

DEVELOPMENT OF HIGH POWER CW YB-DOPED FIBER LASER SYSTEM

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By
Elif Gül Özkan
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DEVELOPMENT OF HIGH POWER CW YB-DOPED FIBER LASER
SYSTEM

By Elif Gül Özkan

January, 2015

We certify that we have read this thesis and that in our opinion it is fully
adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Assist. Prof. Dr. Bülend Ortaç (Supervisor)

Prof. Dr. Mehmet Bayındır

Assoc. Prof. Dr. Hakan Altan

Approved for the Graduate School of Engineering and Science:

Prof. Dr. Levent Onural

Director of Graduate School

ABSTRACT
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SYSTEM

Elif Gül Özkan

M.S. in Materials Science and Nanotechnology

Supervisor: Assist. Prof. Dr. Bülend Ortaç

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High-average-power fiber lasers are interesting for many applications, including scientific instrumentation, industrial material processing, imaging, medical and military technologies. Fiber concept has well established them as a very attractive beam delivery system and gain medium for laser applications. Rare-earth-doped fibers are one of the most promising solid-state laser concepts for efficient diode-pumped high power continuous wave laser systems. In fiber laser systems, the new generation fiber optical cables are used. Fiber laser systems are preferred due to the ease of usage in the field, high beam quality, low cost and low thermo-optic problems. Fiber laser system has an active medium where the light is amplified all along the fiber. The long active medium leads to reduced heat problems, high absorption rate of the light, high quality beam and less need for optimization of the cavity. We designed and developed a high power fiber laser system for metal processing. Material drilling and cutting, which are significant processes in industry, are performed with the powerful fiber laser systems. The main purpose of this thesis is to develop a laser system which enables fast and accurate cutting process with impressive properties such as compactness, low maintenance problems and so on. The fiber laser resonator was first numerically studied by using software and then various laser parameters and laser architectures were designed. In order to perform the numerical results, we designed a compact high power all-fiber laser cavity. In real world applications, the use of free space components to constitute the cavity

leads to environmental instabilities and power loss, which results in a decrease of the fiber laser efficiency. One of the most important advantages of all fiber laser system is to handle environmental factors such as humidity, vibrations. To achieve high power level from the fiber laser systems, it is significant to use powerful pumping systems (high power diode lasers), passive laser cavity components (combiner, FBG) and also double-clad active fiber that operate at high power level. In this study, we used new generation laser cavity components. The pump sources have been analyzed in terms of power and wavelength stabilities. Also, experiments have been performed to keep pump sources at optimum temperature to obtain accurate wavelength to excite ytterbium atoms located in the active media. In order to constitute high power laser system, we integrated all fiber optic components for efficient operation. The laser has stable continuous wave regime in temporal domain due to the cavity design. The output power of the system is about 548 W. The M^2 value of the system is less than < 1.7 . The operation wavelength of the fiber laser was stabilized with FBG at 1.08 μm . We also demonstrate the capability of our fiber laser system for material processing. We successfully drilled and cut 1.7 mm thickness steel target with lower output power of fiber laser (100 W).

Keywords

Fibers, Lasers, High-Power Laser Systems, Powerful Fiber Laser Components, Material Processing with Laser

ÖZET
YÜKSEK GÜÇLÜ DOĞRUSAL İTERBİYUM KATKILI FİBER LAZER
SİSTEMİ

Elif Gül Özkan

Malzeme Bilimi ve Nanoteknoloji Yüksek Lisans

Tez Yöneticisi: Yard. Doç. Prof. Dr. Bülend Ortaç

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Yüksek güçlü fiber lazerler bilimsel araçlar, endüstriyel malzeme işleme, görüntüleme, medical ve askeri alanlar gibi pek çok uygulama açısından önem taşırlar. Fiber lazerler lazer uygulamaları için sinyal kazanım ortamı ve ışık iletim sistemi açısından iyi kurulmuş konsepttir. Nadir element katkılı fiberler, katı hal lazer konspti içerisinde verimli diyot pompalama, yüksek güçlü ve devamlı dalga açısından geleceği en parlak olan konsepttir. Fiber lazer sistemlerinde, yeni jenerasyon fiberler kullanılmaktadır. Fiber lazer sistemleri, alanda kolay kullanımı, yüksek ışık kalitesi, düşük maliyet ve düşük termo-optik problemler açısından tercih edilmektedirler. Fiber lazer sisteminde bulunan aktif ortam ile ışık ortam boyunca yükseltilir. Uzun aktif ortam sayesinde ısınma problemi azaltılır, ışığın yüksek oranda absorbsiyonu, yüksek ışık kalitesi sağlanır ve kavitenin optimizasyon ihtiyacı azaltılır. Metal işleme için yüksek güçlü fiber lazer sisteminin dizaynını ve geliştirilmesini yaptık. Endüstride önemli bir işlem olan malzeme delimi ve kesimi güçlü fiber lazerler ile gerçekleştirilmektedir. Bu tezin ana amacı, hızlı ve doğru kesim işlemeyi örneğin; kompakt, düşük bakım ihtiyacı ve benzeri açılardan üstün özellikler ile

gerçekleştiren fiber lazer sistemi geliştirmektir. Fiber lazer rezonatörü öncelikle numeric olarak yazılım yardımı ile çalışılmış ve sonra değişik lazer parametreleri ve lazer mimariliği ile dizayn edilmiştir. Numerik çıktıları gerçekleştirebilmek için, yüksek güçlü tamamı ile fiberden oluşan lazer kavite oluşturulmuştur. Gerçek uygulamalarda, kaviteyi oluşturmak için kullanılan, açık uzay komponentleri, çevresel dengesizliklere, güç kaybına ve bu etkenlerde fiber lazerin verimliliğinde düşüşe yol açmaktadırlar. Tamamı fiberden oluşan lazer sistemlerinin en önemli avatajlarından biride nem titreşim gibi çevresel faktörlerin üstesinden gelebilmesidir. Güçlü pomplama sistemleri (yüksek güçlü diyot lazerler), pasif lazer kavite komponentleri (kombiner, FBG) ve ayrıca yüksek güç seviyelerinde çalışan çift kabuklu aktif fiberler kullanmak, fiber lazer sistemlerinden yüksek güç seviyesine çıkabilmek için,büyük önem taşırlar. Bu çalışmada, yeni jenerasyon lazer kavite komponentleri kullnılmıştır. Pompalama kaynakları gü. Ve dalga boyu stabiliteleri açısından analiz edilmiştir. Ayrıca, aktif ortamda bulunan ittebiyum atomlarını doğru dalga boyunda uyarabilmek için, pompalama kaynağının optimum sıcaklığı ile ilgili çalısmalar gerçekleştirilmiştir. Yüksek güçlü fiber lazer sisteminde, tamamı fiberden oluşan komponentler verimli çalışma için entegre edilmiştir. Elde edilen lazer sistemi kavite dizaynından dolayı, zamansal alanda stabil devamlı dalga boyu sahiptir. Sistemin çıkış gücü 547 W' tır. Sistemin M^2 değeri 1.7' den düşüktür. Sistemin çıkış dalga boyu 1.08 μm de FBG ile stabildir. Ayrıca geliştirdiğimiz fiber lazer sisteminin malzeme kesimi için uygun olduğunu göstermiş bulunmaktayız. 1.7 mm kalınlığına sahip çelik hedefleri başarılı bir şekilde fiber lazerin çıkış gücü ile kesilip delmiş bulunmaktayız (100W).

Anahtar Kelimeler

Fiberler, Lazerler, Yüksek Güçlü Lazer Sistemleri, Güçlü Fiber Lazer Komponentleri, Lazerle Malzeme İşleme

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Chapter 1

1.1 Introduction

Stimulated emission is a quantum mechanical phenomenon which was discovered by Albert Einstein in 1917 [1] and the idea of laser concept is realized. Since then, various types of lasers have been developed. As a gain media, there are many types of materials such as solid state materials, gases, liquids. Also, laser transitions of many types of elements have been demonstrated. To achieve high power laser operation with high brightness can be obtained efficiently by using diode pumped rare earth solid state lasers technology [2]. The first semiconductor laser was developed by Robert N. Hall *et al.*, in 1962 [3]. The kW regimes have been achieved by the new diode systems such as stacks and bars.

In classic solid state lasers gain media is a rod hence when this media is pumped, there is a temperature increase in the center of the rod. This situation leads to limitation in power scaling and obtaining good beam quality. Therefore different shapes of gain media have been invented such as slab [4] or fiber designs [5]. Snitzer *et al.*, proposed the use of fibers as an active medium in 1961. They used small fibers as a mode selector for masers. Fibers have a maser material core, surrounded by cladding which has lower refractive index when compared to core. They investigated similarities of the cavity with Fabry-Perot interferometer. Because of the stronger mode coupling and mode selection, they used these principle advantages. In this study, core was small enough to carry only HE_{11} modes. During this study, they encountered with difficulties such as pumping the light into small volume of fiber [6]. One of the most up and coming type of solid state laser system is rare-earth doped fiber laser system.

In 1964, the first operating Neodymium fiber laser was demonstrated at Bell Labs by J. E. Geusic, H. M. Marcus and L. G. Van Uitert [7]. Due to the preferred properties of yttrium aluminum garnet doped with trivalent Neodymium such as optical isotropy, hardness, and stability, it was used as the gain medium and system was pumped at room temperature with tungsten lamp. The emitting light was near infrared which was 1064 nm. They used multilayer dielectric reflectors at 99% at 1.06 μm .

The inadequacy to couple high power pumps into the single clad fibers leads to failure in the system. The first developed double clad fibers was demonstrated in 1974. In this concept, core of the fiber was covered with a lower refractive index material. Hence light can be guided in the inner cladding. This concept is used for active fibers to couple the high power low beam quality diode fibers so that this limitation was overcome [8].

In 1988, Hanna *et al.* showed ytterbium doped (YDFL) fiber laser which had wide turning range between 1.015 μm and 1.40 μm when they pumped by a dye laser at 840 nm [9]. Developments in the area of lasers are in progress since then.

In 1999, Dominic *et al.* demonstrated 110 W fiber laser. In this study they used Yb doped fiber which had a rectangular inner cladding. They pumped the system at 915 nm wavelength with diode bars. The total input power was 180 W. They used dichroic mirror, which was used high reflective mirror, to couple the light into the fiber and fiber and was polished so that they obtained laser output coupler. They obtained 110 W output power at 1120 nm wavelength [10].

In 2004, Barannikov *et al.* presented 250W single-mode linearly-polarized Yb doped fiber laser. Their system consisted of two stages. First one was master oscillator. To achieve linear polarization they used polarizer in the laser cavity. Also to couple the light they used mirror which had 99% of reflectivity. First

stage emitted 90 W pump power. The second one was booster amplifier and they used 14 m panda type fiber. The system was pumped 450 W and the output signal was at 1076 nm wavelength. The M^2 of the system was < 1.04 [11].

In 2004, Khitrov *et al.* showed 306W all-fiber linearly polarized Yb fiber laser. They used polarization maintained (PM) large mode area (LMA) Yb doped fiber which was 33 m long. They used FBG with $> 99\%$ reflectivity. On the other end of the fiber was cleaved which provided 3.5% Fresnel reflectivity. They coiled the fiber to eliminate transverse modes. The system was pumped at 915, 940, 976 nm wavelengths and total pump power was 496 W. The output signal of the laser was 1086 nm wavelength [12].

In 2004 Jeong *et al.* demonstrated Yb doped 610 W fiber laser. They used Yb doped fiber as an active medium. The fiber had D shape to increase the cladding mode to overlap with the Yb doped core which was 9 m long. The pump wavelength was at 972 nm. The pump power of the system was 760 W. The cavity was obtained by using high reflectivity dichroic mirror at 1.1 μ m and the other end of the fiber has 4% reflecting face. The obtained the laser centered at 1090. The laser spectrum was between at 1070 and 1100 nm [13].

In 2004, Jeong *et al.* developed a Ytterbium-doped fiber laser with 1.36 kW output power and cw regime. The output wavelength was 1100 nm and the slope efficiency of the laser was 83%. They pumped the system at 975 nm wavelength with diode stacks and the total pump power was 1.8 kW. Their active medium was D-shaped inner cladding. Their beam quality M^2 was 1.4. They used dichroic mirrors to couple the pump light into the fiber and the fiber end cleaved perpendicularly which leaded to 4% reflectivity. In order to achieve these parameters we can increase the pump power, change the fiber type [14]. Also this design can be improved by using FBGs to avoid the free space losses.

The new generation of active fiber results the increase of the fiber laser output. The long interaction path of the light in the active medium permits very large gains. Furthermore, due to single mode light, high beam quality is obtained which is not connected with the output power of the fiber laser. Also, using fiber based reflectors which are known as fiber bragg garting (FBG), combiner leads to avoid alignments and free space components. Moreover, heat can be dissipated due to the large surface-to-active-volume ratio of active fibers. These are the main reasons of power handling property of fibers. To use rare-earth materials advances these properties. The most attractive one is the ytterbium which has a very close signal wavelength compared to pumping wavelengths. On the other hand, power scaling results in some phenomena such as nonlinear effects and thermal problems in fibers. The new generation of large mode area fiber is overcome this issue at certain level. Theoretical studies have also become crucially important in order to fully understand those parameters and to design efficient fiber devices and systems [15].

The motivation of this thesis is to develop 500 W fiber laser resonator for metal processing. The fiber laser resonator was firstly numerically simulated by using software and various parameters which are studied in simulations. In order to do the simulation, we designed the fiber laser cavity architecture. In order to achieve high powers, it is vital to increase the pump power of the system. Also fibers which is used in the system should handle high power and temperature. So in this study we used new generation fibers to overcome thermal problems. Moreover, as it is explained in the literature using the free space components to constitute the cavity causes power loss which leads to decreasing of the fiber laser efficiency. Therefore we used fiber based components. Instead of using dichroic mirrors we used FBGs in our system. Also high power combiner was used to couple the light in to the fiber rather than using lenses and mirrors so that we avoid power losses and thermal problems. One of the most important advantage of the all fiber laser system is that it does not suffer from environmental factors such as humidity, vibrations. In this study, pump sources

have been analyzed in terms of power and wavelength. Also, experiments have been performed to keep pump sources at optimum temperature to obtain accurate wavelength to excite ytterbium atoms. The fiber laser is operating in the continuous wave regime due to cavity design. The fiber laser was cavity established with FBGs and the active fibers. The output power of the system is 547 W. The M^2 of the system is < 1.7 . The laser has continuous wave regime in temporal domain. The output wavelength of the fiber laser was 1.08 μm . We tested our fiber laser system for cutting and drilling process. We demonstrated the cut and drill results on steel material.

1.1.1 Fiber Laser Technology

Fiber lasers are different than standard solid state lasers in terms of gain medium being rod, slab or disk. From the central core of the fiber, laser light is emitted. Due to the fact that fiber has a large surface to volume ratio, heat can be dissipated relatively easier than other type of lasers [16]. Fiber lasers are optically pumped usually with diodes. Fiber laser systems are usually composed of fiber components most of which are fiber-coupled to one to another.

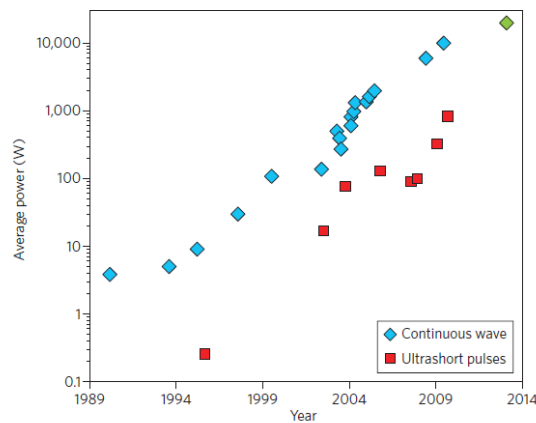


Figure 1. 1: Evolution of the average output power of fiber lasers [15]

Fiber laser systems are known with high beam qualities and high average output powers. These properties of fiber laser systems have wide range area ranging from to industrial military to scientific applications. In the last two decades, the power of the continuous wave, diffraction limited fiber lasers is increasing. Between in 1990 and 2000 the output power was more than 100 W. After 2000 fiber laser systems have reached kW ranges. In 2009 the output power was 10 kW. The evolution of the average output power of fiber lasers is shown in fig. 1.1 [15].

All fiber laser systems has many advantages such as, low thermo-optical problems, high quality and efficient laser light, environmental stability, compactness, low cost. Fiber laser systems, with the ease of use provided by the field, are preferred especially for high-power laser systems because of reduced heating problem, higher productivity level for increased rate of absorption of the pumped light, and high-quality optical cavity laser light produced during the use and optimization of the system [17].

1.1.2 Principles of Fiber Laser

The word laser corresponds to Light Amplification by the Stimulated Emission of Radiation. Stimulated emission is a quantum mechanical phenomenon which is discovered by Einstein in 1917 [1]. It is possible to create an emission by stimulating an electron with electromagnetic field which is already found in the upper energy state. When electrons absorb second photons, the emitting light is in same direction with the incoming photon. All of the irradiated photons are in the same phase, frequency, polarization and direction. Coherent light is obtained by stimulated emission [18].

Due to light-matter interaction three physical phenomena occurs; absorption, spontaneous emission, and stimulated emission. A simplified scheme of these

processes, when only two energy levels E_1 and E_2 are involved, is shown in Fig. 1.1.

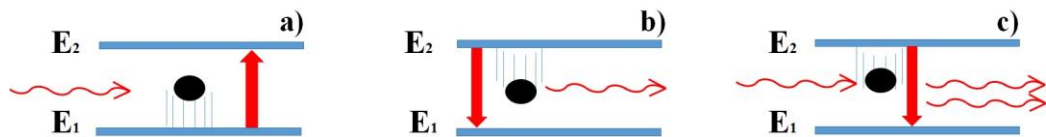


Figure 1. 2: Scheme of a) absorbtion b) spontaneous emission c) stimulated emission

Electrons which are found in ground state have the energy of E_1 . If a photon hits electrons with enough energy to excite them into upper energy state, this process is called as absorption. This event can lead to population inversion which is explained as when more electrons found in the excited energy state compared to lower energy state and the population inversion is the building block of the laser systems.

Excited electrons can go back to their ground state by emitting a photon randomly. This is so called spontaneous emission or luminescence which in this process the emitting photons have different phase, frequency, polarization, and direction. It can be defined as incoherent radiation [18].

A working laser is composed of resonator with gain media and pump sources which is called pump diodes or laser diodes to provide energy to electrons in the gain medium.

Pump source can be a single diode, or many separate pump diodes each of which has a fiber going into a combiner. The fiber which is doped with rare earth material is the gain medium. The cavity mirrors, which are so called fiber bragg

gratings, can be fabricated in the fiber. The cavity mirrors are found on each end of gain medium fiber. In fiber lasers, there are no bulk optics at the end, as long as the output beam does not go into anywhere other than a fiber. The gain medium can be long so it can be coiled according to bending ratio[2]. The result is all fiber laser system. In fig 1.2 shows the scheme of all fiber laser system.

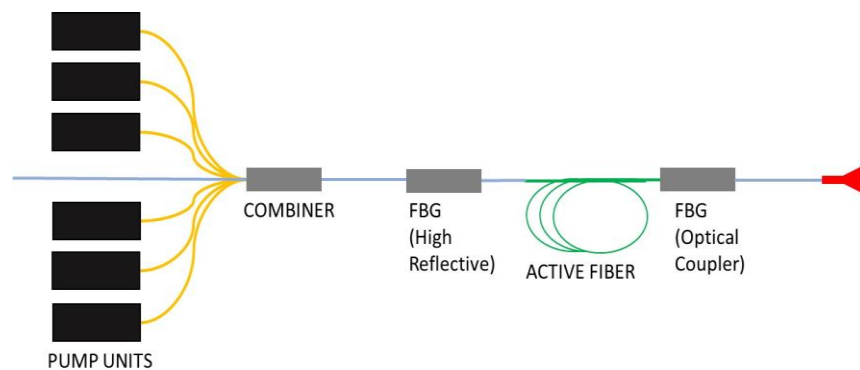


Figure 1. 3: Schematic of all fiber laser system

A long interaction length is given by using fiber as a gain medium which this situation serves very efficiently for pump diodes. High photon conversion efficiency results from this design along with durability and compactness [20]. Owing to the fact that fiber components are spliced with each other, there is no need for optics to make alignment.

1.1.3 Application Areas of Fiber Lasers

In fiber laser systems, light is coupled into a flexible fiber so that it allows light to be delivered easily. Because of the fact that fiber lasers have low thermo-optical problems, high vibrational stability, extended lifetime, free maintenance, low cost and high peak power, they can be used in the areas of material processing such as marking, engraving, cutting, telecommunications, spectroscopy, medicine, military and so on [21].

The fiber-based laser systems are highly adaptable [22]. These kind of systems can be adapted to various application areas from welding, drilling marking of metal sheets to producing femtosecond or nanosecond pulses even fiber amplifiers.

There are several new breakthroughs that build upon the unique properties of the laser. Due to fact that laser light is coherent, it forms highly order light waves. This leads to applications such as holography, astrophysics. Also laser light emits monochromatic light which means emitting ultra-pure colors. Hence the applications of this property is atomic clocks, astronomy, and metrology. Moreover, laser light has high frequency that encodes enormous amounts of information so that it is used for supercomputing, telecommunication. Furthermore laser light can be focused small spots less than 1/100 width of hair which opens the doors of application of optical data storage. One of the other important property of the laser is that laser light can have high power which means delivering the high intensities to small areas. Therefore it is used for manufacturing, cutting, welding, and surgery. Laser light can generate short pulses which are shorter than a femtosecond so that applications of this property are advancing our understanding of biology, physics, chemistry, stroboscopic pictures of atoms and molecules in action. Finally, laser light has large pulse energies. It creates pulses shorter than 10 billionths of a second with energies greater than a stick of dynamite. It can be taken advantage of the applications such as drilling, laser fusion [21].

1.2 Fiber Technology

Fiber technology depend on the basic principle of total internal reflection. Total internal reflection can be explained as a phenomenon which occurs when a propagating wave hits a medium boundary such as water or glass at an angle which is larger than normal of the surface. In order to occur total internal reflection there are two conditions;

1. The wave must propagate from a medium which has a high refractive index to another medium which has less refractive index.
2. The angle of the propagating wave must be larger than critical angle.

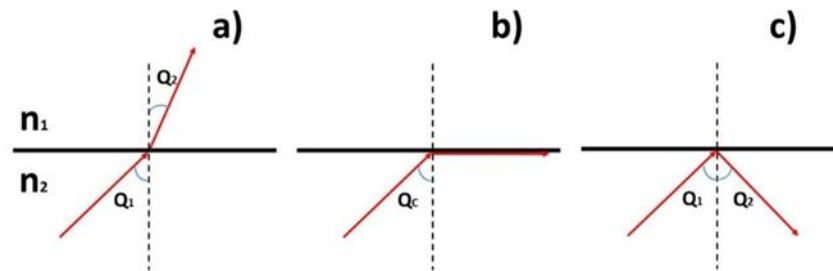


Figure 1. 4: $n_1 < n_2$ a) Refraction of light b) Critical angle c) Total internal reflection

Critical angle is the angle that the waves cannot pass through to the other medium which has lower refractive index. When a propagating wave hits a boundary between mediums, the wave can be partially reflected and partially refracted. On the other hand, when the incident wave hits a boundary with an angle larger than the critical angle, the wave is reflected and the wave cannot cross the boundary leading to a total back reflection to the internal part [23].

The optical fibers are composed of core and cladding which are highly pure solid glass. An acrylate polymer is covered the cladding to protect the fiber. This is so called coating which protects the glass dust, scratches and gives the glass durability. The coating can be easily removed from the glass by stripping in the case of fiber processing such as cleaving, splicing [24].

1.2.1 Double-clad fibers

Double-clad fibers are extremely important for high power fiber laser technology and amplifiers. H. Po *et al.* invented cladding pumping and this is one of the most important step offiber amplifiers and lasers[25]. It is possible to reach continuous power and several kilowatts by using this method. In the meantime output signal is near diffraction limited beam quality [13].

Good beam quality depends on single mode of the output of the active fiber. Pumping units have single mode core which is desirable for beam quality. However, they are limited interms of power for high power fiber laser systems. Multimode fibers can carry high power but output is poor interms of beam quality. Therefore, to obtain high beam quality, the core of the active fiber should be in single mode.

This contradiction was solved with double-clad fiber by Snitzer *et al.* in 1988 [26]. They studied with fibers by coupling high power multi-mode pump laser into a large inner cladding (ic) index lower than core but higher than outer cladding (oc).

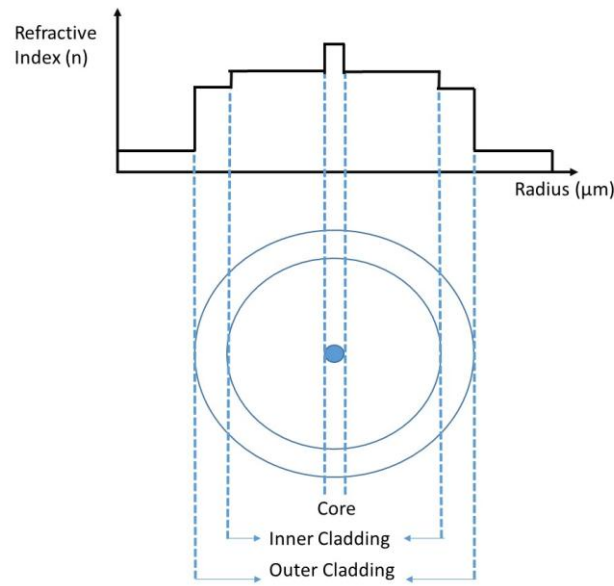


Figure 1. 5: Refractive index profile of double clad fibers

This can be expressed by $n_{\text{core}} > n_{\text{ic}} > n_{\text{oc}}$ so that the guiding of the light is maintained by total internal reflection in inner cladding and same for the core, but for a different range of wavelengths. Hence, high power diode lasers can be used as the optical pump source. The inner cladding has larger area than the core therefore has a higher numerical aperture. This leads to carrying of many propagation modes in inner cladding. Pump light is absorbed by active dopants in the core when it is coupled to active fiber. In active fiber, the pump light is amplified so that even by using low beam quality of the multimode diode laser, single mode beam quality can be obtained. In fig. 1.5 cladding pumped double clad active fiber was shown.

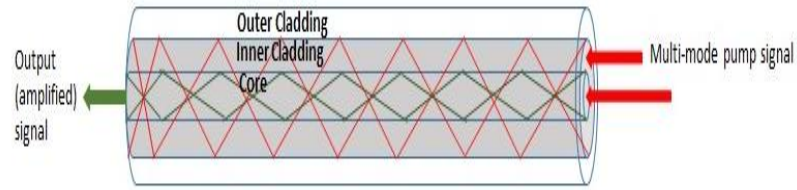


Figure 1. 6: Light guidance in the cladding pumped double-clad fiber

It is an easy process to couple the pump light into the inner cladding because of its large numerical aperture. When pump light propagates into the inner cladding, output signal propagates into the core. Because of the fact that core is doped with rare-earth material, while light propagates into the core, it stimulates atoms and amplification of light occurs [27]. It is called cladding pumping.

To increase the coincidence of the pump modes with core of the fiber, different inner cladding geometries were developed. In fig 1.6 double clad fiber designs with non-circular inner cladding geometry were shown.

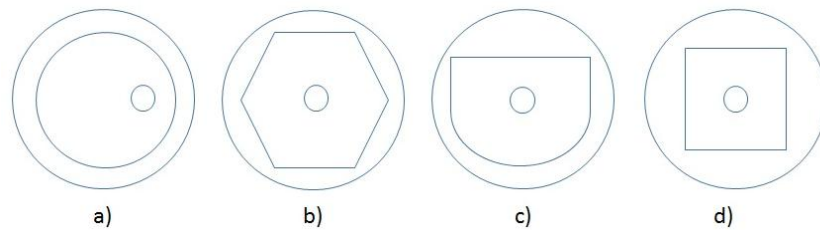


Figure 1. 7: Different fiber inner cladding and core geometries used for increasing pump absorption: (a) offset core fiber, (b) octagonal inner cladding, (c) "D" shaped inner cladding, (d) square inner cladding.

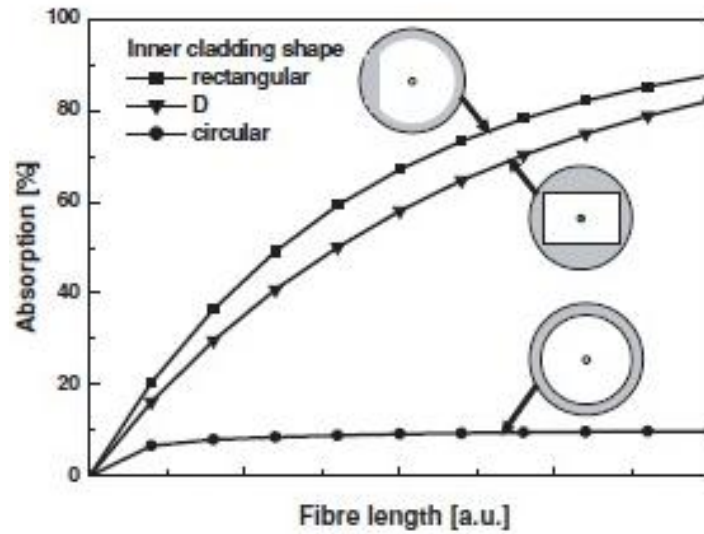


Figure 1. 8: Light absorption of different type of double clad fibers [2]

The disadvantage of the double-clad fibers have reduced pump light absorption. The reason of that is the intensity distributions mainly found in the inner cladding. It is not coincide with the doped core. Therefore, efficiency reduces. This situation can be overcome by altering the symmetry of the inner cladding. Geometries which are shown in fig 1.7 can avoid the undesired modes of the pump light by mode mixing. Also, another option to overcome this undesired modes is to bend the fibers periodically [2].

1.2.2 Large mode-area fibers

It is possible to maintain both diffraction limited beam quality and high output powers with double clad fibers, especially large-mode-area (LMA) DC fibers. LMA fibers support few modes so that excellent beam quality is obtained. By using single mode (SM), it is possible to obtain diffraction limited outputs. However, SM fibers cannot be used for high power applications due to their small mode area. On the other hand, multi-mode fibers (MM) can handle

high powers but they have poor beam quality because of the presence of many modes in them [28].

LMA fibers have reduced optical intensities so that possibility of occurring nonlinear effects decreased and damage threshold of fibers are increased. Typically, SM fibers have low effective area. On the other hand, LMA fibers have very large area than SM fibers. To eliminate nonlinear effects and damage in the fibers, the core size has to be increased [29]. Those fibers are called LMA fibers. LMA fibers supports few modes. By bending the LMA fibers, extra modes can be eliminated as it given .n fig.1.9 [30].

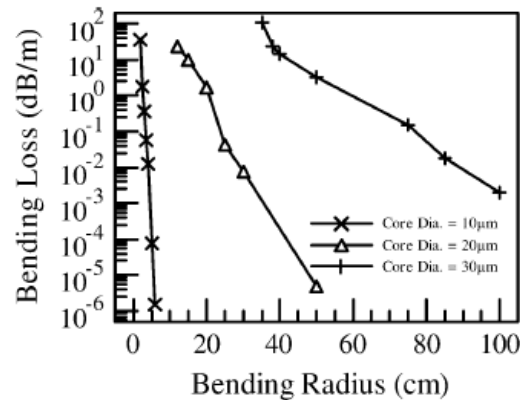


Figure 1. 9 :Bending loss as a function of bending radius for SM, SI and LMA fibers [30].

The dilemma is that when the core size increases, the beam quality reduces. To overcome this effect and to maintain single mode, there are several options. The most significant one of them is that numerical aperture can be decreased while increasing the core diameter, so that high powers can be achieved without nonlinear effects and damaging the fiber [21].

Recently, because of the advantages of LMA fibers, in fiber laser technology has significant increment about diffraction limited beam outputs from diode

lasers which have high brightness, continuous-wave (cw). The output power of Yb-doped fiber lasers have reached tens of kilowatts in 2014 [15].

1.2.3 Attenuation in fibers

Attenuation can be explained as the reduction of intensity of light in fiber optic cables. Attenuation in fibers can be caused by optimization, fiber geometry, design of system and environmental factors. More specifically, it can be caused by the structure of glass such as atomic structure, point defects, fiberization process, interfacial structure of core-clad surface, and uniformity of core-clad structure. The loss of light power is expressed by decibel (dB) in optical fibers. Loss in fiber optical cable is the attenuation per 1-km length and expressed as dB/km, which is the attenuation coefficient. It is calculated by below equation 1 (eqn.1); [31]

$$\alpha_{total} \left(\frac{dB}{km} \right) = 10 \log \frac{P_{input}}{P_{output}} \quad (\text{eqn. 1})$$

Here, P_{input} is the input power of light in to the fiber; P_{out} is the output power of the light; α_{total} is the loss of light. To obtain total loss in fiber, the result is multiplied with total length of fiber. There are several parameters that effects the attenuation;

1. Extrinsic parameters
2. Intrinsic parameters
3. Bending losses
4. Splice and connector losses
5. Fiber structure
6. Fiber fabrication
7. Rayleigh scattering
8. Absorption
9. Simulated nonlinear scattering [31]

1.2.4 Nonlinear effects

Nonlinearity is an optical phenomenon which is the nonlinear response to a light field [32]. Basically, under an applied electric field electrons act in anharmonic motion. Because of the fact that the anharmonic motion electric dipoles is not linear, polarization P can be calculated with the following equation 2 (eqn. 2):

$$P = \epsilon_0 X^{(1)} E + \epsilon_0 X^{(2)} E^2 + \epsilon_0 X^{(3)} E^3 + \dots \text{(eqn. 2)}$$

where ϵ_0 is the permittivity of vacuum and $X^{(k)}$ ($k = 1, 2, \dots$) is k^{th} order susceptibility [33].

$X^{(1)}$ which is the linear susceptibility makes the major contribution to P . $X^{(2)}$ is the second order susceptibility which is responsible for second harmonic generation, frequency doubling, sum and difference frequency generation, and parametric amplification. For instance, silica terminates $X^{(2)}$ due to asymmetric molecule of silica [31]. Hence, second order nonlinear effects are not seen in optical fibers. On the other hand, second harmonic generation can reveal itself under certain conditions. For instance, defects in the fiber core can contribute to second harmonic generation. Finally, $X^{(3)}$ has the minor contribution to nonlinear effects in fibers [32].

Below, the explanations of nonlinearities in order to sum up all nonlinear effects are given;

- $X^{(2)}$ is responsible for effects such as frequency doubling, sum and difference frequency generation, and parametric amplification [32].
- $X^{(3)}$ is responsible for the Kerr effect which increases the refractive index which is directly proportional to the intensity. This situation reveals effects such as

self-focusing, self-phase modulation, cross-phase modulation, and four-wave mixing [33].

- There are two types of Raman scattering, which are linear and non-linear. Nonlinear optics based on stimulated Raman scattering. It is related to $X^{(3)}$ nonlinear polarization. Raman scattering can be spontaneous and stimulated. If monochromatic light (laser) propagates in an optical fiber, spontaneous Raman scattering (SRS) happens. Some of these photons are introduced to different frequencies. Hence scattered photons can lose or gain energy. In stimulated Raman scattering, if there is linearly polarized pump light, the polarization of the scattered light can be parallel or perpendicular. In case when the photons are already within other frequencies, these photons in these frequencies can be increased. This is called stimulated Raman scattering [31].
- At large intensity in an optical fiber, Brillouin scattering occurs. Because of the fact that the electric field generates stress in the core of the fiber, electrostriction is formed. It causes difference in the refractive index of the medium. The scattered pump light is called as Brillouin scattering [32].

One of the differences between Raman scattering and Brillouin scattering is that while optical phonons are participated in Raman scattering, acoustic phonons are participated in Brillouin scattering. Another difference is that Raman scattering can form in back and forward directions but Brillouin scattering occurs in only one direction [32].

- If two photons are simultaneously absorbed, this process is called two-photon absorption. This is related to $X^{(3)}$ nonlinear polarization. It is usually bigger for semiconductor media with small bandgap energy [33].

1.2.5 Ytterbium-doped gain media

The first Ytterbium-doped fiber laser was developed in 1988 by Hanna *et al.* [9]. Due to the fact that ytterbium-doped systems have higher excited state absorption and emission bandwidth, Yb-doped systems became popular among the other rare-earth doped fibers. Yb- doped fibers have broad wavelength range between 975 and 1200 nm which this can be considered as a very broad range [34]. Because of the fact that ytterbium ion has simpler energy level scheme compared to the other rare earth materials, it is suitable for diode pumping applications [35]. Yb-doped systems also have no concentration quenching and have small thermal loading.

In 1971, Reinberg *et al.* used a GaAs: Si light-emitting-diode (LED) as a pumping unit which had 1.03 μm wavelength. They used YAG:Yb laser rod which had been constructed with the rod and they cooled it at very low temperatures. Finally, they obtained pulsed operation with a peak laser power of 0.7 W [36].

In 1991, Lacovara *et al.* used InGaAs diode laser as a pump unit which was 968 nm wavelength. Thermoelectric cooler was used to control the temperature. They showed that high efficiency diode-pumped operations could be possible with using more diode lasers [37].

1.2.6 Electronic level structure of Yb³⁺ ions

Ytterbium (Yb) is an element which is known as rare earth metal. The ytterbium ion which is Yb³⁺ is used as a doping material in lasers that is called active/gain medium in solid state lasers and fiber lasers [38]. In general, Yb doped lasers operate at 1.06–1.12 μm wavelength when they pumped at 900 nm – 1 μm wavelength optically [35, 39].

The Yb^{3+} is a suitable ion for diode pump due to the fact that it has simpler level scheme and desirable for laser systems [35]. Yb^{3+} has $4f_{13}$ shell which lacks one electron compared to filled shell [35]. In Yb^{3+} ions, the two energy levels is comprised for light amplification which are $^2F_{7/2}$ and $^2F_{5/2}$ with near infrared or visible ranges. The first one is the ground level and the second one is the higher excited level [33, 35].

Due to the stark effect, these energy levels in pump and laser transitions are split into sub-energy levels. Stark effect is the splitting of atomic energy levels of radiating atoms, ions or molecules when they subjected to an exterior electric field [40]. It is shown in fig. 1.8.

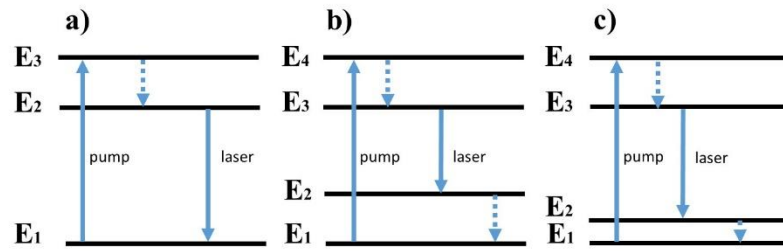


Figure 1. 10: Energy level diagrams of different laser systems. Energy levels are shown as horizontal lines. The higher the line, the higher the energy they correspond to. a) Represents three-level system as it is seen the transitions of laser ends at ground energy level. b) Represents four-level system. The transitions of the laser ends where the laser transition ends at energy level E_2 . c) Represents quasi-three-level system. In thermal equilibrium, population occurs at the lower laser energy state.

There are several advantages of Yb-doped active medium. One of the most important advantage is that only one excited state level is comprised for laser transitions. Comparing to other rare earth materials Yb has smaller energy band gap between ground and excited states leading to low quantum defects. Generally, wavelength of lasing photons is higher than the pump photons which

meanthat energy of lasing photons is lower than that of the pump photons. It is called Stokes shift. 100% of power efficiency cannot be obtained even every pump photons transformed into laser photons. The quantum defect can be explained as the difference of photon energies which is given in equation 1.2.6(eqn. 1.2.6); [41].

$$q = hv_{pump} - hv_{laser} = hv_{pump} \cdot \left(1 - \frac{hv_{laser}}{hv_{pump}}\right) \quad (\text{eqn. 1.2.})$$

Yb-doped active medium has small quantum defect,in other words it has a few percent of the pump photon energy, so that Yb-doped laser devices has higher power efficiency and low heat generation. On the other hand, small quantum defect causes quasi-three-level behavior of active medium. The transitions of laser end on ground state for three level systems. The strong absorption occurs in unpumped active medium during the laser transition. The threshold pump power gets higher due to the fact that population inversion and laser gain emanates when atoms or ions are pumped into upper energy level. In quasi three level mediums, there is an intermediate level which is very close to the ground state [42]. A significant part of population in that level is presented in heat balance at the operating temperature. Hence, the unpumped active medium provokes reabsorption loss at the laser wavelength. Therefore higher pump intensities is needed for laser operations.

It can be seen that quasi-three-level or four level in Yb doped fibers can vary according to pump and seed wavelengths. Around 1030 nm, it is seen strong three-level behavior. After 1080 nm the transitions of laser arises at energy levels which is higher than ground level so system presents four-level behavior which produces very small reabsorption. In this case, there is a large band gap between ground level and lower lasing level, so population inversion can be achieved and laser threshold gets lower [43].

1.2.7 Spectroscopic analysis of Yb doped fibers

Yb silica fiber has wide range of application areas such as fiber lasers and amplifiers[44]. Between 800 nm and 1064 nm pumping wavelength, the gain can be obtained between 976 nm and 1200 nm which shows that it is a very wide range [27]. Yb has simple electronic structure which leads to high absorption and emission cross-sections. It is also dependent on the medium which Yb atoms are doped. The absorption and emission cross-sections is presented in fig 1.11.

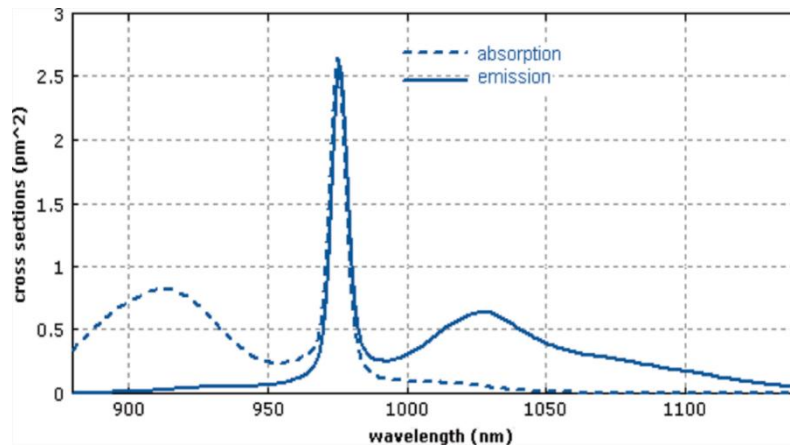


Figure 1. 11: Absorption and emission cross-sections of Yb-doped fibers [34]

As it can be seen from the fig 1.11 there are two choices for pump wavelengths. One of them is at 910 nm wavelength and the other one is at 975 nm wavelength. The absorption cross-section is broad at 910 nm wavelength but at that wavelength, higher pumping energy is required to obtain high gain. At higher pumping energies, amplification of stimulated emission (ASE) leads to a limit for the maximum gain. The higher absorption cross-section is at 975 nm wavelength which eliminates ASE. Also, the system results in high efficient pumping at 975 nm wavelength.

The broad absorption bandwidth at high cross-section is very suitable for continuous-wave (cw) fiber lasers. Hence, gain can be reached at 1000 nm to 1100 nm range. Because of the fact that 975 nm pumping wavelength has quasi-three level behavior and re-absorption loss, the length of the fiber must be optimized cautiously.

Even if there are some disadvantages of Yb-doped fibers, it has also many advantages such as high power efficiency, low thermal effects and high gain bandwidth [34]. These advantages make Yb doped fibers very attractive for high power fiber laser gain medium.

1.3 Modelling of fiber laser resonator

Reduced two level systems can be used instead of three level systems if the non-radiative relaxations to the meta-stable state are extremely rapid[45]. When Yb^{3+} doped gain medium is pumped at 975 nm wavelength, it can be modeled as simple two level laser scheme shown in fig 1.12.

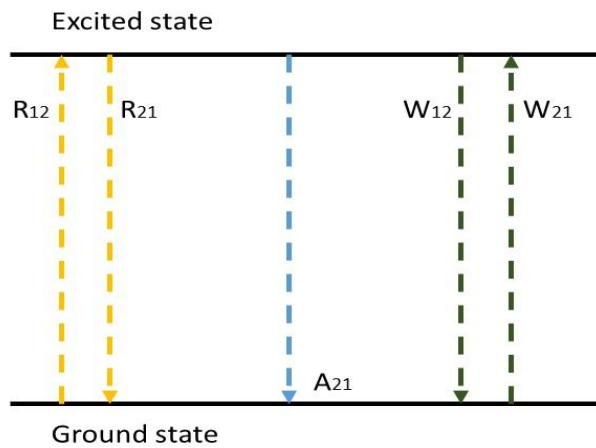


Figure 1. 12: Scheme of two level laser

The relative equations of Yb^{3+} ions in excited energy level and ground energy level are given in equations 3.1 and 3.2 (eqn. 3.1, 3.2) :

$$\frac{dn_2}{dt} = (R_{12} + W_{12})n_1 - (R_{21} - W_{21} + A_{21})n_2 \quad (\text{eqn. 3.1})$$

$$\frac{dn_1}{dt} = -(R_{12} + W_{12})n_1 + (R_{21} - W_{21} + A_{21})n_2 \quad (\text{eqn. 3.2})$$

Here n_1 and n_2 are normalized populations of excited energy level and lower energy level. R_{12} and R_{21} are pump excitation and relaxation rates. W_{12} and W_{21} are core absorption and emission rates. A_{21} is the spontaneous emission rate. According to the conservation of energy law which is in equation 3.3 (eqn. 3.3);

$$n_1 + n_2 = 1 \quad (\text{eqn. 3.3})$$

If the system is steady state (which means that $\frac{dn_i}{dt} = 0$); the normalized population equations are given in equation 3.4, 3.5 (eqn. 3.4, 3.5);

$$n_1 = \frac{R_{21} + W_{21} + A_{21}}{R_{12} + R_{21} + W_{12} + W_{21} + A_{21}} \quad (\text{eqn. 3.4})$$

$$n_2 = \frac{R_{12} + W_{12} + A_{21}}{R_{12} + R_{21} + W_{12} + W_{21} + A_{21}} \quad (\text{eqn. 3.6})$$

In an optical fiber, the pump and core transition rates are related to the absorption and emission cross-sections of the ions which are found in the gain medium. Those transitions are given in equations 3.7, 3.8, 3.9, 3.10 (eqn. 3.7, 3.8, 3.9, 3.10);

$$R_{12} = \frac{\sigma_{ap} I_p}{h\nu_p} \quad (\text{eqn. 3.7})$$

$$R_{21} = \frac{\sigma_{ep} I_p}{h\nu_p} \quad (\text{eqn. 3.8})$$

$$W_{12} = \frac{\sigma_{ac} I_c}{h\nu_s} \quad (\text{eqn. 3.9})$$

$$W_{21} = \frac{\sigma_{ec} I_c}{h\nu_c} \text{(eqn. 3.10)}$$

Here σ_{ap} (σ_{ep}) and σ_{ac} (σ_{ec}) are the pump and the core absorption and emission cross-sections, respectively. I_p and I_c are the intensities. ν_p and ν_c are transition frequencies. The spontaneous emission rate is given in equation 3.11 (eqn. 3.11);

$$A_{21} = \frac{1}{\tau} \text{ (eqn. 3.11)}$$

Here, life time of the Yb^{3+} ions is shown by τ which is found in the excited state.

Those formulas, which are given above, is used for quasi-two-level fiber systems. To find the pump power along the fiber length, the propagation equations are used. These are given in equations 3.12, 3.13 (eqn. 3.12, 3.13);

$$\frac{dP_p}{dz} = \Gamma_p N_t (\sigma_{ep} n_2 - \sigma_{ap} n_1) P_p(z) \text{(eqn. 3.12)}$$

Here, Γ_p is the overlap factor of pump which can be explained as the pump core area over doped area ratio which is $\frac{S_{pc}}{S_d}$. Total ion density is shown by N_t . The propagation of core along the fiber length is given;

$$\frac{dP_c}{dz} = \Gamma_c N_t (\sigma_{ec} n_2 - \sigma_{as} n_1) P_c(z) \text{ (eqn. 3.13)}$$

The equation of small signal gain co-efficient is given in 3.14 (eqn. 3.14);

$$g(z) = \Gamma_c N_t (\sigma_{ec} n_2 - \sigma_{as} n_1) \text{ (eqn. 3.14)}$$

Here, the overlap mode field area with doped area is Γ_c .

For two level systems the relative inversion (RI) is calculated from equation 17 (eqn. 17);

$$RI = n_2 - n_1 \text{ (eqn. 3.15)}$$

From equation 17 different levels of relative inversion is obtained. If RI equals to 1, it means there is complete population inversion and if it equals to -1, it means that there is zero population inversion. When RI equals to 0, there is 50% population inversion. Hence, the length of fiber must be determined cautiously.

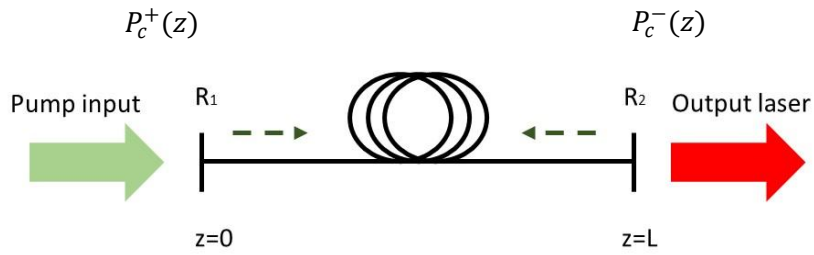


Figure 1. 13: Schematic of pumped fiber laser cavity

In fig 11 $P_c^+(z)$ and $P_c^-(z)$ are the boundary conditions of propagating laser forward and backward, respectively. Those conditions are given in equations 3.16, 3.17, 3.18 (eqn. 3.16, 3.17, 3.18);

$$P_s^+(0) = R_1 P_s^-(0) \quad \text{(eqn. 3.16)}$$

$$P_s^-(L) = R_2 P_s^+(L) \quad \text{(eqn. 3.17)}$$

$$P_s^-(z) P_s^+(z) = \text{constant} \quad \text{(eqn., 3.18)}$$

Here, reflectivity of the resonator cavity are R_1 and R_2 . To obtain gain, equation 3.14 is used by integration over the length of fiber which is given in equation 3.19 (eqn. 3.19);

$$\begin{aligned}
G &= \int_0^L g(z) dz \\
&= \Gamma_c N_t \int_0^L (\sigma_{ec} n_2 - \sigma_{as} n_1) dz \quad (\text{eqn. 3.19});
\end{aligned}$$

To obtain the stationary condition of the cavity the equation is given in 3.20 (eqn. 3.20);

$$R_1 R_2 e^{(2G)} = 1 \quad (\text{eqn. 3.20})$$

By applying the equations 3.12, 3.13 and the stationary condition (eqn. 3.20), the gain can be found as in equation 3.21 (eqn. 3.21);

$$\begin{aligned}
G_p &= \ln \left(\frac{P_p(L)}{P_p(0)} \right) \\
&= \frac{\Gamma_p \sigma_p}{2 \Gamma_c \sigma_c} \ln \left(\frac{1}{R_1 R_2} \right) - \frac{\sigma_{ec} \sigma_{ap} - \sigma_{ep} \sigma_{ac}}{\sigma_c} \Gamma_p N_t L \quad (\text{eqn 3.21})
\end{aligned}$$

The output power of the laser can be calculated from equation 3.22 (eqn. 3.22);

$$\begin{aligned}
P_{output} &= (1 - R_1) P_c^-(0) \quad (\text{eqn. 3.23}) \\
&= \frac{\lambda_p}{\lambda_c} * \frac{(1 - R_1) P_p^{sat}}{1 - R_1 - \sqrt{R_1 R_2} + \sqrt{\frac{R_1}{R_2}}} * \left(\frac{P_p(0)}{P_p^{sat}} (1 - e^{G_p}) - G_p - \Gamma_p N_t \sigma_{ap} L \right)
\end{aligned}$$

If P_{output} equals to zero, it can be obtained the threshold power of the fiber laser. The equation is given in 3.24 (eqn. 3.24)

$$P_{th} = P_p^{sat} \times \frac{G_p + \Gamma_p N_t \sigma_{ap} L}{1 + e^{G_p}} \quad (\text{eqn. 3.24}) \quad [55]$$

Chapter 2

Experiments

In this study, we used Yb doped fibers (Nufern, USA) which are called active fibers as laser gain medium. Active fiber has 20 μm core and 400 μm cladding diameter. To constitute cavity, we used fiber bragg grating (FBG) (ITF Labs, Canada) having two mirrors one of which has higher than 99.9% reflectivity and the other one, the optical coupler, which has 10.4% reflectivity which are working at 1080 nm wavelength. Optical pump units were used to stimulate the gain medium which were laser diodes. Pump units (Dilas, Germany) had 135 W output power and worked at 976 nm wavelength on average. We used drivers to drive laser diodes and controller (Ermaksan, Turkey) was designed to pass the enough current to the diodes. We designed cooling plate to cool combiner and FBG. Also we used cooling units (OmiTurk, Turkey) to cool diodes.

2.1 Fiber laser design

The continuous wave regime model for fiber laser resonator was explained in modelling section. It is obvious that such models are complex and time consuming. Also, advanced and new generation fiber designs are making those equations even more complex so, modeling such systems becomes more difficult. This is one of the main reasons why the commercial software tools are being popular. RP-Fiber Power V5 is one of these kind of software which can be used for the simulations. The software is also practical for modelling fiber specifications and spectroscopic data of both active and passive fibers. Furthermore, it is a useful tool for analyzing the mode distribution in fiber. In other words, light propagation in optical fibers, cavity design and transverse

profiles of light can be obtained by using this software. It is also possible to obtain various laser parameters by applying different pump power, wavelength and reflective ratio. Fiber devices are defined with graphically or script editor.

There are several parameters for all-fiber laser systems. By using these parameters, it is possible to obtain cavity. In order to achieve high power, those parameters are vital. Moreover, reflectivity of FBG, input power of diodes, pumping wavelength, fiber core/cladding diameters are the key features of high power laser systems. Each parameter plays a critical role in fiber laser. While determining those parameters, it is crucial to take into account the heating problems. Before designing the fiber laser we determined some parameter that can be used in fiber laser system. We put parameters in the RP Fiber Power software and run the program. We obtained output powers for different cavity design. Those parameters are given in table 1.

Table 2. 1: The parameters for different type of fiber laser resonator

Design Number	Pumping Wavelength (nm)	Fiber Core/Cladding Diameters (μm)	Laser Wavelength (nm)	High Reflection (%)	Low Reflection (%)	Pumping Input Power (W)	Laser Output Power (W)
1	975	20 / 400	1080	99	10	850	763
2	975	20 / 400	1080	99	15	850	721
3	975	20 / 400	1080	99	5	700	558
4	975	20 / 400	1080	99	10	700	550
5	975	20 / 400	1080	99	15	700	543
6	975	20 / 400	1080	99	5	1200	957
7	975	20 / 400	1080	99	10	1200	944
8	975	20 / 400	1080	99	15	1200	931
9	940	20 / 400	1080	99	5	700	453
10	940	20 / 400	1080	99	10	700	442
11	940	20 / 400	1080	99	15	700	430
12	940	20 / 400	1080	99	5	1200	779
13	940	20 / 400	1080	99	10	1200	759
14	915	20 / 400	1080	99	5	700	513
15	915	20 / 400	1080	99	10	700	505
16	915	20 / 400	1080	99	5	1200	880
17	915	20 / 400	1080	99	10	1200	867
18	975	20 / 400	1080	99	5	700	561
19	975	25 / 250	1080	99	10	700	554

20	975	25 / 250	1080	99	5	1200	1064
21	975	25 / 250	1080	99	10	1200	1064
22	940	25 / 250	1080	99	5	700	578
23	940	25 / 250	1080	99	10	700	574
24	940	25 / 250	1080	99	5	1200	991
25	940	25 / 250	1080	99	10	1200	984
26	915	25 / 250	1080	99	5	700	576
27	915	25 / 250	1080	99	10	700	563
28	915	25 / 250	1080	99	5	1200	973
29	915	25 / 250	1080	99	10	1200	966

We choose the design number 1. The design number 1 parameters were entered into the RP Fiber Power software simulations. According to the table... there are several options that we can choose. The parameters of design number 12 has higher pumping power. To achieve high power, pump power should be increased. The reflectivity of output coupler also can be decreased. The parameters of design number 15 are different than our system. According to literature if we choose design number 15, we should use longer active medium than the design number 1 to obtain 500 W output power. Below the results of RP simulations are given.

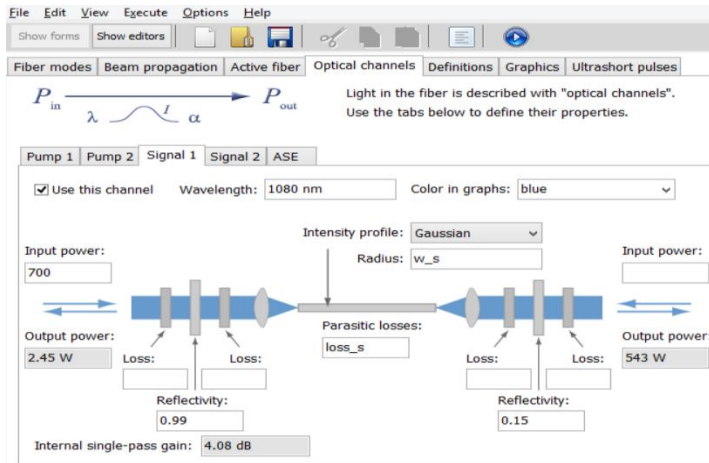


Figure 2. 1: Cavity design of fiber laser with RP simulation

Hence, the cavity design was performed according to this result. Active medium was composed of Yb^{3+} doped fiber and the active fiber length was 15.5 meters.

FBGs were selected with 99% high reflectivity and %10.4 low reflectivity. Also pump units were chosen at 975 nm wavelength and 135 W power.

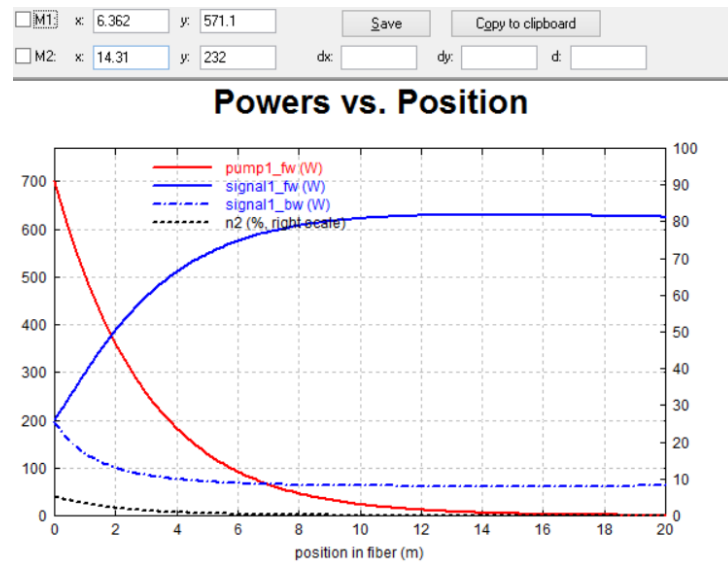


Figure 2. 2: RP simulation of power vs position.

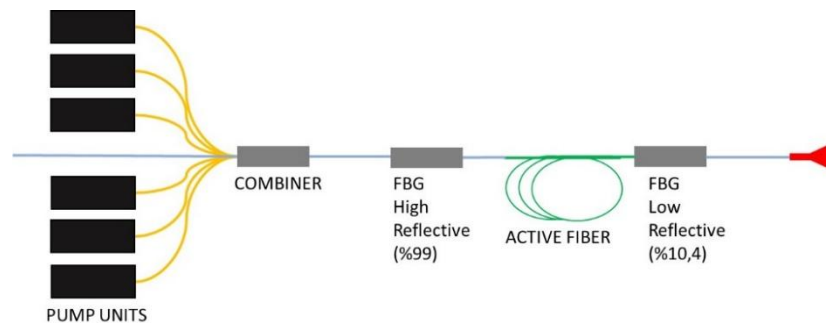


Figure 2. 3: Schematic of fiber laser resonator

After RP simulations, we started to integrate the components. We integrated diodes with combiner ports with no specific specialty.

Fiber ends should not have hackles, mists and cracks. Those failures cause bubble during the splicing process which is shown in fig. 2.4 Fibers also should

not cleave with an angle. In this case splicing process will be poor and power of light will be decreased.

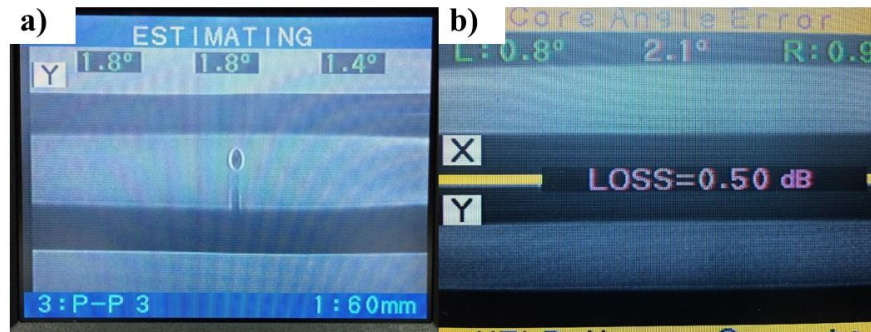


Figure 2. 4: Splice processes a) Bubble formation in splicing b) Mismatch of core angle in splicing

In fig. 2.4 a) 1.8° presents the cleave angle of left fiber and 1.4° presents the cleave angle of the right fiber. In the middle 1.8° presents the angle of fibers according to each other. In the case of cleaving fiber with hackles, mists, and cracks bubble forms which leads to power losses and eventually system will be compromises. In fig 2.4 b) 0.8° presents the cleave angle of the left fiber and 0.9° is the cleave angle of the right angle. In the middle 2.1° is the angle of the fibers according to each other. This value is too high for fiber laser systems. In the case of high core angle, system losses light which leads to decreasing of power.

Before the splicing of diode fibers with combiner fibers, we measured the output power of the all diodes which is given in fig 2.5

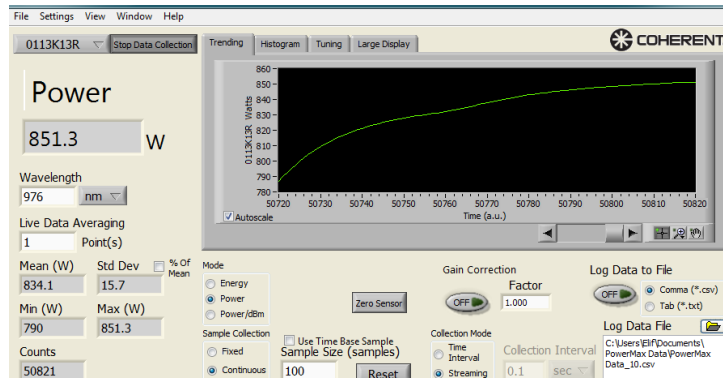


Figure 2. 5: The output power of all diodes.

Diode integrations were made successfully by considering all of those effects. Below fig 2.6, show the integration process of diode and combiner.



Figure 2. 6: Splicing process between diode fibers and combiner fibers

We made the splicing process between diode fiber and the combiner diodes. In fig 2.6 shows that the cleave angles are very low and the angles of diode and combiner fibers according to each other are very low. After splicing process we used optic power meter to measure the power of combined diodes.

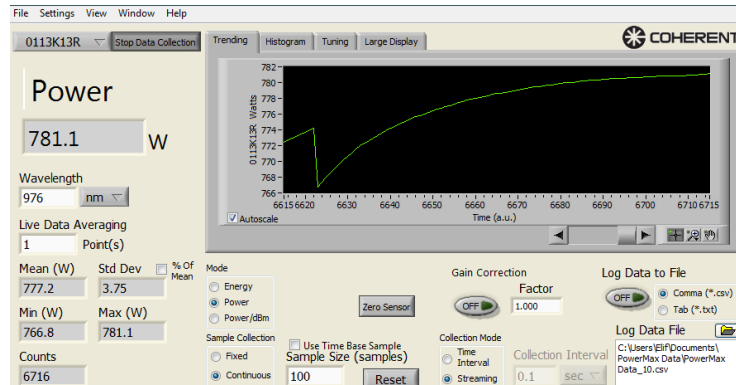


Figure 2. 7: The output power of diodes after splicing with combiner

Due to the high power, we needed to cool the combiner. In order to cool the combiner, we designed a cooling unit. The cooling unit consists of many water channels and it has high temperature conductivity. It worked at low temperatures which is $17 \pm 1^\circ\text{C}$ degree to overcome the heating of combiner. The designed unit is shown in fig 2.8 and 2.9. The cooling unit was designed in UNAM and fabricated by ERMAKSAN (Turkey).

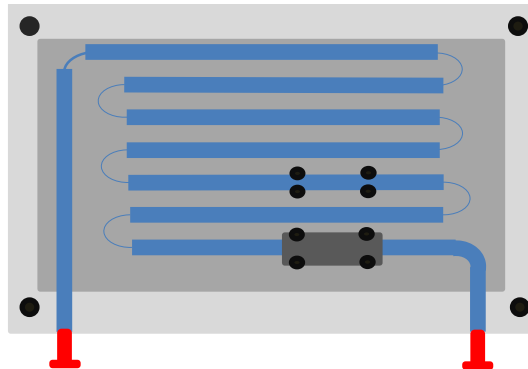


Figure 2. 8: Design of the cooling plate for combiner



Figure 2. 9: The cooling plate for combiner(produced by Ermaksan)

The integration of combiner and the FBG (high reflective) was the next step of the project. We integrated these fibers accurately. In fig 2.10 combiner and the FBG splicing process is shown.

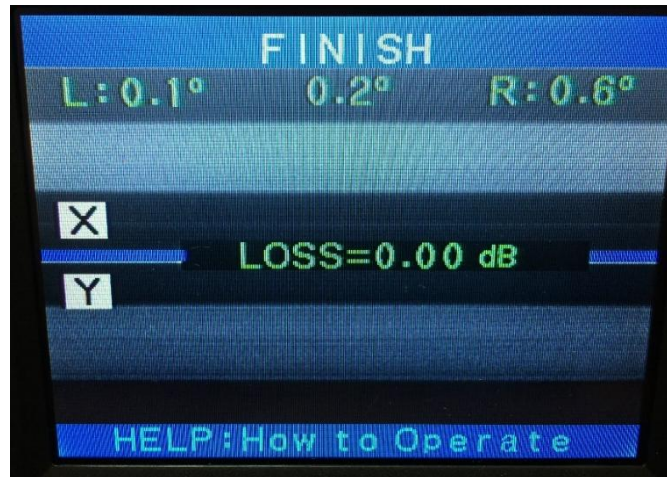


Figure 2. 10: Splicing process between combiner output fiber and the FBG fiber.

The most important step of splicing process is the splicing between active fiber and the FBG fiber since the active fiber geometry is different than the FBG fiber. The active fiber has octagonal cladding structure and the FBG has spherical structure. The loss must be very low to operate the system with quietly

reduced losses. In fig 2.11 is shown the end faces of the active fiber and the FBG fiber.

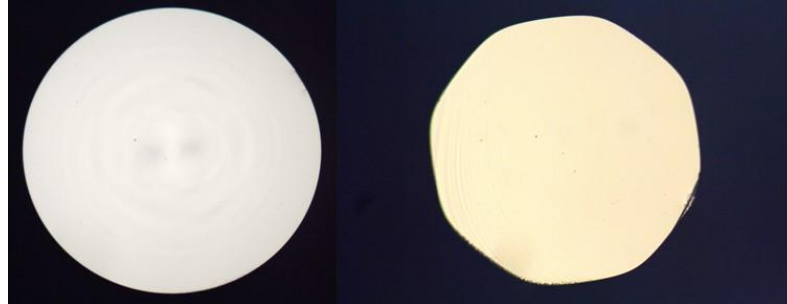


Figure 2. 11: The cross-section images of fibers

As it seen from the fig 2.11 fiber ends cleaved perpendicularly. There is no hackles, mists and cracks end face of the fibers. Hence we obtained appropriate fiber ends for integration process.

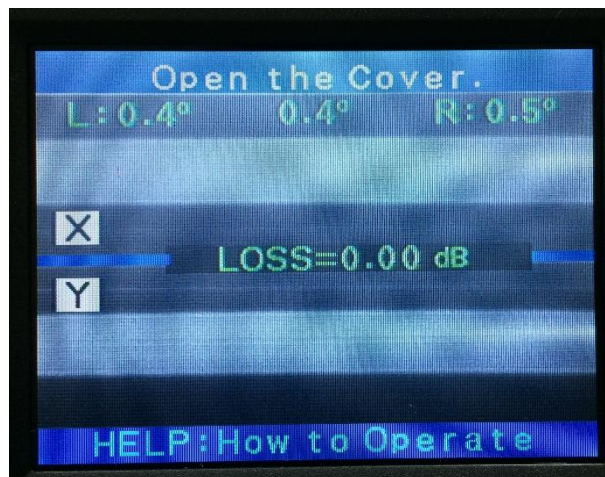


Figure 2. 12: The splicing process between FBG fiber and the active fiber

We then spliced the active fiber and the FBG (low reflective). The integration is shown in fig 2.13.



Figure 2. 13: Splice operation between FBG (low reflective) and the active fiber

In our system we used fusion splicing which is the most widely used splicing process. In this process, basically, arc hits the fibers while fibers are getting closer so that fibers become as a whole. It is a vital process for our fiber laser system. Splicing of the fibers must be done very without loss. Splice loss can be caused several factors such as coaxially, end face, mismatch of cores, concentricity, axial run out. It is directional with these variables. Furthermore, it can be minimized by aligning the fiber cores perfectly. After splicing process there must no bubbles, core mismatch. As it is mentioned, it compromises the laser system. There are several type of splicing processes.

2.2 Characterization of equipments

In this study, we firstly characterized the diodes. In order to characterize the diodes, we needed to drive diodes with appropriate current and voltage values. Those values were indicated in data sheet of diodes. The diodes were driven one by one. Connections between drivers and diodes were provided as shown in fig 2.14.

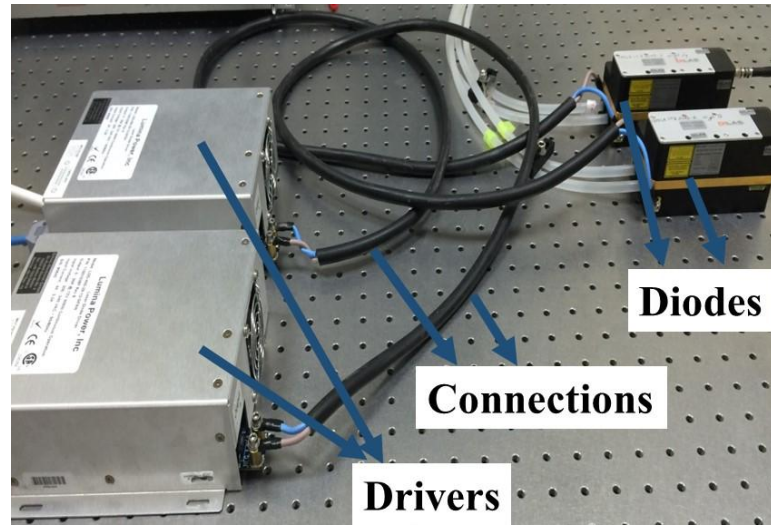


Figure 2. 14: Connections between drivers and diodes

After making connections between diodes and drivers, we developed control panel. With the aid of control panel, six diodes, which are used in the project, were controlled by giving same voltage and ampere values. The control panel is given in fig 2.15. By this means, we concluded the part for the needed voltage and current for pumping units. Control panel was designed and fabricated in ERMAKSAN (Turkey).



Figure 2. 15: Control panel (produced by Ermaksan)

The second important step is to control cooling of pumping units. Diodes produce high pumping power under high current, so it reveals heat generation. We controlled this situation by cooling them actively with a water-based system. For each pumping unit, the heating value was determined according to experimental results and cooled with cooling units. Cooling units worked between 20°C-27°C and has 2 bar pressure. Active cooling procedure was completed by integration of diodes and cooling units as shown in fig 2.16. In further steps we characterized diodes in terms of optical spectrum and power and we determined the needed cooling values for diodes.

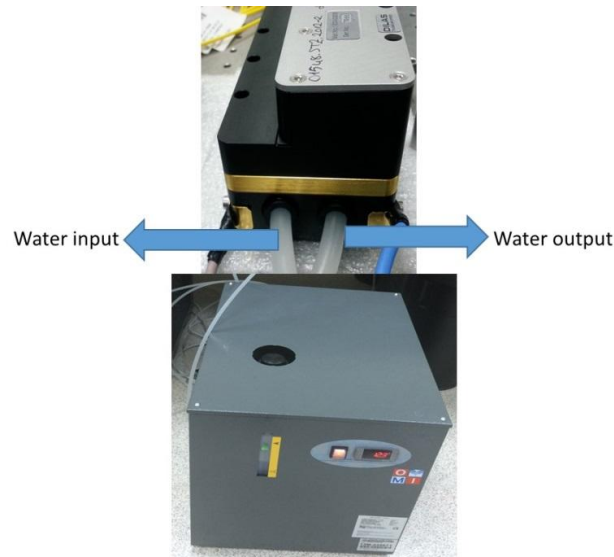


Figure 2. 16: Integration of diodes and cooling units

The next step was to prepare output fibers of diodes. This procedure consisted of many stages. We need to prepare diode fibers with high quality. Fiber optic cables of diodes consist of a core and cladding, which covers core, and the cladding has higher refractive index than that of core. On top of the cladding, there is a fluoroacrylate polymer coating. First of all, we need to strip the coating polymer to prepare the diodes for integration process. After stripping the polymer coating from the surface of the fiber, it should be cleaned with isopropanol to remove any residual coating material. In cleaving process, one of

the substantial part is to obtain smooth end faces such as cleaving fibers without hackles, lips, cracks, chips and angle. If fiber end face is not cleaved properly, it causes problems such as back reflected light, which causes problems in the system, scattering of light, angled cleave causing gap between fibers splice operations, leading to ununiformed splice and light loss.

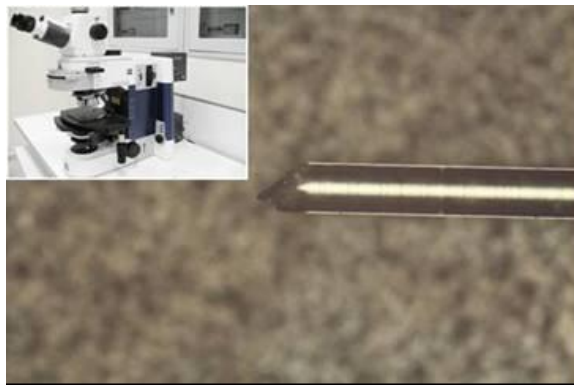


Figure 2. 17: Stripped fiber before cleaving

Progress for preparation of fibers is investigated by using optical microscope. For this investigation we used optical microscope and the result is shown in fig 2.17. After we cleaved this fiber with fiber pen, the obtained fiber end was shown in fig 2.18 a). This fiber cannot be used for integration step. In fig 2.18 b) hackles, cracks, and chips on the surface of fiber end can be easily seen. If this fiber was integrated, we would see bubble on the spliced area and this causes light loss and eventually fiber would burn. Cleaving process was obtained properly by using automatic cleave machines. After cleaving fibers, we obtained surfaces as displayed in fig 2.18.

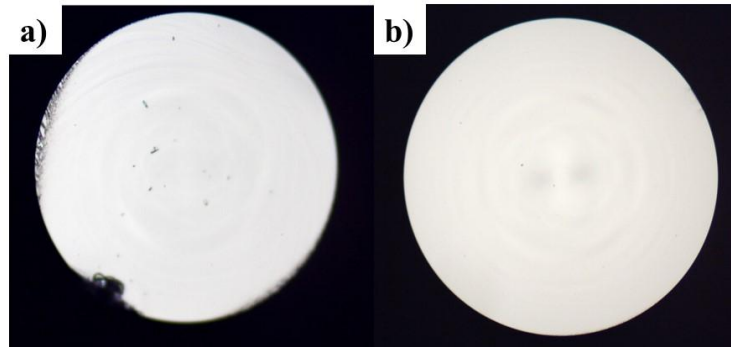


Figure 2. 18: a) Poor cleaving process b) Accurate cleaving process

After stripping and cleaving process, the end faces are cleaned with ultrasonic cleaner. After obtaining cleaved and cleaned surfaces, we characterized diodes. Each one of the diodes were cooled and driven individually. The driving currents and the optimum cooling temperatures of each individual diodes are given in Table 2.2. The equipments that we used for characterization are optic spectrum analyzer and power meter.

Table 2. 2: Parameters used for diodes

Diode Number	Driving Voltage (V)	Driving Current (A)	İdeal Cooling Temperature at 975 nm Wavelength (°C)
1	12	28	24 ± 1
2	12	28	22 ± 1
3	12	28	26 ± 1
4	12	28	26 ± 1
5	12	28	24 ± 1
6	12	28	22 ± 1

The figures between 2.19 and 2.30 represent the diode, power data of each diodes. In fig. Power of diodes were measured with Cohorent Power Max. The

optical spectrum analyses of diodes were measured with Yokogawa AQ6370C Optical Spectrum Analyzer.

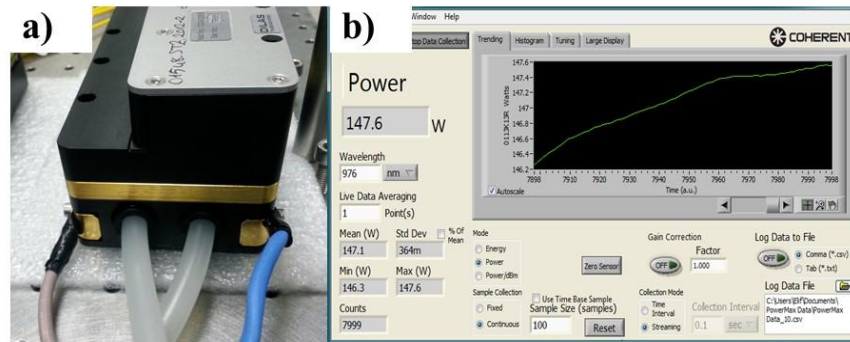


Figure 2. 19:a) Diode 1 b) Power of diode 1

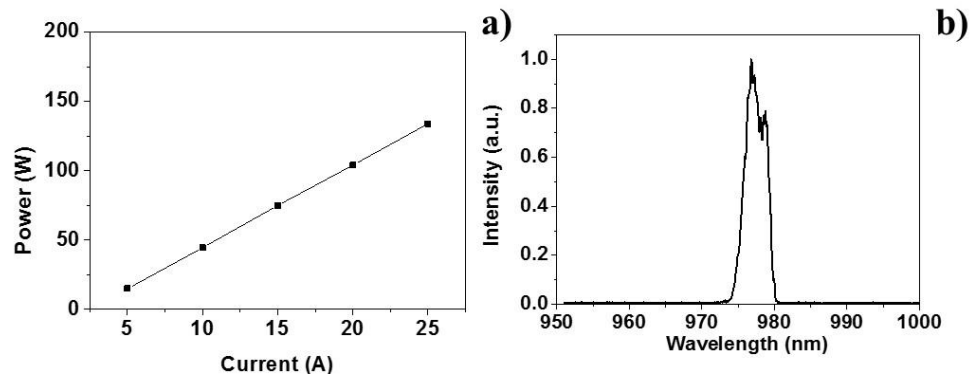


Figure 2. 20: a) Power of diode 1 b) Optical spectrum of diode 1

Table 2. 3: Output power of diode lasers

Diode number	Current (A)	Power (W)
1	28	147.6
2	28	134.7
3	28	148.3
4	28	120.6

5	28	137.1
6	28	127.7

Fig 2.20 shows the power of the diode 1 at 28 A. Fig 2.20 a) shows that ampere vs. power increases linearly. Fig 2.20 b) shows the wavelength of the diode at 28 A, 12V and 24°C. The Pump power of the diode 1 is 148 W. The wavelength of the all diodes were determined according to table 2.2.

After characterization of diodes, we cooled them by dividing into 2 group. Groups of diodes were determined according to their cooling temperatures and wavelength. First group consisted of diodes 6, 1 and 3 respectively. The reason of why we put in order is that their wavelengths depend on the temperature. Diode number 6 has 975 nm wavelength at lower cooling temperatures than the number 1 and 3. Hence, the first cooled water circulated in diode 6 and the output water of diode 6 went into the diode number 1 so warmed water circulates in diode 1. Finally, output water of the diode 1 went into the diode 3. By applying the same conditions second group was formed. In the second group the cooled water first went into the diode 2, then 5 and finally 4.

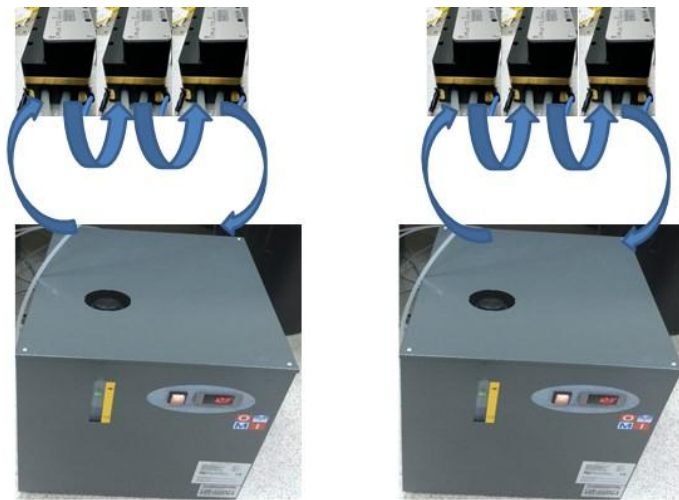


Figure 2. 21: The scheme of cooled diodes in group

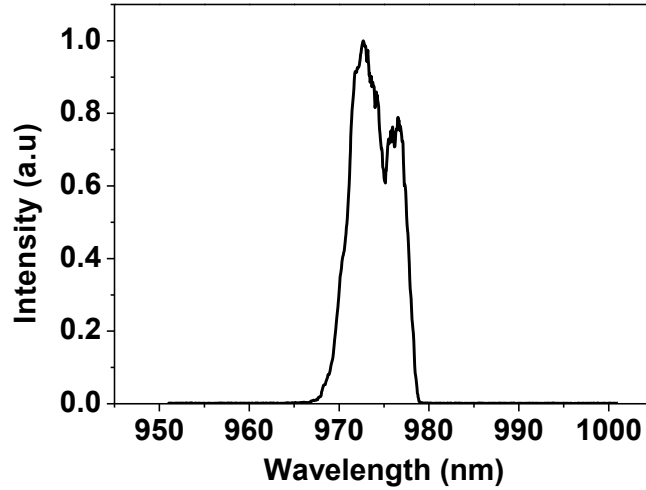


Figure 2. 22: Optical spectrum of all diodes

Spectrum of all diodes are shown in fig 2.32. As it seen from the fig 2.32it is hard to obtain an exact 976 nm wavelength pumping. We obtained very close pumping wavelength to stimulate the Yb ions. Even multiple diode pumping wavelength has 976 nm range and it is broad. Also diode groups were obtained at 975 nm wavelength.

2.3 Analysis of fiber laser

After integration of the equipments and then stabilizing them, we worked on the analysis of the all fiber laser resonator. The optical spectrum is one of the most important part of the fiber laser resonator. The second one is the beam quality (M^2) of the laser. We also examined the cw regime in temporal domain with oscilloscope assisted photo detector.

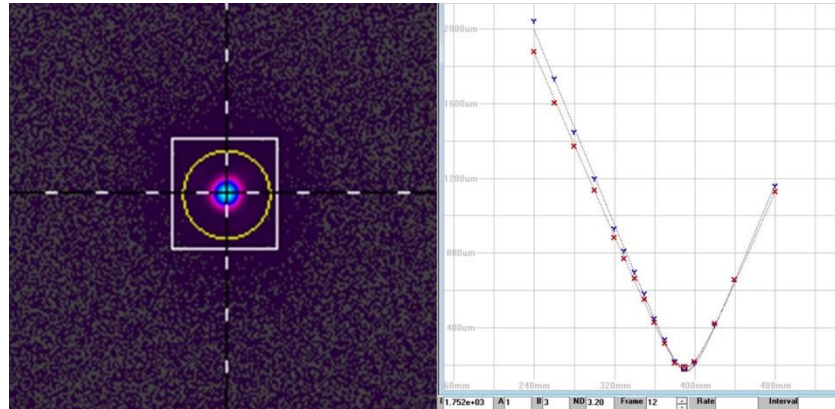


Figure 2. 23: M^2 data of fiber laser resonator M^2_x is 1,6 and M^2_y is 1,7

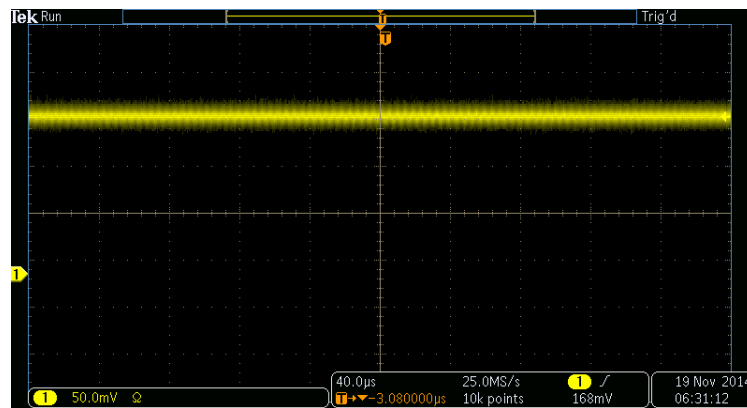


Figure 2. 24: Temporal image of fiber laser resonator indicates cw regime

The optical spectrum was measured with Yokogawa AQ6370C Optical Spectrum Analyzer. The beam quality of the system was obtained by using M^2 -200SSpiricon. To find the regime of the laser in temporal domain, we used Tektronix MDO3104 Mixed Domain Oscilloscope assisted with photo detector which is DET 36A.

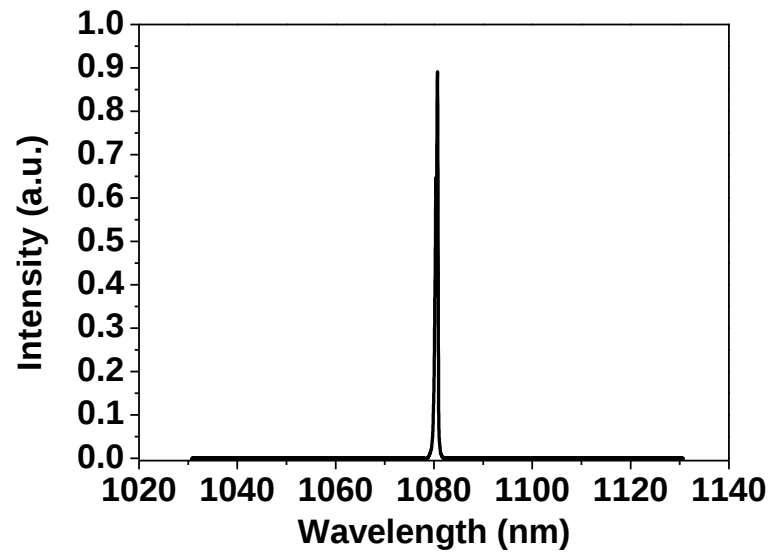


Figure 2. 25: The optical spectrum of fiber laser resonator at 100 W

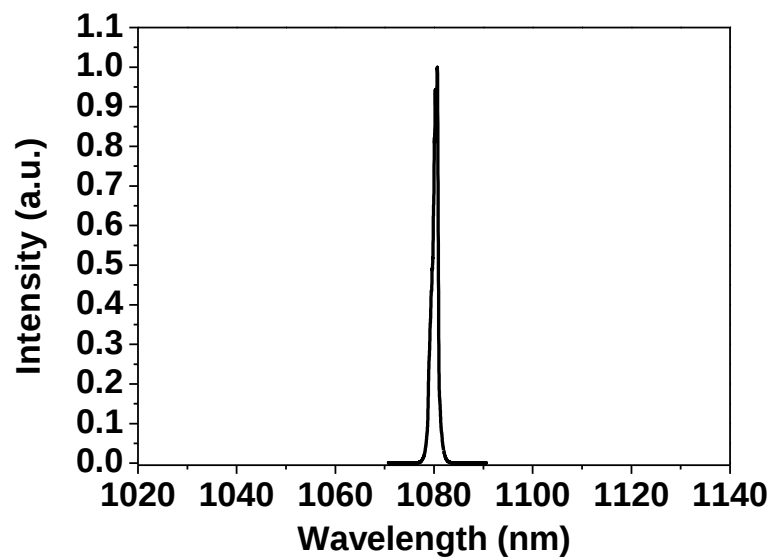


Figure 2. 26: The optical spectrum of fiber laser resonator at 200 W

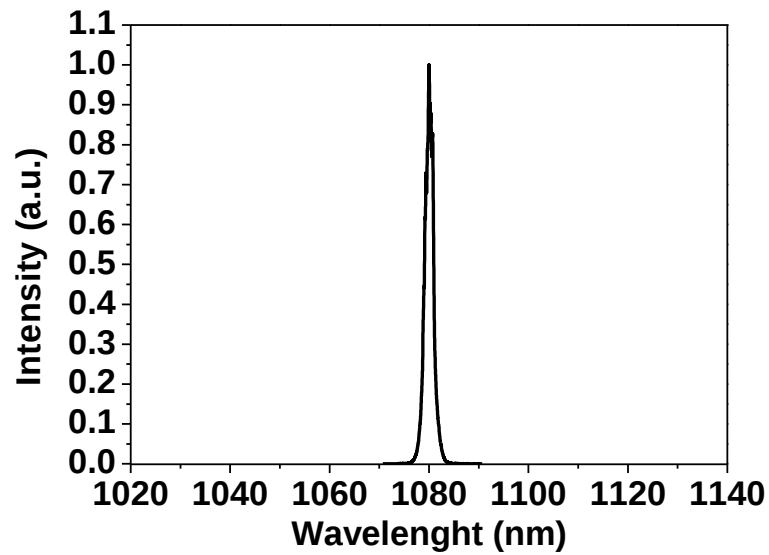


Figure 2. 27: The optical spectrum of fiber laser resonator at 300 W

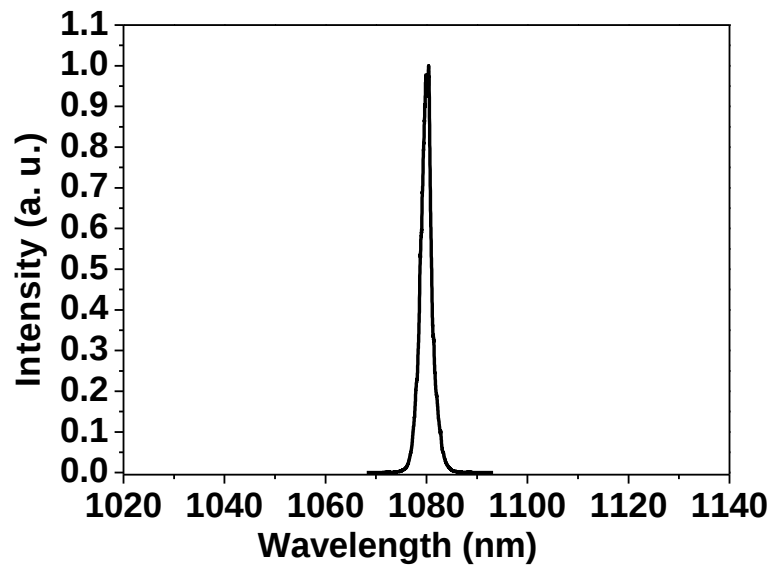


Figure 2. 28: The optical spectrum of fiber laser resonator at 547 W

As it can be seen from the figures between 2.25 and 2.28 laser has 1080 nm wavelength centered. With the increase of the laser power optical spectrum has some broadening, typically. The optical spectrum of laser obtained with a

resolution of 0.05 nm. In fig. 2.30 power stabilizes and 548 W output power of the fiber laser resonator. In fig. 2.23 M^2 data presents the beam quality of the laser system is < 1.7 . In fig. 2.24 shows that the system has CW regime in temporal domain at 400 μ s.

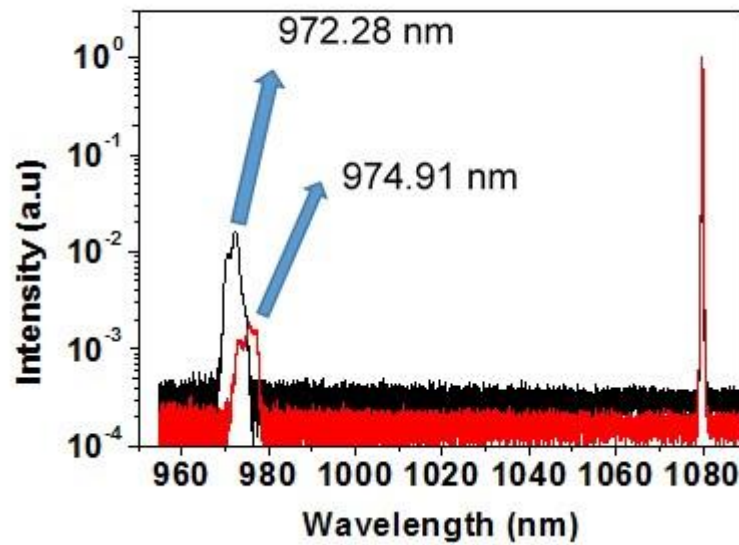


Figure 2. 29: Optic spectrums of fiber laser with different thermal management of pumping units. Black line shows that diode lasers are operating at 972.28 nm wavelength. Red line shows that diode lasers are operating at 974.91 nm wavelength after accurate thermal management

Fig. 2.29 shows the optical spectrum evolution of fiber laser output with different thermal management of pumping units. When the pumping units operate at lower temperature, it emits the pumping wavelength at 972.28 nm. This operation wavelength results lower absorption ratio in the active media resulting lower fiber laser output efficiency. On the hand, the accurate thermal management of the pumping units allows to operate the pumping units at 974.91 nm, which is highest absorption ratio from the active media. By optimizing the operation wavelength of the diode lasers, we successfully decreased the intensity

of unabsorbed pump at the output of the fiber laser resulting the development of efficient fiber laser system. The output power of the fiber laser resonator is given in fig 2.29. We finally obtain high power fiber laser output at 547 W average power.

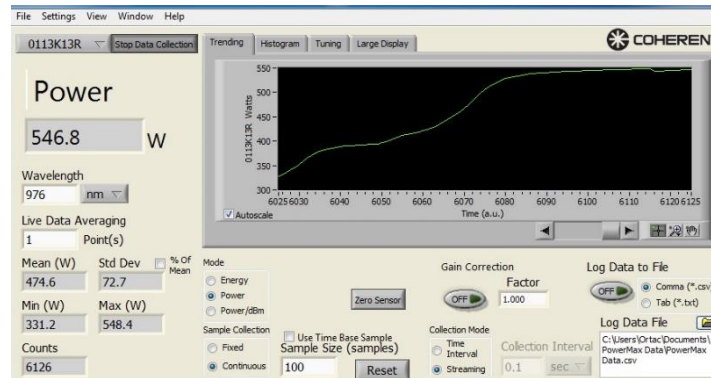


Figure 2. 30: The output power of the fiber laser resonator

2.4 Material processing of fiber laser

In previous section, we demonstrated the development of high power fiber laser system. The motivation of the material processing is to demonstrate the capability of fiber laser system. In order to do the material processing, we study drilling and cutting performance of fiber laser on the steel with different thickness. We built a materials processing setup (see fig. 2. 31). The steel pieces used in the experiments were 1 mm and 1.7 mm thickness. The steel piece was fixed to XYZ stage and located in front of the lens. To focus the light we used 80 mm lens. The used of longer focal lens is to reduce the power density on the optic. Fiber laser power was 60 W average output power during drilling and the cutting process.

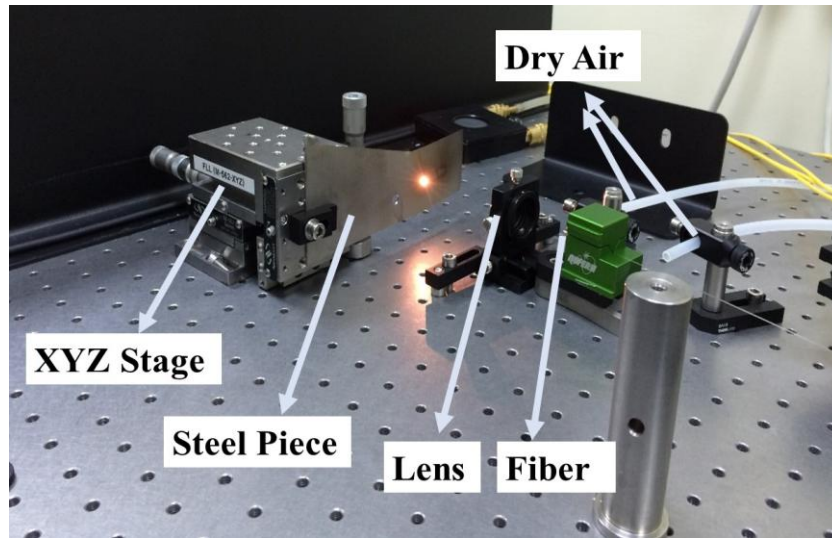


Figure 2. 31:Experimental setup for material cutting and drilling

The drilling process result is shown in fig. 2. 31. We used the steel piece with 1.7 mm thickness for drilling process. The diameter of the drilled hole is $169\ \mu\text{m}$ given in fig. 2.32. The drilling process takes less than 10 seconds. For the cutting process, we used the steel piece with 1 mm thickness. The width of the cutting area is about $751\ \mu\text{m}$ (see fig. 2. 33). During the cutting process, we needed to move the XYZ stage with equal time period. To obtain more accurate cut and drill process, optimize laser material processing system is required.

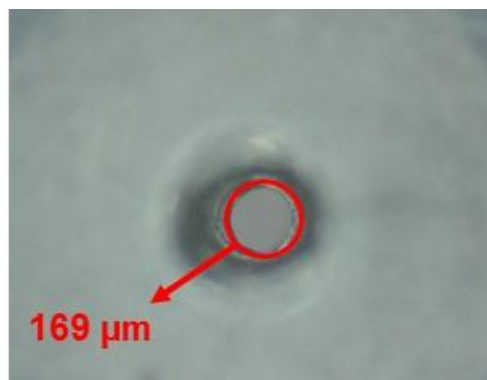


Figure 2. 32: Optical microscope image of drilled steel which is 1,7 mm thickness

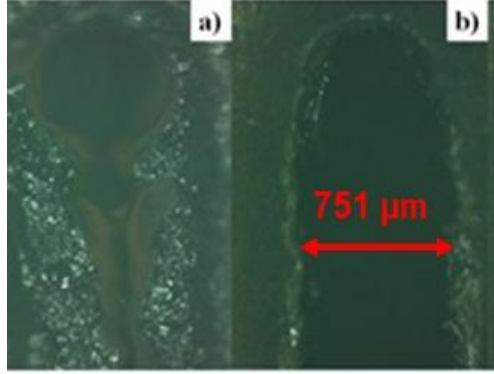


Figure 2. 33: Optical microscope image of cut steel a) preliminary work of cutting mechanism b) improved cutting mechanism

Conclusion

In this study, we developed high power fiber laser system. The fiber laser resonator was firstly numerically simulated by using software. In order to obtain high power level from the laser, we designed and numerically studied different fiber laser cavity architectures. In this study, high power diode lasers as pump sources have been analyzed in terms of output power and operation wavelength. Output power of each pump diode was in the range of 135 W. Diodes were operated at 975 nm wavelength after thermal management. We used new generation fibers to overcome thermal problems. When free space components used in the systems causes power loss which leads to decreasing of the fiber laser efficiency. Therefore we preferred use all fiber based components. Moreover we used high and low reflective FBGs instead of mirrors and lenses to obtain optical feedback in the system. The fiber laser is operating in the continuous wave regime due to the cavity design. The output power of the system was 547 W. The M^2 of the system was < 1.7 . The laser has continuous wave regime in temporal domain. The output wavelength of the fiber laser was

1.08 μm . We demonstrated the capability of our fiber laser system for material processing. We drilled and cut steel target (thicker than 1 mm) with lower output power of fiber laser (100 W).

Discussion

The most important reason of choosing number 1 design is that the Yb^{3+} ions have maximum absorption at 975 nm wavelength. Hence, we can avoid the heating problems and use less fiber. Also, absorption emission cross-section is higher which is given in fig. 1.9. If we compare the design number 1 with 2, design number 2 has higher low reflective FBG. This parameter causes lower output power it is seen in table 2.1. The reason of that is higher low reflective FBG sends more photon into the cavity so that each back reflected photon causes energy loss. If pumping wavelength was chosen at 915 nm, fiber length would be longer to obtain the same power when compared to 975 nm which is given in section 2.7.

In 1999, Dominic *et al.* demonstrated Yb-doped double clad 110 W cw fiber laser. The pump power was 180 W and the output laser was > 110 W. In their study, the laser diodes worked at 915 nm wavelength and the laser output wavelength was at 1120 nm. They used free space mirrors to couple light into the active medium. The M^2 was < 1.7 . The heat values and cooling values are crucial. Optimum output power and wavelength of diodes depend on cooling of the diodes [46]. Wavelength of pumping units shifts according to cooling temperature. In our study, our pump power is much higher than the Dominic *et al.* Their open space mirrors causes the loss of output power of laser. Their optical to optical conversion efficiency was 58.3% while ours 70%. In our system we used all fiber so that we obtained higher optical to optical conversion efficiency.

In 2003, Barannikov *et al.* presented 250W cw linearly-polarized Yb-doped fiber laser system. The output wavelength of fiber laser system operated at 1076 nm. Their system was all fiber and the pump power was 450 W. The beam quality $M^2 < 1.04$ which is lower than our system [47]. The reason of higher M^2 is related to output power. Also another difference from our system is that their laser was polarized and ours was random. Moreover, their schematic of laser system is different than our system. The system that Barannikov *et al.* presented had lower slope efficiency than ours which was 59%.

In 2003, Limpert *et al.* manifested that 500 W cw fiber laser. Their active medium consisted of Neodymium and Ytterbium doped fibers and laser output wavelength was between 1080 and 1100 nm. If we compare their system with ours, the active medium of our system consisted of Yb-doped fibers and output wavelength was 1080 nm. They pumped the system with 350 W at 976 nm, 175 W at 940 nm and 175 W at 808 nm. Also their active fiber length was 35 m while ours 15.5 m [48]. The reason of longer active fiber results from the pumping wavelength due to obtain sufficient absorption. The mirrors that they used was similar to ours. High reflective mirror had 99% reflectivity and optical coupler had 4% Fresnel reflection results from the cleave angle of fiber. In our system we used optical coupler which had 10.4% reflectivity. Their slope efficiency was 72%. To coil the fibers leads to reduction of transverse mode profiles which causes better beam quality. The same process had been performed in our system for same reasons. They obtained beam quality $M^2 < 1.5$ while ours $M^2 < 1.7$. These values are close to each other. In order to improve our beam quality splicing process of the fibers can be done better diode wavelength can be changed and also to obtain better beam quality fiber design can be altered.

In our system we designed combiner cooling plate to wrap up all fiber to gain the space and compact product and reduce the heat of combiner. Also, we

integrated FBGs on the same cooling plate. It is vital to integrate these fibers properly due to the fact that they are carrying very high power.

As it can be seen from the literature [46, 47, 48] integration of the fibers is vital to obtain high power. If fiber integration process is poor, the output power of the laser will be low. Also, to obtain good beam quality and to avoid the heating problems of fibers, this process has the number one priority. If fiber ends cleave with an angle more specifically more than 2° the splicing process will be poor. Consequences of poor splicing are bubbles, high loss and eventually fibers will burn due to the high back reflection rate. If fibers cleaved with angle, it causes loss of light at very increased rates due to the mismatches of the cores which is given in fig. 2.4 If we couple light into such kind of spliced fiber, fiber will eventually burn and system will be compromised.

In our laser system we cooled diodes as group. The reason of why cooling together was that the needed cooling temperatures can be obtained by serially connecting. Also, by cooling the diodes we were able to achieve appropriate pumping wavelength. Moreover, we gained space and more compact system.

In the progress of reliable high brightness all solid state pump sources, rare-earth-doped fibers, system can be advanced. The power of the system can be increased. To achieve the higher powers system cavity can be altered by different type of fibers such as D-shape or rectangular. As it is given the literature, to improve the absorption of the pump light different type of fibers are efficient. Also, pumping wavelength of the light can be changed. In literature Yb has an absorption at 915 and 975 nm wavelength. At 915 nm wavelength heat dissipation in the fiber is lower due to longer fiber usage. The reason of longer fiber usage is to low absorption intensity of the Yb at 915 nm wavelength. Furthermore, higher pump sources can be used to increase the power of the system such as instead of using 135 W diodes, 200 W diodes can be used. Hence, the higher powers are reachable by the guidance of the mentioned knowledge.

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