, V. Petrov, and A. Sennaroglu, "Upconversion pumping of a 2.3 μm Tm³⁺:KY₃F₁₀ laser with a 1064 nm ytterbium fiber laser," *Opt. Lett.* **45**, 931-934 (2020).

130. R. Soulard, A. Tyazhev, J.-L. Doualan, A. Braud, A. Hideur, M. Laroche, B. Xu, and P. Camy, "2.3 μm Tm^{3+} :YLF mode-locked laser," *Opt. Lett.* **42**, 3534-3536 (2017).
131. A. Toncelli, M. Tonelli, A. Cassanho, and H. P. Jenssen, "Spectroscopy and dynamic measurements of a $\text{Tm,Dy} : \text{BaY}_2\text{F}_8$ crystal," *J. Lumin.* **82**, 291-298 (1999).
132. F. Cornacchia, A. Toncelli, and M. Tonelli, "2- μm lasers with fluoride crystals: Research and development," *Prog. Quant. Electron* **33**, 61-109 (2009).
133. N. Coluccelli, D. Gatti, G. Galzerano, F. Cornacchia, D. Parisi, A. Toncelli, M. Tonelli, and P. Laporta, "Tunability range of 245 nm in a diode-pumped $\text{Tm} : \text{BaY}_2\text{F}_8$ laser at 1.9 μm : a theoretical and experimental investigation," *Appl. Phys. B-Lasers O* **85**, 553-555 (2006).
134. F. Cornacchia, D. Parisi, C. Bernardini, A. Toncelli, and M. Tonelli, "Efficient, diode-pumped $\text{Tm}^{3+} : \text{BaY}_2\text{F}_8$ vibronic laser," *Opt. Express* **12**, 1982-1989 (2004).
135. N. Coluccelli, G. Galzerano, P. Laporta, D. Parisi, A. Toncelli, and M. Tonelli, "Room-temperature Q-switched $\text{Tm} : \text{BaY}_2\text{F}_8$ laser pumped by CW diode laser," *Opt. Express* **14**, 1518-1523 (2006).
136. A. Sennaroglu, U. Demirbas, S. Ozharar, and F. Yaman, "Accurate determination of saturation parameters for Cr^{4+} -doped solid-state saturable absorbers," *J. Opt. Soc. Am. B* **23**, 241-249 (2006).
137. A. Sennaroglu, "Classification of power-degrading mechanisms in an optically pumped four-level laser: an analytical approach," *J. Opt. Soc. Am. B* **36**, 2202-2209 (2019).
138. A. Braud, S. Girard, J. L. Doualan, and R. Moncorge, "Spectroscopy and fluorescence dynamics of (Tm^{3+} , Tb^{3+}) and (Tm^{3+} , Eu^{3+}) doped LiYF_4 single crystals for 1.5- μm laser operation," *IEEE Journal of Quantum Electronics* **34**, 2246-2255 (1998).
139. A. Muti, I. Baylam, M. Tonelli, and A. Sennaroglu, "Tunable continuous-wave laser operation of $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ near 2.3 μm ," *Opt. Lett.* **45**, 4104-4107 (2020).
140. K. Bilici, A. Muti, F. D. Duman, A. Sennaroglu, and H. Y. Acar, "Investigation of the factors affecting the photothermal therapy potential of small iron oxide nanoparticles over the 730-840 nm spectral region," *Photoch. Photobio. Sci.* **17**, 1787-1793 (2018).
141. K. Bilici, A. Muti, A. Sennaroglu, and H. Y. Acar, "Indocyanine green loaded APTMS coated SPIONs for dual phototherapy of cancer," *J. Photoch. Photobio. B* **201**(2019).
142. M. Hashemkhani, K. Bilici, A. Muti, A. Sennaroglu, and H. Y. Acar, "Ag₂S-Glutathione quantum dots for NIR image guided photothermal therapy," *New Journal of Chemistry* **44**, 5419-5427 (2020).
143. K. Bilici, N. Atac, A. Muti, I. Baylam, O. Dogan, A. Sennaroglu, F. Can, and H. Yagci Acar, "Broad spectrum antibacterial photodynamic and photothermal therapy achieved with indocyanine green loaded SPIONs under near infrared irradiation," *Biomaterials Science* (2020).

Vita

Abdullah Muti received his B.S. degree in Physics from Bilkent University in 2010. He took his M.S. degree again from Bilkent University where he worked on fabrication and characterization of InAs/GaSb superlattice based mid infrared photodetectors. After receiving the M.S. degree, he continued for the Ph.D. degree in Physics in Bilkent University. In 2015 he was admitted to Koç University to pursue the Ph.D in Physics under the supervision of Prof. Dr. Alphan Sennaroğlu. The research topics that he is interested in include the development of femtosecond lasers operating in the near and mid infrared.

Publications

- A. Muti, I. Baylam, M. Tonelli, and A. Sennaroglu, "Tunable continuous-wave laser operation of $\text{Tm}^{3+}:\text{BaY}_2\text{F}_8$ near 2.3 μm ," *Opt. Lett.* **45**, 4104-4107 (2020).
- K. Bilici, N. Atac, A. Muti, I. Baylam, O. Dogan, A. Sennaroglu, F. Can, and H. Yagci Acar, "Broad spectrum antibacterial photodynamic and photothermal therapy achieved with indocyanine green loaded SPIONs under near infrared irradiation," *Biomaterials Science* (2020).
- M. Hashemkhani, K. Bilici, A. Muti, A. Sennaroglu, and H. Y. Acar, "Ag₂S-Glutathione quantum dots for NIR image guided photothermal therapy," *New Journal of Chemistry* **44**, 5419-5427 (2020).
- A. Muti, F. Canbaz, M. Tonelli, J. E. Bae, F. Rotermund, V. Petrov, and A. Sennaroglu, "Graphene mode-locked operation of $\text{Tm}^{3+}:\text{YLiF}_4$ and $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ lasers near 2.3 μm ," *Opt. Lett.* **45**, 656-659 (2020).
- K. Bilici, A. Muti, A. Sennaroglu, and H. Y. Acar, "Indocyanine green loaded APTMS coated SPIONs for dual phototherapy of cancer," *J. Photoch. Photobio. B* 201(2019).
- A. Muti, M. Tonelli, V. Petrov, and A. Sennaroglu, "Continuous-wave mid-infrared laser operation of $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ at 2.3 μm ," *Opt. Lett.* **44**, 3242-3245 (2019).
- C. Cihan, A. Muti, I. Baylam, A. Kocabas, U. Demirbas, and A. Sennaroglu, "70 femtosecond Kerr-lens mode-locked multipass-cavity Alexandrite laser," *Opt. Lett.* **43**, 1315-1318 (2018).
- A. Muti, A. Kocabas, and A. Sennaroglu, "5-nJ Femtosecond $\text{Ti}^{3+}:\text{sapphire}$ laser pumped with a single 1 W green diode," *Laser Phys. Lett.* **15** (2018).

- K. Bilici, A. Muti, F. D. Duman, A. Sennaroglu, and H. Y. Acar, "Investigation of the factors affecting the photothermal therapy potential of small iron oxide nanoparticles over the 730-840 nm spectral region," *Photoch. Photobio. Sci.* **17**, 1787-1793 (2018).
- O. Salihoglu, A. Muti, and A. Aydinli, "A Comparative Passivation Study for InAs/GaSb Pin Superlattice Photodetectors," *IEEE Journal of Quantum Electronics* **49**, 661-666 (2013).
- T. Tansel, K. Kutluer, A. Muti, O. Salihoglu, A. Aydinli, and R. Turan, "Surface Recombination Noise in InAs/GaSb Superlattice Photodiodes," *Appl. Phys. Express* **6** (2013).
- O. Salihoglu, A. Muti, K. Kutluer, T. Tansel, R. Turan, and A. Aydinli, "Skin-like self-assembled monolayers on InAs/GaSb superlattice photodetectors," *J. Phys. D. Appl. Phys.* **45** (2012).
- O. Salihoglu, A. Muti, K. Kutluer, T. Tansel, R. Turan, Y. Ergun, and A. Aydinli, "'N' structure for type-II superlattice photodetectors," *Appl. Phys. Lett.* **101**(2012).
- O. Salihoglu, A. Muti, K. Kutluer, T. Tansel, R. Turan, C. Kocabas, and A. Aydinli, "Atomic layer deposited Al_2O_3 passivation of type II InAs/GaSb superlattice photodetectors," *J. Appl. Phys.* **111** (2012).

Proceedings

- A. Muti, M. Tonelli, J. E. Bae, F. Rotermund, V. Petrov, and A. Sennaroglu, "Continuous-Wave and Graphene Mode-Locked Operation of a $\text{Tm}^{3+}:\text{KY}_3\text{F}_{10}$ Laser at $2.3\ \mu\text{m}$," in *Laser Congress 2019 (ASSL, LAC, LS&C)*, (OSA Technical Digest (Optical Society of America, 2019), 2019).
- A. Muti, A. Kocabas, and A. Sennaroglu, "Generation of 4-nJ Pulses from a Diode-Pumped Femtosecond $\text{Ti}^{3+}:\text{sapphire}$ Laser," in *Laser Congress 2017 (ASSL, LAC)*, OSA Technical Digest (online) (Optical Society of America, 2017), ATu1A.5.
- S. Omer, M. Abdullah, T. Rasit, E. Yuksel, and A. Atilla, "Low dark current N structure superlattice MWIR photodetectors," in *Proc.SPIE*, (2014),