

DEVELOPMENT AND INVESTIGATION OF HIGH POWER YTTERBIUM-DOPED FIBER LASERS OPERATING AT 1018 NM

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ABSTRACT

DEVELOPMENT AND INVESTIGATION OF HIGH POWER YTTERBIUM-DOPED FIBER LASERS OPERATING AT 1018 NM

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The development of ytterbium-doped fiber lasers (YDFL) operating around 1018 *nm* with two major pumping schemes are reported. The study on the developed all fiber lasers were characterized based on parameters such as pump source, active fiber type and output-coupling fiber bragg gratings.

Diode lasers operating at around 915 *nm*, and 976 *nm* were used as primary pump sources for the experiments. While several works had reported 1018 *nm* YDFLs using 976 *nm* pump sources, up until now, there were no reports of the use of 915 *nm* for 1018 *nm* YDFLs in the literature. Active fiber types, based on length and doping concentration of ytterbium ions were also considered. The choice of output-coupling (OC) fiber bragg gratings (FBG) were made based on laser model simulation and manufacturing feasibility. Simulations were also carried out for every tested set of implemented parameters so as to minimize undesired optical effects such as amplified stimulated emission (ASE) and inadequate pump absorption.

For both pump sources, high power ytterbium-doped all-fiber lasers operating in the 1018 *nm* region with good efficiency and amplified stimulated emission (ASE) suppression were established. In addition, the broad absorption cross-section of ytterbium-doped glasses around 915 *nm* was exploited as tunable pump sources for the fiber laser systems demonstrated.

Keywords: Lasers, diode-pumped lasers, fiber lasers, fiber bragg gratings, ytterbium, amplified stimulated emission.

ÖZET

1018 NM DALGA BOYUNDA ÇALIŞAN İTERBYUM KATKILI YÜKSEK GÜÇLÜ FİBER LAZER ARAŞTIRILMASI VE GELİŞTİRİLMESİ

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1018 *nm* dalga boyunda çalışan iterbiyum katkıli yüksek güçlü fiber lazerler iki önemli pompalama şemasına sahiptir. Bu fiber lazerler pompalama kaynağı, aktif fiber tipi ve Fiber Bragg Izgara (FBI) yansıtma katsayısına göre karakterize edilir.

915 *nm* ve 976 *nm* dalga boyunda çalışan diyot lazerler bu fiber lazerin başlıca pompalama kaynaklarıdır. 976 *nm* merkez dalgaboyunda çalışan pompalama diyotları ile 1018 *nm*'de çalışan fiber lazerler literatürde gösterildiği halde 915 *nm* pompalama diyotları ile 1018 *nm*'de çalışan fiber lazerler şuna kadar incelenmemiştir. Deneylerde kullanılan aktif fiber tipleri, fiber uzunluğu ve aktif iyon katkılama miktarı göz önünde bulundurularak seçilmiştir. Düşük yansıtma katsayılı FBI ise yapılan simülasyon ve üretim kabiliyetine göre seçilmiştir. Simülasyonlar yetersiz pompa emilimi ve yükseltilmiş uyarılmış salım gibi lineer olmayan istenmeyen etkileri minimize edebilmek için her bir parametre için ayrı ayrı yapılmıştır.

Bu iki pompalama çeşidiyle yüksek güçlü iterbiyum katkıli fiber lazer sistemleri yüksek verimlilik ve düşük yükseltilmiş uyarılmış salım ile kurulmuştur. Buna ek olarak; iterbiyum katkıli camların 915 *nm* dalga boyu civarındaki geniş emilim bandından faydalanarak 1018 *nm* fiber lazer sistemleri için ayarlanabilir pompalama kaynakları gösterilmiştir.

Anahtar sözcükler: Lazerler, diyotla pompalanan lazerler, fiber bragg ızgara, fiber lazerler, iterbiyum, yükseltilmiş uyarılmış salım.

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Chapter 1

Introduction

Over the years, the progress of fiber lasers in terms output powers and application has been a tremendous successful trend. Fiber lasers are known for their high average powers and beam qualities compared to other types of lasers. These features of fiber lasers are of importance to many industrial, defence and scientific applications, which points to the reason of fiber lasers being one of the most important developments in laser technology [1]. This success can be attributed to the recognition of the use of fibers as both active media and waveguides in laser systems [2].

The flexibility of ytterbium ion in doped silica fibers is one its strong points. Ytterbium offers a myriad of very scientifically captivating properties, especially in its broad absorption band that ranges from less than 850 *nm* to more than 1070 *nm* [3]. Consequently, ytterbium-doped fiber lasers (YDFLs) have attracted a lot of interest from various fields, for their excellent characteristics, such outstanding conversion efficiency, enormous prospect for power scaling, and broad emission bandwidth [3–6]. The optical properties of Yb-doped fibers is able to facilitate lasing over a wide spectral range from 0.98 μm to 1.2 μm [3, 7, 8].

Ytterbium-doped fiber lasers (YDFLs) operating at 1018 *nm* wavelength have a lot of applications especially as pump sources in tandem configuration for high

power amplifiers [3,9,10], pulsed lasers [11] , and random fiber lasers [12]. In the case of tandem pumping, 1018 *nm* YDFLs are very good pump sources for high power lasers with outputs at higher wavelengths, such as 1060 *nm* - 1080 *nm*, due to lower quantum defect and higher brightness compared to the conventional 915 *nm* or 976 *nm* diode pump sources [13]. The quantum defect defined as the difference of photon energies between the pump and laser photons sets a lower limit to the loss in the conversion from pump power to laser power, i.e. an upper limit to the output power or optical-to-optical efficiency [14]. The quantum defect is about 8% - 10% when a 1060 *nm* - 1080 *nm* YDFL is pumped by a 976 *nm* pump source, compared to 4% - 6 % when the YDFL is pumped by a 1018 *nm* fiber laser. This low quantum defect by using a 1018 *nm* pump source allows for potentially high power efficiency, and fiber laser amplifiers pumped by 1018 *nm* YDFLs with good efficiencies have been reported in some previous studies [9,10]. Core-pumped, single mode, high power 1018 *nm* YDFLs usable for high power pump sources have also been demonstrated [15,16].

Yb-doped fibers have two prominent absorption regions; the narrow region with relatively high absorption cross-section around 976 *nm* and the broad region with lower absorption cross-section around 915 *nm*. For these reasons, almost all 1018 *nm* YDFL pump sources employ the use of pump sources around the 976 *nm* region. However, a major challenge that arises with using 976 *nm* sources is ensuring the wavelength stability of pump sources during laser operation. This arises due to the narrowness of the absorption region around 976 *nm* in the spectrum ytterbium ion. Parameters such as operating temperature and electrical requirement affect the output center wavelength of the pump diodes. This situation can be overcome through the use of wavelength-stabilized diode lasers. Wavelength stabilization can be achieved by several approaches including the use of volume Bragg gratings (VBG) [17]. On the other hand, the low absorption spectral cross-section region around 915 *nm* offers a broad range of wavelengths usable for pumping 1018 *nm* YDFLs. Although, utilizing these wavelengths for pumping 1018 *nm* YDFLs will yield lower efficiency due to the lower absorption cross-section for Yb-ions compared to the region 976 *nm*. However the efficiency drops from pumping wavelength shifts -due to temperature rise or increase in

diode driving current- can be overcome using the 915 *nm* broad region as shown in this study.

The main challenge in general with regards to emission at 1018 *nm* using ytterbium doped silica glasses is the serious gain competition around 1030 *nm*. Because the local emission maximum of Yb ions is around 1030 *nm*, this can lead to parasitic lasing due to gain competition as decreasing wavelength increases the gain competition [15]. Nevertheless, it has been shown that increasing the core-cladding square-diameter ratio, minimizing the ion concentration and decreasing the length of the active fiber are effective approaches to suppressing the unwanted amplified spontaneous emission (ASE) gain at around 1030 *nm* and enforcing the lasing at 1018 *nm* [13].

Chapter 2

Theory of Laser Generation

2.1 Laser Theory

The basics of a functional laser combines the fundamental phenomena between electromagnetic wave and material interaction. These fundamental processes are absorption and emission. The process of emission occurs in two ways that are distinct from each other on the quantum level; spontaneous and stimulated emission. Thus a laser function can be based on the phenomena of the processes of spontaneous and stimulated emission and the process of absorption [18].

2.1.1 Absorption

Considering any two energy levels (out of the infinite energy levels) of a material, say E_1 and E_2 with $E_2 > E_1$. E_1 and E_2 correspond to energy level 1 and level 2 respectively of the proposed material with an atom or molecule of the material initially in level 1. Assuming an electromagnetic wave travelling with a frequency ν and characterized by the energy difference of the two considered energy levels: $E_2 - E_1$, is incident on the material. Since the incident wave carries a minimum energy that is the difference of the energy levels, there is a chance that the atom

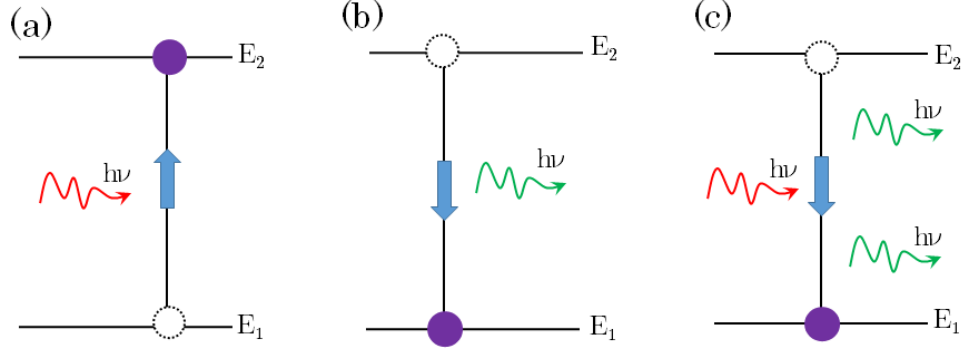


Figure 2.1: An illustration of (a) absorption, (b) spontaneous emission, and (c) stimulated emission processes

in level 1 gets energized, thus excited to level 2. This is the phenomenon of the absorption process [18].

Absorption phenomenon is dependent and characterized by the intensity of the incident beam. The parameter, absorption rate W_{12} is defined by the equation

$$\frac{dN_1}{dt} = -W_{12}N_1 \quad (2.1)$$

where N_1 is the number of atoms (per unit volume) that, at the given time, are occupying level 1. The relationship between the intensity of the incident wave, in terms of flux density Φ can be derived as

$$W_{12} = \sigma_{12}\Phi \quad (2.2)$$

where σ_{12} is the area of the material (called absorption cross-section) where the absorption process is taking place.

2.1.2 Spontaneous Emission

Consider the proposed material depicted in Fig.(2.1) as well as the two energy levels. Assuming an atom or molecule of the material is initially in level 2. The atom will tend to decay to level 1 as $E_2 > E_1$. As the atom decays, it

must release an energy equal to the energy difference of level 1 and level 2, i.e. $E_2 - E_1$. Spontaneous emission is the process involved when this energy is released as an electromagnetic wave or photon. The direction of the emitted photon is random. It should be noted that spontaneous emission is one of the two methods for the atom to transit to a lower energy level [19]. The transit can also occur in a nonradiative process. In this case the energy difference $E_2 - E_1$ is released in another form different than electromagnetic energy; for example, this energy difference can be released in form kinetic energy to the neighboring atoms or molecules: phonon). The frequency of the radiated wave is then given by

$$\nu = \frac{E_2 - E_1}{h} \quad (2.3)$$

where h is the Plancks constant. The probability of spontaneous equation can be characterized thus: Supposing that there are N_2 atoms per unit volume in level 2 at a given time t . The decay rate of the atoms from spontaneous emission which is, $\left[\frac{dN_2}{dt}\right]_{sp}$ is proportional to N_2 . Thus the relationship between $\left[\frac{dN_2}{dt}\right]_{sp}$ and N_2 can be written as

$$\left[\frac{dN_2}{dt}\right]_{sp} = -A_{21}N_2 \quad (2.4)$$

The coefficient A_{21} is called the spontaneous emission probability.

2.1.3 Stimulated Emission

Once again, considering a two-energy level model (Fig.(2.1)), with an atom found initially in level 2 (E_2). Suppose an electromagnetic wave with a frequency ν (which is the atomic frequency) characterized by the energy difference of the energy levels ($E_2 - E_1$) is incident on the material. As the incident wave has the same frequency as the atomic frequency, there will be probability that this wave will coerce the atom to transit from level 2 to level 1. On this occasion the energy difference $E_2 - E_1$ is released as an electromagnetic wave in addition to the incident wave. The emitted wave travels in the same direction as the incoming wave, thus the incident wave is amplified.. This is the fundamental basis of amplification in lasers. [20]. This process is the stimulated emission phenomenon.

Stimulated emission can only occur for incoming electromagnetic wave that have a photon energy similar to the energy required laser transition [20]. Therefore, the lasing can only occur for specific frequencies within a limited gain bandwidth depending on the electronic structure of the medium. Essentially a laser will normally operate at the wavelength in which the gain medium achieves the highest gain. In this case, as well stimulated emission process can be described by the equation

$$\left[\frac{dN_2}{dt} \right]_{st} = -W_{21}N_2 \quad (2.5)$$

here W_{21} denotes the stimulated transition probability. Furthermore, similar to equation (2.2),

$$W_{12} = \sigma_{21}\Phi \quad (2.6)$$

where Φ is the photon flux of the incident wave and σ_{21} is the stimulated-emission cross-section, which is the area of occurrence of the process of stimulated emission.

A crucial refinement between the spontaneous and stimulated emission forms. On account of spontaneous emission, the particle emanates an electromagnetic wave that has no coherent phase relation with the radiation another atom, even over short distances. Moreover, the wave is radiated in an arbitrary direction. However on account of stimulated emission, since the process is constrained by the incident wave, the emission of any particle includes a phase relation to that of the incident wave. The incident wave additionally decides the bearing of the radiated wave.

2.1.4 The Laser Phenomenon

With respect to laser phenomenon, and, in terms of photons, the processes that govern a functional laser can be briefly characterized as follows (see Fig.(2.1)): During spontaneous emission, the atom transits from level 2 to level 1 releasing a photon in the process. And during stimulated process, the incident photon stimulates the transition from level 2 to level 1 releasing an addition photon to the incident photon.. As for absorption, the incident photon is absorbed, thus

exciting the atom and the atom transits from level 1 to level 2. Finally, $\sigma_{21} = \sigma_{12}$, as Einstein proved [21]. This shows that the probabilities of stimulated emission and absorption are equal.

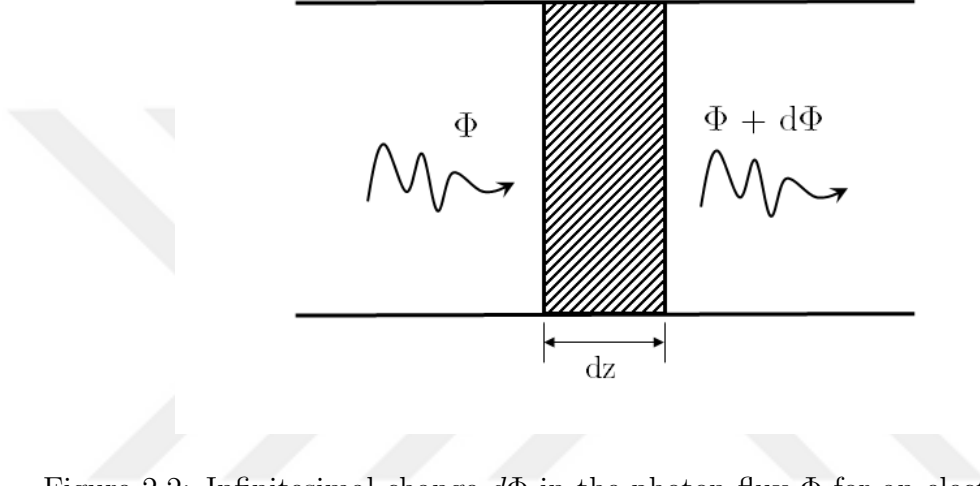


Figure 2.2: Infinitesimal change $d\Phi$ in the photon flux Φ for an electromagnetic wave in traveling a distance dz through the material.

Now, considering any two energy levels 1 and 2 of an assumed material and let N_1 and N_2 be the respective populations of level 1 and level 2. Energy levels are assumed to be nondegenerate. Suppose a wave with an intensity characterized by its photon flux Φ travels along the z direction in the material. The infinitesimal change of this flux considering the contribution from both the processes of stimulated emission and absorption (shaded region of Fig.(2.2)), according to equations (2.1), (2.2), (2.5), (2.6), can be derived as

$$d\Phi = \sigma\Phi(N_2 - N_1)dz \quad (2.7)$$

Equation 2.7 explains the behavior of the material under normal and excited conditions, i.e.,

when $N_2 < N_1$, material behaves like an absorber (normal condition)

when $N_2 > N_1$. material behaves like and amplifier (excited condition)

In the case of thermal equilibrium, material behavior is characterized by Boltzmann statistics. So if N_2^{eq} , N_1^{eq} represent the population of level 2 and level 1 at

thermal equilibrium, then we have

$$\frac{N_2^{eq}}{N_1^{eq}} = \exp \left[-\frac{E_2 - E_1}{kT} \right] \quad (2.8)$$

where k is Boltzmann's constant and T is absolute temperature. Under thermal equilibrium it can be seen that $N_2 < N_1$, implying the material acts as an absorber. However, if a non-equilibrium condition, where $N_2 > N_1$, is established then the material acts as an amplifier and **population inversion** is achieved and the transition frequency ν is given as in equation (2.3).

In order to achieve oscillation from an amplifier, the introduction of a suitable positive feedback is necessary. This can be realized by situating the gain medium (active material) between two highly reflecting mirrors. Thus, an electromagnetic wave traveling in a direction orthogonal to the mirrors will bounce back and forth between the two mirrors and can be amplified on each pass through the gain medium as illustrated in Fig.(2.3a). A way of extracting useful laser beam is making one of the two high reflecting mirrors partially transparent. In the case of fiber lasers, the active medium is an active fiber. An active fiber is a usually a normal fiber doped with rare earth elements, and the amount of dopants in the fiber has effects in its function. Fiber bragg gratings (FBG) act as mirrors (see Fig.(2.3)b). In most cases, a fiber laser has the active fiber placed between highly reflecting (HRFBG, with $\sim 99\%$ reflectivity) and partially reflecting (also called output coupler FBG, OCFBG with reflectivity ranging from 5% to 80%) fiber bragg gratings. It is important to realize that for oscillation to occur, a certain threshold condition must be attained; for example, a laser, the oscillation will start when the gain of the active material compensates the losses in the laser [18].

From equation (2.7), the gain per pass in the active material (i.e., the ratio between the output (Φ_o) and input photon flux (Φ_i)) is

$$\frac{\Phi_o}{\Phi_i} = \exp [\sigma(N_2 - N_1)l] \quad (2.9)$$

where l is the length of the gain medium. Assuming the only losses present in the cavity are from transmission losses, then threshold will be reached when

$$R_1 R_2 \exp [2\sigma(N_2 - N_1)l] = 1 \quad (2.10)$$

where R_1 and R_2 are the power reflectivities of the two mirrors. From the above equation it can be shown that the threshold condition is achieved when the population inversion reaches a critical value $(N_2 - N_1)_c$ known as critical inversion and given by

$$(N_2 - N_1)_c = -\frac{\ln(R_1 R_2)}{2\sigma l} \quad (2.11)$$

After the critical inversion is reached, oscillation starts to rise from spontaneous emission process occurring the laser cavity. Amplification is then initiated from the axially spontaneously emitted photons in the cavity [20].

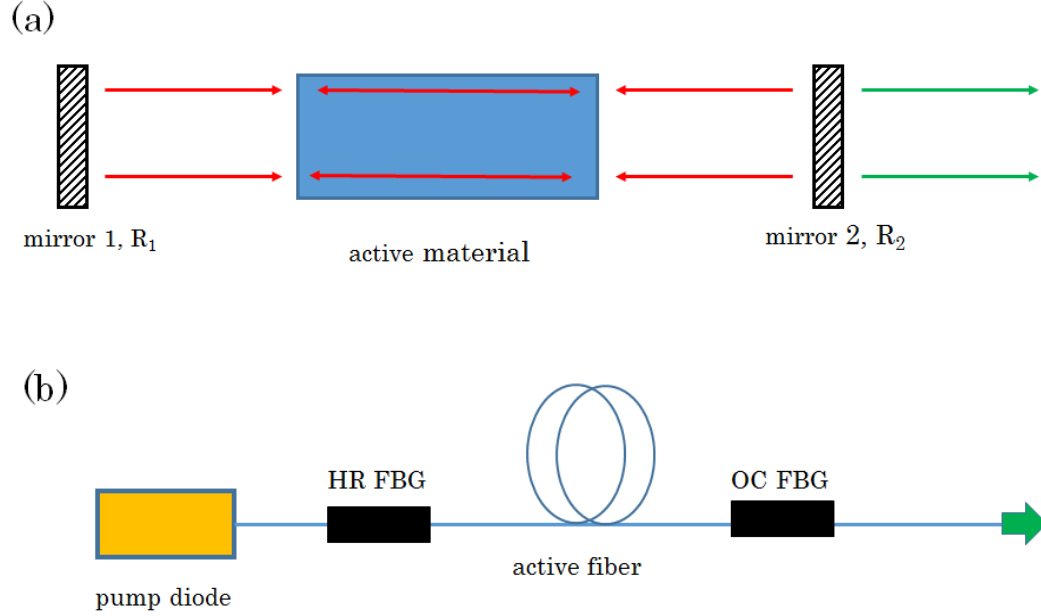


Figure 2.3: (a) Generic scheme of a laser, (b) scheme of a fiber laser with FBGs as mirrors

2.1.5 Population Inversion, Pumping Schemes

Absorption and emission are natural phenomena arising from the interaction of photons with matter. For the laser generation, stimulated emission is paramount. As stated by Einstein in 1917 [21] i.e. *"when the population inversion exists between upper and lower levels among atomic systems, it is possible to realize*

amplified stimulated emission and the stimulated emission has the same frequency and phase as the incident radiation". Stimulated emission must be either allowed to occur naturally or induced by external sources.

Since it is now established that population inversion is compulsory for laser generation, it is worth considering the challenges of how a population inversion can be attained in a material. Initially, it might be thought that that it population inversion is achievable provided a situation where interaction of the material with a sufficiently strong electromagnetic field at the frequency ν given by 2.1. At thermal equilibrium, the population of level 1 is more than that of level 2. This means that absorption process will dominate stimulated emission in this state. The incident electromagnetic energy will favor more transtions from level 1 to level 2 than transitions in the opposite direction. However, a system of this configuration will not yield lasing in the steady state. In fact when a condition, such that the populations of level 1 and level 2 are equal ($N_2 = N_1$), is reached, then the absorption and stimulated processes will remunerate each other and, according to equation (2.7), the material will then be transparent (neither an amplifier nor an absorber) [18]. This situation is referred to as *two-level saturation*. Nevertheless, population inversion is possible for three energy levels. In fact population inversion is possible for energy level schemes with three or more levels depending on how the material is *pumped*. The term ***pumping*** will be defined as the process of raising atoms from ground level to a higher level with the aim of achieving population inversion. Pump sources are usually electromagnetic waves supplied to interact with the active material.

For a three-level system, external power sources with high photon energy (short wavelengths) can facilitate atomic transitions from the ground state to the uppermost energy level. Thereon, spontaneous emission or nonradiative process can induce atomic transition to energy levels much higher than the ground level. And from these levels back down to the ground state, stimulated emissions may induce laser transitions. These transitions can be achieved even with a much lower excitation level in four-level energy systems [20]. In the case of three-level systems, the lower level (intermediate) of the laser transition is just above the

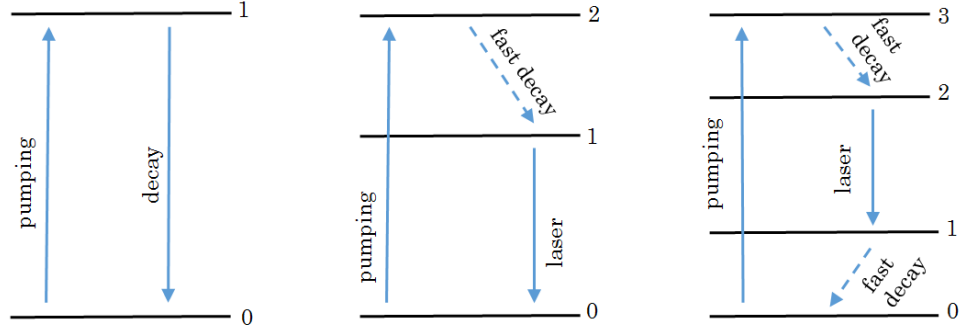


Figure 2.4: Illustration of two-level, three-level and four-level energy profiles

ground state, where a fast transition from this level to the ground state maintains a very low population [20]. Therefore the population in the intermediate level which can be moderated by pumping (also at moderate intensity) can yield lasing.

2.2 Light Propagation in Fibers

2.2.1 Optical Fiber

Construction-wise, an optical fiber, (Fig.(2.5)) is a solid cylindrical glass structure comprising of a core, through which light travels [22]. This rod-like structure is encased by another coaxial cylindrical glass material with lower refractive index than the core. This is the cladding. The fiber may be coated with coaxial materials called jacket so as to provide mechanical support. The jacket only serves as a mechanical support and do not have any optical functions supporting light propagation. In fiber lasers, the active medium is usually an optical fiber that acts as a waveguide, where light amplification occurs.

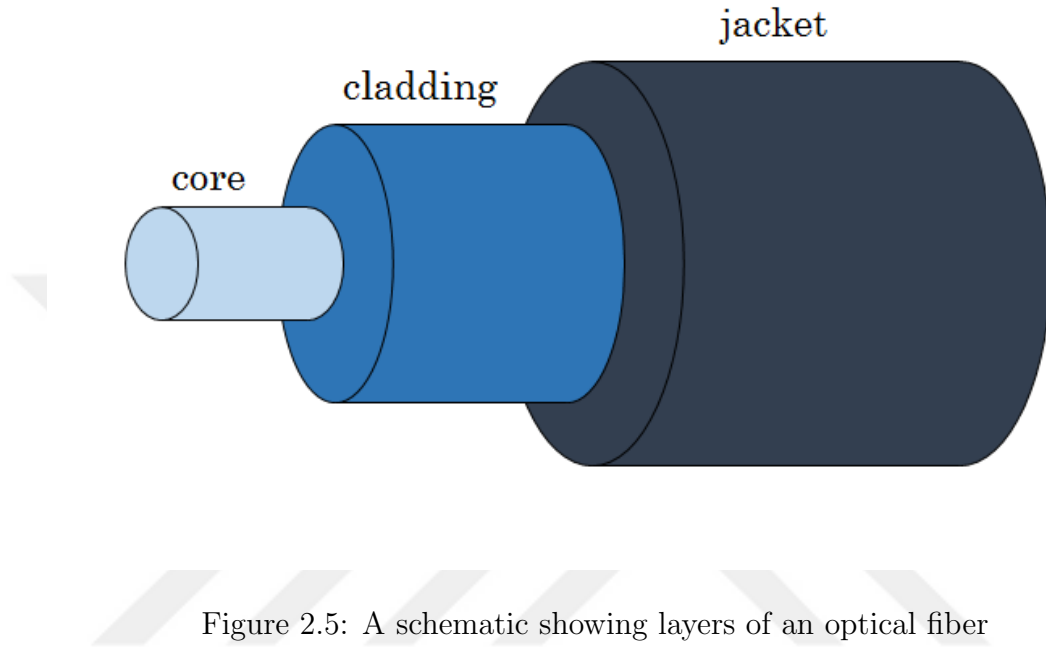


Figure 2.5: A schematic showing layers of an optical fiber

2.2.2 Ray Theory

Electromagnetic energy can be modeled with regards to the context of the physical situation e.g., propagation or matter interaction. Quantum and wave models have been widely implemented to further understand the electromagnetic wave. The Ray model characterizes electromagnetic energy in the simplest possible context [22]. The ray model treats light as a ray vector, i.e., a scalar information with a defined direction. The ray model, however, does not adequately explain some of the phenomenon exhibited by photons; in these situations implementing other models is appropriate.

The interaction between light impinging upon a surface of a media with a different refractive index than the index in where the incident light is propagating is explained by Snell's Law. Snell's explains the relationships between the angles in which light is incident on the interface of materials and their different refractive indices [23]. Snell's Law, follows from the continuity of a wave across a boundary, where the boundary condition instigates a constant phase of the said wave

regardless on the plane. This results to the equation;

$$\theta_1 = \theta_3 \quad (2.12)$$

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (2.13)$$

From equation (2.12), angle of incidence θ_1 equals angle of reflection θ_3 . While equation (2.13), is actually Snell's Law where n_1 and n_2 are indices of refraction of the media through which light is propagation as illustrated.

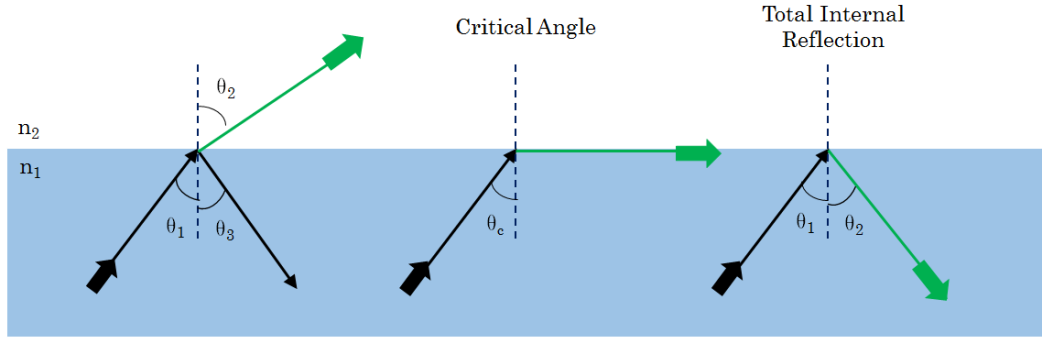


Figure 2.6: Diagram depicting refraction as light propagates through two media with different refractive indices and the total internal refraction phenomenon

An interesting case of refraction is when light is refracted at an angle higher than the critical angle. The critical angle is the angle where the refracted ray travels just at the interface boundary ($\sin \theta_2 = 90^\circ$). This case can only occur when light travels from a medium of larger to smaller index as allowed by Snell's Law. In this situation, the ray bends as such that it never goes beyond the interface of the two media [24]. This phenomenon is called total internal reflection Fig.(2.6). This only occurs when the incident angle $\theta_1 > \theta_c$ which is the critical angle as shown in Fig.(2.6).

The light could be guided by; refraction (using lenses), reflection and total internal reflection (TIR) (Fig.(2.7)). Using the phenomena of refraction and reflection to guide light is lossy and hence is limited only to shorter distances. However, guiding light by the phenomenon of total internal reflection is most

efficient, as such, often used, since the losses are only due to absorption in the medium [24].

The core-cladding refractive index profile allows the facilitation of total internal reflection, and also ensures that light only propagates inside the fiber, i.e., regardless of the angle of incidence, light coupled into the core of the fiber is maintained propagated in the core of the fiber. Coupling light into the core of a fiber is achievable due to the numerical aperture ranges of the core and cladding of the fiber.

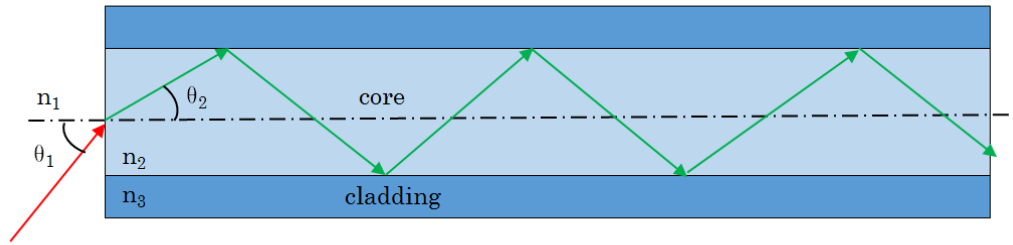


Figure 2.7: Light propagation in an optical fiber guided by total internal reflection.

2.2.3 Propagation Modes

Optical fibers have two modes of propagation, namely the single mode or multimode. The performance and effectiveness of these modes of propagation are affected by phenomena such as attenuation and dispersion along the fiber [25]. Understanding the difference between areas where single mode and multimode propagation are useful is key.

Operating modes of a physical system are defined by boundary conditions imposed by laws of physics. In terms of lasers, laser modes mean the number of possible standing waves in laser cavity. Operating modes of lasers are composed of longitudinal and transverse modes. The transverse modes (which is the focus of this section) is of importance because it characterizes the intensity distributions

on the cross-sections of the output laser beam. The simplest mode (single mode) is the Gaussian mode [26]. Due to the feasibility of manipulation, intensity, stability, and propagation form-maintenance and symmetry, Gaussian beams are often the preferred output of most beams [26]. With all that said, the cross-sectional intensity distribution of the laser beams is not homogeneous. Modulation of the intensity is transverse to the direction of propagation. This causes a steady decrease of intensity at the boundaries rather than an abrupt decrement. This non-homogeneity is due to diffraction during propagation which can be attributed to the wave nature of light. [27]. This leads to the formation of more modes during propagation, hence multimode.

In fiber lasers, while single mode propagation is always preferred, due to certain limitations such as high power level, or laser operation stability multimode mode propagation occurs. There are cut-off conditions that determine the number of modes a fiber can support. One of the key parameters associated with these cut-off conditions is the V-number. Mathematically V-number is a dimensionless parameter given by

$$V = \frac{2\pi d_{core}}{\lambda} \sqrt{n_{clad}^2 - n_{core}^2} \quad (2.14)$$

where d_{core} is the diameter of the core of the fiber, λ is the propagating wavelength of the field in the fiber, n_{core} and n_{clad} are the refractive indices of the core and cladding materials of the optical fiber.

2.3 Ytterbium Doped Fibers

The flexibility of ytterbium ion in doped silica fibers is one of its strong points. Ytterbium offers a myriad of very scientifically captivating properties, especially in its broad absorption band that ranges from less than 850 nm to more than 1070 nm because of the $^2F^{7/2} \rightarrow ^2F^{5/2}$ transition, as shown in its absorption spectrum in Fig.(2.8) [7, 28]. This versatility of this ion in silica fibers allows for the usage of a wide selection of pump sources. The feasibility of the choice of pump sources from a broad pump band also makes the considerations of pump wavelengths and operating temperature and stability. In addition, Yb-doped silica

can have an impressive effective fluorescent that is similar to its emission range from around 970 nm to 1200 nm [28].

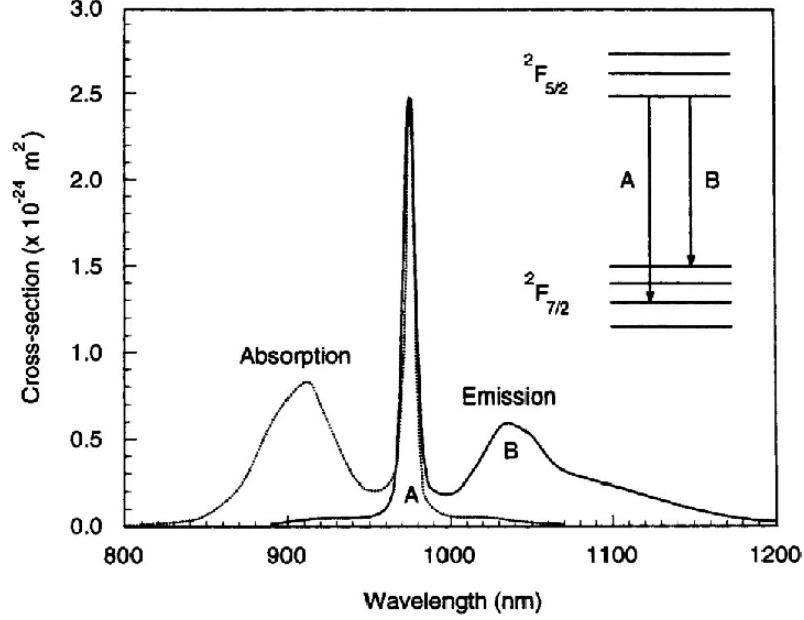


Figure 2.8: The ytterbium spectrum in a silica host showing absorption and emission peaks as well as the energy scheme (inset). It should be noted at both absorption and emission occur around 976 nm. (From [7])

The Yb-doped fiber laser, as thus, can lase at various output wavelengths of general interest, such as the use as pump sources for fiber lasers and amplifiers that have outputs at higher wavelengths. A highly studied and popular advantage of Yb^{3+} is the simplicity of its energy level diagram. As illustrated in the inset of Fig.(2.8), Yb^{3+} exhibit a single ground state ($^2F_{7/2}$) and a metastable state ($^2F_{5/2}$) with a bandgap of around $10,000 \text{ cm}^{-1}$. The other energy levels fall in the ultraviolet region [29].

Compare to other rare-earth doped glasses, another significant advantage of Yb-doped glasses is the unusually high absorption and emission cross-sections, which are much higher than other doped glasses [30]. The integration of these attractive properties facilitates very strong pump absorption in yb-doped glasses, consequently leading to the use of very short fibers in laser systems. High levels of Yb-ion doping concentration in silica is readily possible due to the absence of

higher energy levels. [7, 28] From the spectrum of ytterbium shown in Fig.(2.8), it is readily seen that sources that emit around 915 *nm* and 976 *nm* make good pump sources, while ytterbium, as described above offer a wide range of possible emission wavelengths.

2.4 Laser Generation around 1018 nm

The earliest interests in YDFLs arose after an extensive study of the performance of Yb^{3+} in a silica host showing its versatility, and wide emission spectrum that spanned over 152 nanometers [28, 31–33]. Ytterbium-doped glasses exhibits a number of interesting features, which are different from those of other active media. They possess a very simple energy level structure, with only one excited energy level state ($^5F_{7/2}$) not so far from the ground-state ($^2F_{7/2}$) with near-infrared or visible photons. Pumping and laser amplification of Yb-doped gain materials are characterized by atomic transitions between the several sublevels of the ground-state and excited energy level states [34]. Increasing the fiber length of Yb-doped glasses in a system causes a red shift in the output of the laser. This is due to the three-level structure of the energy level system [31]. Wavelength shifts from 975 *nm* in a 1 *m* laser to nearly 1100 *nm* in a 100 *m* laser has been reported [29]. Also multiple wavelengths oscillation with varying fiber length has also been reported [29]. Such is the versatility of Yb-doped fibers that enough gain is available on the short-wavelength emission band of Yb^{3+} . Sufficient and efficient laser oscillation has been obtained two weak (4%) Fresnel reflections from cleaved fiber ends [34].

Experimentally, the use of double-clad fibers contributed to the success of YDFLs in terms of raw output power. One of the major problems encountered during early phase development of YDFLs -or fiber lasers in general- was attempting to guide pump light into the active fiber [35, 36]. However this can be overcome by proper fiber design and illumination optics. Subsequently in 1988, an excellent solution to this problem was proposed; implementing of pumping of the cladding

of the active fiber. This implementation turned out to be to be the most powerful methods for breaching the bottleneck associated with power scaling in fiber lasers [37, 38]. This feat, also led to the advancement of research in double clad

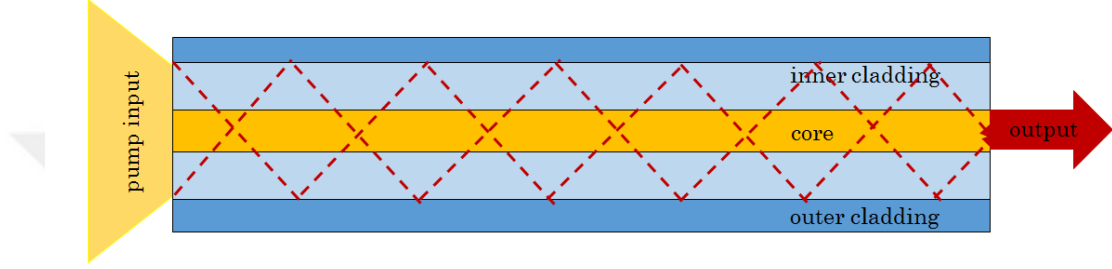


Figure 2.9: Clad pumping scheme.

fibers. In cladding pumping (see Fig.2.9), the pump power is coupled into the inner cladding of the active fiber. The inner cladding has a much higher numerical aperture (NA) and diameter than the core of the active fiber. This makes the coupling more effective and feasible. Because of the profile of the refractive indices of the inner cladding and core, light propagating in the inner cladding are refracted to the core, but not vice-versa. Thus, light from the inner cladding that inevitably gets into the core are trapped. Due to the much lower NA and diameter of the core the resulting output beam are much more intense (fewer propagation modes) and bright. This makes the method of cladding pumping very efficient and powerful [35]. One of the earliest reports of cladding-pumped YDFLs [28, 39] reported an efficient 69% laser operating at 1090 nm . The YDFL was pumped using laser diode operating at 875 nm . However the output power being 50 mW was very low. Nevertheless, this was an achievement as it was the first YDFL pumped using this pumping scheme. Another important modification in fiber design was the change in symmetry of the optic fiber layers [28]. Improving the overall pump absorption, had sparked a whole new interesting in engineering optics. Several designs and ideas had been proposed, all pointing towards distorting the rotational symmetry of the inner cladding and increasing the the overlap between the cladding propagating modes and those of the fiber core [40–46].

One of the more exciting properties of ytterbium-doped fiber lasers is the power scalability while maintaining very good beam qualities. This is due to the fact that Yb-doped fibers maintain a relatively small quantum defect. This property potentially allows the realization of very high power lasers with very good efficiencies and very low thermal effects. Since thermal effects in high power laser generally result from quantum defects. With the historical pace and developments discussed above, the progress made by YDFLs has been spectacular. In particular, remarkable output power of up to kilo-watts in emission range of 1030 *nm*–1100 *nm* have been realized consecutively in recent years [47–50].

2.4.1 Development of 1018 *nm* YDFLs

Development of high power YDFLs that operate around 1018 *nm* proposes a challenge due to the intrinsic absorption and emission cross section of Yb-doped silica fibers. Absorption cross-section decreases rapidly from 1000 *nm* towards 1100 *nm* making 1018 *nm* operating YDFLs good pump sources as pumping at longer wavelengths becomes increasingly inefficient [7, 15]. Since the emission cross-section around 1018 *nm* is much smaller compared to 1030 *nm* YDFLs operating at shorter wavelengths than 1030 *nm* face the challenge of gain competition between useful laser and amplified stimulated emission (ASE). Amplified stimulated emission (ASE) in the laser system can lead to a decrement in laser output power, or even completely dominate the oscillation of the wanted laser wavelength in the cavity [13]. Thus suppression on gain around 1030 *nm* is foremost the key condition to successfully obtain lasing at 1018 *nm*.

Theoretical studies have been carried out on the effect of gain parameters for 1018 *nm* operating YDFLs. Yangshan *et.al.* [13], and H. Xiao *et.al.* [51], obtained relationships between gain around 1030 *nm* and physical parameters of the active fiber in equations (2.15) and (2.16) respectively using the gain formulae derived from [52, 53].

$$G_{1030} = 0.25G_{977} + 0.36\left(\frac{d_{clad}}{d_{core}}\right)^2 \alpha_{976} \quad (2.15)$$

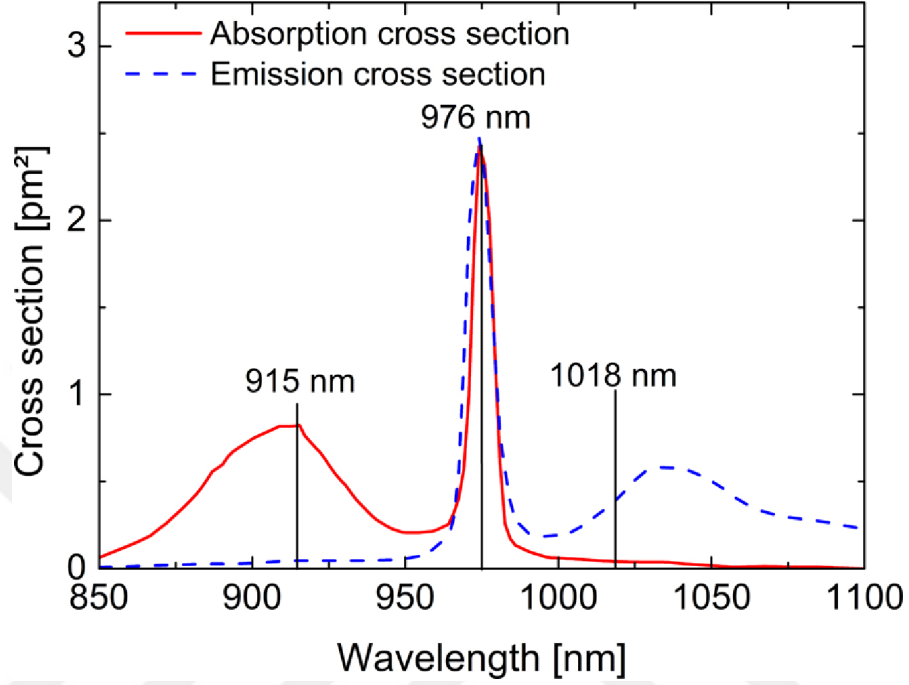


Figure 2.10: Absorption and emission cross-sections for Yb-doped silica fiber. From [15]

$$G_{1030} = 1.48G_{1018} + 0.012\left(\frac{d_{clad}}{d_{core}}\right)^2 \alpha_{976} \quad (2.16)$$

where G_x is gain at x nm, α_{976} is absorption at 976 nm, d_{core} and d_{clad} are active fiber core and clad diameter respectively.

Equations (2.15) and (2.16) both emphasize the importance of the core-cladding ratio as well as the absorption of the fiber. It can be followed that increasing the core-cladding ratio, while reducing Yb ion doping concentration as well as decreasing the length of the active fiber help the suppression of gain in 1030 nm. Optimizing the the length of the active fiber plays a vital role to 1018 nm oscillation. Longer fibers allow reabsorption of unabsorbed pump which may lead to increased gain in the cavity, which in turn can lead to ASE. Shorter fibers have less probabilty of reabsorption, but also inadequate pump absorption. Thus, fiber optimization is important as the perfect compromise between risk of ASE and adequate pump absorption is to be determined.

Another important factor in suppressing ASE is the cleaving of the output end

of the fiber. As discussed earlier, straight cleaving (Fresnel reflection) is enough to facilitate oscillation in a Yb-doped gain medium. However, the oscillation is not wavelength selective, that is, wavelengths with higher emission cross-sections will be favored. Since the emission cross-section is much higher around 1030 nm than around 1018 nm , unwanted wavelengths oscillate in the gain cavity. Angle-cleaving the fiber eliminates the Fresnel reflection, thus allowing the FBGs of the YDFL to selectively allow the lasing of 1018 nm .

The properties of the pump source are also key factors to both the power and output beam quality of the 1018 nm laser. Since the absorption cross-section around 976 nm is very narrow, when using 976 nm pump sources, it is paramount to keep the linewidth of the pump source as narrow as possible [51, 54]. Significant increase in output power and efficiency can be realized when using narrow linewidth pump sources [54]. The highest output power reported in detail for a YDFL operating at 1018 nm was 805 W by P. Yan *et.al.* [54] using wavelength stabilized diodes and the configuration shown in Fig.(2.11)

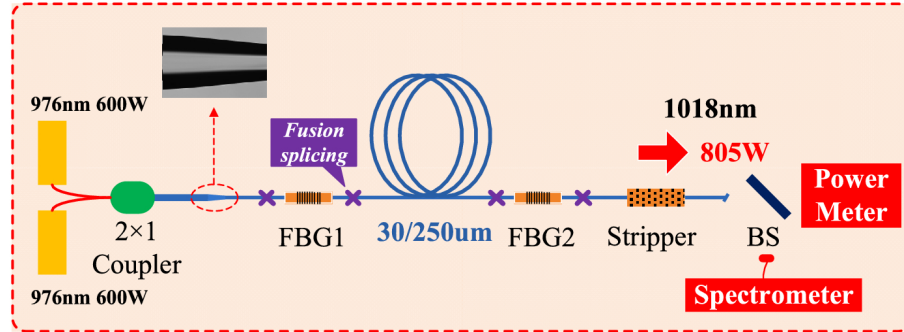


Figure 2.11: System configuration for the 805 W 1018 nm YDFL reported by P. Yan *et.al.*. From [54]

The progress of the development of 1018 nm YDFLs using 976 nm pump sources has been impressive. In the span of about half a decade, detailed scientific reports of output powers have soared from a few watts [55] to near kilowatt-levels [54] as shown in the table(2.1)

	Fiber abs. coeff. (dB/m)	Fiber length (m)	Fiber core-clad diameter ($\mu\text{m}/\mu\text{m}$)	OCFBG reflect. (%)	Output power (W)	Laser eff. (%)
Li <i>et. al.</i> 2011 [55]	3.0	2.6	20/400	9.0	7.5	16
Xiao <i>et. al.</i> 2012 [9]	5	2.5	10/125	20	10.5	55
Xiao <i>et. al.</i> 2012 [9]	6	4	15/130	20	85	71
Yanshan <i>et. al.</i> 2014 [13]	3	5	15/130	10	154.6	71
Xiao <i>et. al.</i> 2013 [51]	4	4	30/250	10	309	71
Xiao <i>et. al.</i> 2015 [9]	5	4	30/250	10	476	78.2
Yan <i>et. al.</i> 2016 [54]	6.3	3.0	30/250	15	805	64.9

Table 2.1: The table shows the development of 1018 nm YDFs over the years using 976 nm pump sources. The term "fiber" corresponds to the active fiber implemented in the system. Important factors such as active fiber absorption coefficient at 976 nm, length, core-cladding diameters, and OCFBG reflectivity values are displayed.

2.5 1018 nm YDFLs and Tandem Pumping

High power single mode YDFLs are of utmost interest due to the several properties discussed, such as scalability, and brightness. However power scaling of high power single mode YDFLs face a potential bottleneck arising from three correlated problems; insufficient pump brightness, thermal load, and contribution of nonlinear effects in the active fiber [56]. This bottleneck creates a digression in the progress of fiber design in opposing directions. This causes a crucial compromise between the length and core size of the active fiber. For example, while nonlinear scattering diminishes in a shortened active fiber length, the output beam may suffer from beam degradation induced by thermal load [57]. Thus making it more challenging to increase the core diameter, while retaining diffraction-limited output beams [57–59]. The most common place solution is to simulate for varying combinations of active fiber core size and length while maintaining a beam with reduced nonlinear effects.

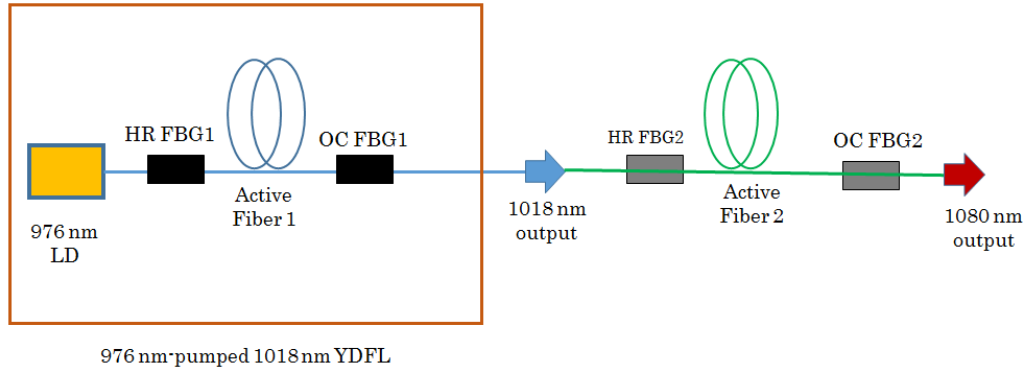


Figure 2.12: A simple tandem-pumped configuration employing a 1018 nm YDFL as pump source

The use of tandem-pumping scheme [57, 59, 60] proposes a method of reducing the total thermal load, due to an effective reduced quantum defect. Tandem pumping scheme allows the use of shorter active fibers with calculated thermal load per unit length [57]. With tandem pump scheme thermal and nonlinear limits can be simultaneously nullified. This makes tandem pumping a prospective pumping scheme for high power scaling compared to the obtainable output powers

from conventional pumping methods. Tandem pumping employs the use of fiber laser with output wavelengths closer to the eventual target output wavelength.

In the case of 1018 *nm* YDFLs, although the absorption cross-section of Yb ions around 1018 *nm* is much smaller than that at 975 *nm*, however YDFLs operating at 1018 *nm* provide much brighter pump light than that from 97x *nm* laser diodes. And also, the pump light from 1018 *nm* YDFLs can be coupled into smaller active fiber inner claddings. Thus, the pump absorption at 1018 *nm* is quite sufficient due to the small cladding-core area ratio [55]. Another important reason for the need of using 1018 *nm* YDFLs is the reduction of quantum defect. The quantum defect is about 8% - 10% when a 1060 *nm* - 1080 *nm* YDFL is pumped by a 976 *nm* pump source, compared to 4% - 6 % when the YDFL is pumped by a 1018 *nm* fiber laser. This low quantum defect by using a 1018 *nm* pump source allows for potentially high power efficiency, with low thermal load as most of the power comes from quantum defect [61]. The use of 1018 *nm* YDFLs as pump sources allows for potentially high power output as evinced by IPG in 2009, where 10 *kW* single mode YDFL was reportedly achieved by the use of tandem pumping [62].

Chapter 3

Numerical Modelling and Simulation

The modelling and simulation of the systems developed in this study were done using the program RP Fiber Power from RP Photonics. The software can model the behavior of laser-active ions and also phenomena such as absorption and emission processes (both stimulated and spontaneous), energy transfer processes and nonradiative ion transitions. The software also simulates arbitrary number of pump and signal inputs and also deal with amplified spontaneous emission (ASE).

The model takes into consideration a single active fiber. The length L of the active fiber is always defined (Fig.3.1). The position along the fiber is characterized with a coordinate z , varying from 0 to L . The number of steps n is defined and the active fiber is numerically represented by N_z sections of length $\Delta L = L/n$ with ΔL the step size. The software calculates the optical powers and the electronic level populations for the position $z_j = j\Delta L$, where the index j varies from 0 to n .

The software calculates the electronic level populations of the active ions in terms of fractional level population (whose total sum is 1) with respect to their

position in the active fiber. Thus the populations of active ions can be calculated for each z_j along the active fiber. The data for the active ion population are obtained from the spectroscopic data of the active fiber uniquely defined in terms of doping concentration and geometry. Active ion population can then be calculated using mathematically solved rate equations. The software also assumes a simple but sufficient energy level scheme where a single metastable level is considered. The transition rates from absorption, spontaneous and stimulated emission can then be defined.



Figure 3.1: Active fiber model showing step size

The gain is calculated using a simple case of absorption of power to upper level and emission to lower level. Since populations change z_j , then it is expected for gain to also vary along the length of the active fiber. Thus, if N_1 and N_2 denote populations of lower and upper energy levels respectively then the gain can be calculated as

$$g(\lambda) = \int_0^L [N_2(z)\sigma_{em}(\lambda) - N_1(z)\sigma_{abs}(\lambda)] dz \quad (3.1)$$

where λ is the wavelength of the beam propagating in the cavity, σ_{em} and σ_{abs} are cross-sections for emission and absorption respectively.

Reflectivities of the mirrors (in this case, FBGs) are also taken into consideration. That is, attenuation from mirrors are considered during propagation of the beam in the cavity. The propagation of beams are also simulated both in terms of optical powers and also in full complex profiles under the influence of arbitrary (but low-contrast) refractive index profiles, laser gain, Kerr effect and other nonlinearities. The software assumes one directional propagation (along z -direction) with very low divergence and well as single polarization.

Numerical modelling of the system and simulation of the lasing operation was

done for every system developed in this work. The modelling and simulations were executed based on the pump sources, active fiber length and FBG reflectivities.

3.1 976 nm Pump Sources

Simulations were carried out to further optimize the active fiber length and OCFBG reflectivity for the systems developed. Optimizing considerations for the active fiber was such that; the length of the active fiber should be long enough for near total pump absorption, and short enough to prevent reabsorption of pump power which leads to ASE. Simulation results are shown in Fig.3.2. The active fiber used in this section was from NUFERN; Nufern LMA 30/250, with 6.30 *dB/m* absorption around 975 *nm*, core and clad NA of 0.06 and 0.46 respectively. The spectroscopic data for the active fiber was loaded in to the software; and from the data, relevant information was obtained to calculate important parameters. Simulations showed that for the chosen optimized active fiber length from Fig.3.2, there is no significant advantage of using 10% reflectivity OCFBG over the 30% reflectivity OCFBG and vice-versa, as also reported in [51,54]. In the simulation, 600 *W* of pump power had been considered because an initial pumping scheme was to pump from two 976 *nm* laser diodes with 280 *W* maximum output power. From the simulations it can be seen that the system is sensitive to active fiber length and the choice of OCFBG reflectivity between 10% and 30% is irrelevant as shown by the simulation results in Fig.3.2. From 600 *W* pumped, the simulations show the output power to be around 550 *W* giving a resounding efficiency of 91.7%.

3.2 Tunable Pump sources around 915 nm

In order to achieve the intended maximum power for the laser system with minimal undesired effects -such as ASE and residual pump-, the performance of the system was first investigated by numerical simulation. Optimal OCFBG

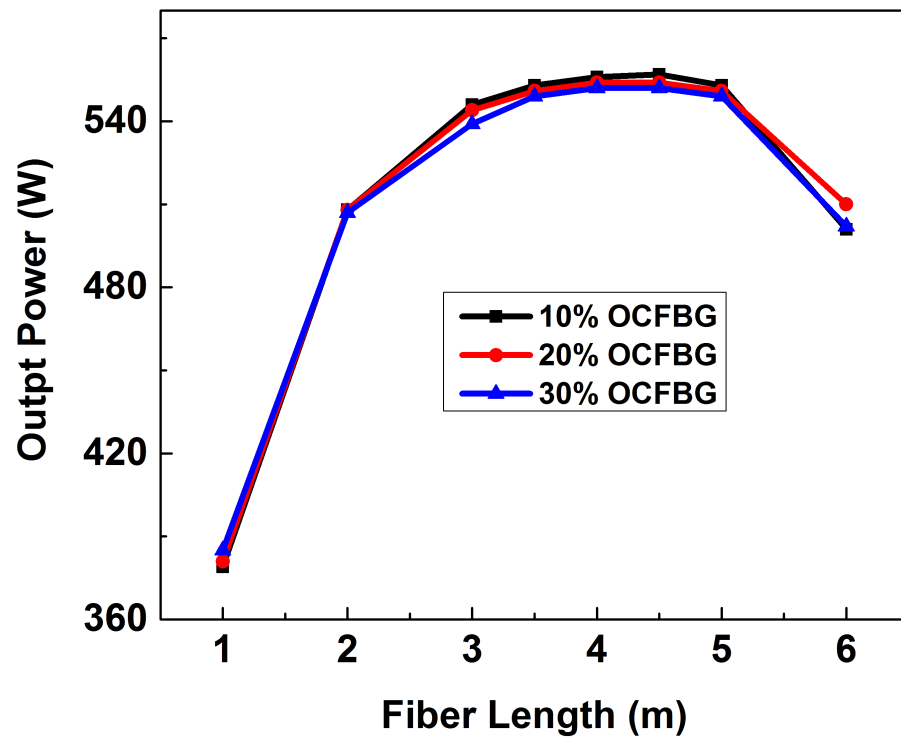
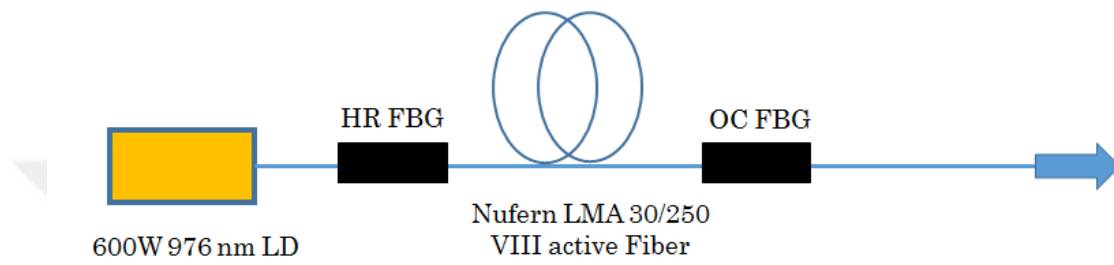


Figure 3.2: System configuration used for simulation, and simulation results for 976 nm pumped system

and active fiber lengths were taken into consideration. Several experimental works [3, 9, 10, 31] on 1018 nm YDFLs pumped 976 nm with high efficiency report that the optimal OCFBG reflectivity could be around 10% - 30%. Maximal output power, in conjunction with laser efficiency was also studied by varying OCFBG reflectivity values from 10% to 30% in the configuration (Fig.3.3) used in this study. Unlike when pumping with 967 nm diodes, the contribution of OCFBG is quite distinctive in this case. The simulations show that the optimal OCFBG could be around 30% compared to 10%. According to the simulations and manufacturing possibilities, an OCFBG of 26% was chosen. The laser output power against varied active fiber length was also studied (Fig.3.3) with respect to different OCFBG values. The active fiber used in this section was from LIEKKI; Liekki Yb700 30/250, with 2.2 dB/m absorption around 915 nm. This absorption cross-section of this fiber was a bit higher than the conventional large mode area (LMA) fibers. This was chosen on purpose since we will be pumping from a region with lower absorption compared to 976 nm. In order to compensate for probable reduced round-trip gains in the cavity, a higher doped active fiber was suggested. This is the first report of the implementation of this configuration and as thus, thorough simulation as well as detailed optimization are required.

The goal of the simulation in this section is to demonstrate the operation of 1018 nm YDFL with minimal efficiency variance by a pumping configuration utilizing the broad 915 nm region. In order to obtain the information about laser operation behavior with pumping wavelengths ranging from 902 nm to 924 nm, the system was numerically analyzed. This simulation result shown in Fig.3.3c is an exact model of the experimental system with HRFBG (99% reflectivity), active fiber length (4 m), and OCFBG (26% reflectivity). The simulation shows the output powers and efficiency of the system under the pumping with center wavelengths ranging from 902 nm to 924 nm with a fixed pump power of 30 W for all pumping wavelengths. The purpose of this simulation is to present that pumping wavelengths around the broad 915 nm region (902 nm - 923 nm) results a minimal output power and efficiency variation. With this approach, from the simulation, laser efficiency between 59% - 61% can be obtained for the pumping configuration of 910 nm - 924 nm wavelengths. Shorter pumping configuration

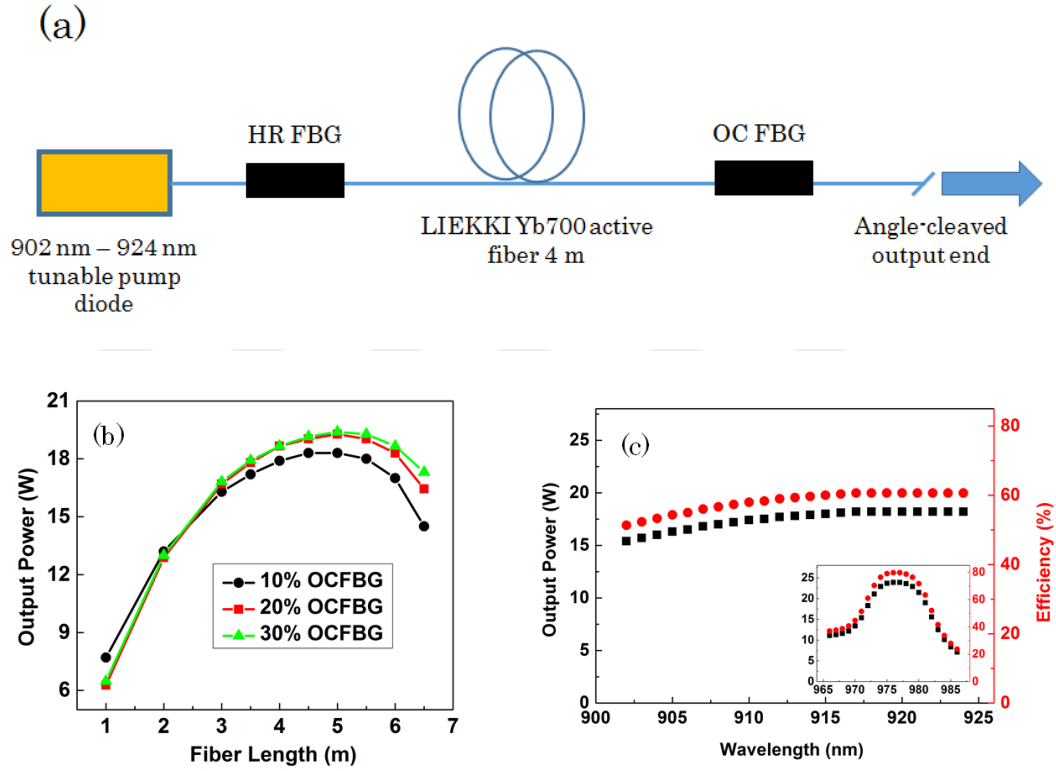


Figure 3.3: (a) System configuration considered for simulation. (b) Simulation showing the effect OCFBG reflectivities and active fiber length on laser output. (c) Simulation of the 1018 nm YDFLs (experimental approach) output power versus pumping configuration from 902 nm to 924 nm and the 1018 nm YDFLs implemented by [3] output power versus pumping configuration from 966 nm to 986 nm (inset) In all simulation analyses, the launched pump power was 30 W.

(902 *nm* - 910 *nm*) resulted in a lower laser efficiency between 53% - 58%. In most experimental works regarding 1018 *nm* YDFs, diode sources around 976 *nm* are frequently used, due to high absorption cross-section in Yb-doped glass at this wavelength. Nevertheless, the viable pumping wavelength range is very narrow thus offers very low tunability as the simulation predicts (inset Fig.3.3c). The simulation is modeled after an optimized system with the active fiber being Nufern LMA 30/250 HI-8 with cladding absorption of 6.3 *dB/m* near 976 *nm*. The length of the active fiber was optimized to be 3 *m* and the OCFBG was chosen to be 10% (as used in [3,9]) and input launched pump power was maintained at 30 *W*. The simulation shows the behavior of the model system when pumped with wavelengths from 966 *nm* through 986 *nm*. The results show that the viable pumping wavelengths, efficiency-wise, are around 971 *nm* - 982 *nm* since other wavelengths yielded an efficiency less than 50%. This viable pumping range is a 10 *nm* wavelength span compared to the more than 20 *nm* span tunability of pump sources around 915 *nm*.

Chapter 4

Experiments and Results

In this study, variety of parameters and conditions have been carefully studied, modelled and simulated before the development of subsequent lasers. Parameters such as ytterbium ion-doping concentration, the length, and the core-cladding ratios of the the active fibers used. The pump sources were also characterized so as to have information on the optimal wavelength and linewidth of the output spectra of pump sources. The temperature profile along red-shifting of the pump laser diodes were also characterized.

4.1 Design Consideration

All the laser systems developed during the course of this study share a similar design. A single diode pump source, followed by high-reflectivity fiber Bragg gratings (HRFBG), the active fiber, the output-coupling FBG (OCFBG) and depending on the system specification a combiner adapter and (or) a cladding light stripper were (was) implemented. Both the HRFBG and OCFBG were centered at 1018 nm as this is the preferred wavelength oscillation in the cavity. The overall system schematic is illustrated in Fig.4.1.

In later part of this work, passive elements such as cladding light strippers

(CLS) and combiners were implemented. The CLS is integral to the output beam quality of fiber laser systems. CLS ensures residual light in the inner cladding of the fiber towards the output end of the fiber laser is coupled out of the system. This out-coupling of residual light is done by refraction by changing the refractive index profile at the inner cladding and outer jacket boundary interface. Stripping the coating off a region on the inner cladding and recoating with a high index material, means total internal reflection does not occur any longer in the recoated region. Instead light in the inner cladding get coupled out of the fiber by refraction.

The combiner generally is a passive component that combines multiple beams either from pump sources or output laser beams into a single beam. However in this work, the combiner served as an adapter to attenuate back reflected light from the HRFBG that normally gets back to the pump laser diode. Avoiding the situation, where backreflected light from the HRFBG reaching the laser diode is important, especially at high power levels, and, when the laser diodes do not have inbuilt protection windows.

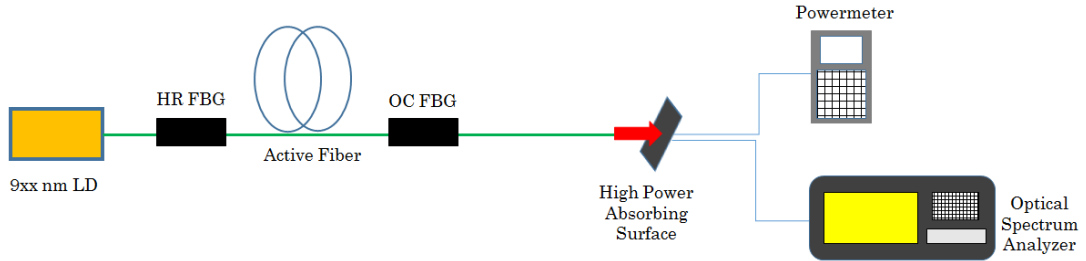


Figure 4.1: Schematic of the laser system configuration

Three pump sources were used in the experiments. The laser diode emitting at 976 nm was VBG stabilized, water-cooled DILAS diode laser. The importance of VBG stabilization for narrow linewidth lasers was explained in the Chapter 1 of this work and in [17]. The second diode used was an nLight diode that pumped from 902 nm to 915 nm . The wavelength shifts (red shift) are due to both increase in the operating driving current operating temperature. The final diode was a JDSU diode that pumped from 915 nm to 923 nm . The red-shifting

occurrence in this diode is same as for the nLight diode discussed earlier. This section will be mainly categorized by the type of diode used to pump the laser system in context.

The active fibers used in all the experiments, while varying in length or ion concentration, share similar cross-section dimensions. As shown in [3, 9, 51, 54] fibers with high core-cladding ratio benefits ASE suppression as well as lasing at 1018 nm. Fibers with core diameter of 30 μm and cladding diameter of 250 μm were used. That said, as expected the beam profile obtained from the experiments would not be single mode since active fibers with large diameter core (30 μm) were used. The reflectivities of OCFBGs were simulated for around 10% - 30% and the most beneficial reflectivity value was selected. Due to manufacturing constraints, only 10% and 26% OCFBGs were available and both were tested. The use of CLS was to remove unwanted power from unabsorbed pump and ASE from the spectrum of the system. A combiner adapter was also implemented in some laser design to squeeze out more power from the pump source with the risk of damaging it from back reflection that occurs at the pump output-HRFBG boundary. Finally, the systems were developed on a water-cooled platform (the active fiber was wrapped around a water-cooled cylindrical block) to ensure safe and optimal performance of the YDFLs (Fig.4.2)

4.2 976 nm pumped 1018 nm YDFLs

Due to the high absorption cross-section of *Yb*-doped silica fibers around 976 nm, pump sources around this wavelength have yielded high power laser with excellent beam profiles with good output efficiency. Based on this, incentive development of 1018 nm YDFLs, in this study, was first tested with 976 nm pump sources.

The active fiber used in this section was from NUFERN; Nufern LMA 30/250, with 6.30 dB/m absorption around 975 nm, core and clad NA of 0.06 and 0.46 respectively. The absorption of this fiber was a bit higher than the value used

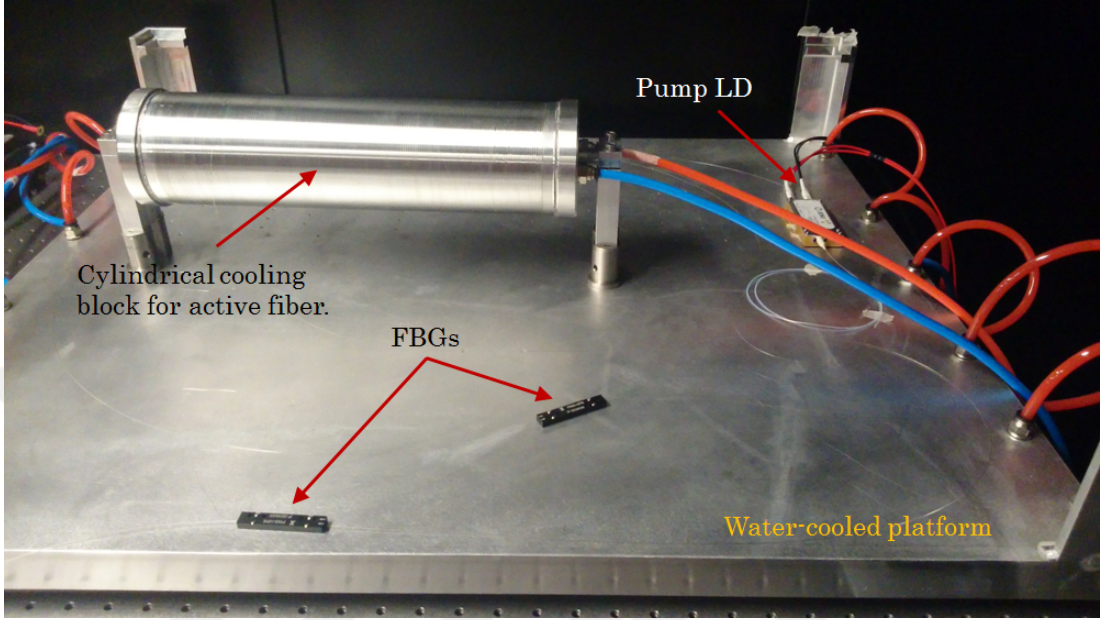


Figure 4.2: The laser system setup with all its components on the actively cooled platform

in [51, 54] however, optimizing the fiber length should compensate the high absorption. The pump source was a very narrow linewidth (0.36 nm at maximum power of 240 W) VBG stabilized DILAS diode (see Fig.4.3)

4.2.1 Results

The first system for the initial attempt was set-up such that, there were neither OCFBG nor CLS implemented in the laser systems. The output end of the system was straight cleaved. The straight-cleaved output end of the laser system acts as the partial reflector of the cavity. This reflection is due to Fresnel reflection [28, 55] and is generally estimated to around 4% reflectivity. From the simulations shown in Fig.3.2, an active fiber length of 3.5 m was used.

No lasing was observed around 1018 nm . The 1018 nm laser was not generated, in its place, the YDFL emitted at wavelengths of about 1030 nm and 1040 nm and 1050 nm . The HRFBG even though centered at 1018 nm did not cause the 1018 nm laser to oscillate in the cavity. This is due to the other end of the

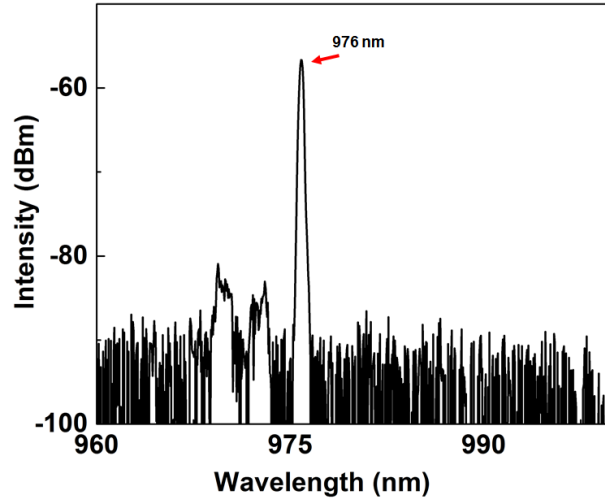


Figure 4.3: Spectrum of the VBG stabilized DILAS pump diode.

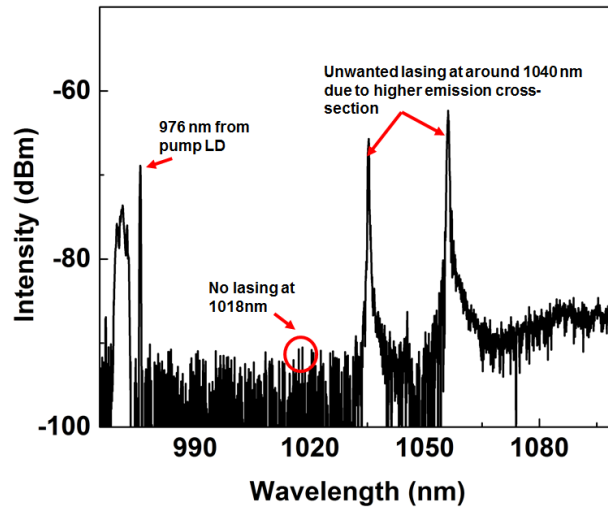
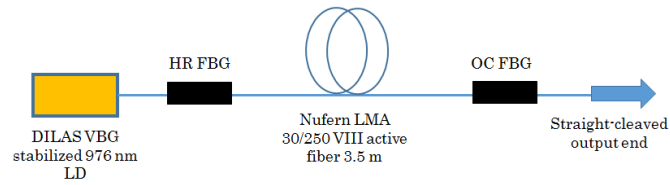


Figure 4.4: System configuration of the second attempt, and spectrum obtained from output laser.

active fiber being straight cleaved forming a 4% Fresnel reflection. The Fresnel reflection from the straight-cleaved end of the active fiber is considered independent of the wavelength, thus reflecting several wavelengths and causing them to oscillate in the cavity. Because Yb ions at 1030 *nm* and 1040 *nm* have larger emission cross-sections and smaller absorption cross-sections compared to that at 1018 *nm*, 1030 *nm* and 1040 *nm* lasers oscillate in the cavity.

The second attempt at generating a YDFL operating at 1018 *nm* involved placing an OCFBG with 30% reflectivity just before the straight cleaved output end as shown in Fig.4.4. The idea behind this setup was to know how much of an impact is the contribution from the non-selective reflection from the Fresnel reflection. Similar to the first attempt, unwanted laser generation was also observed around 1030 *nm* and 1040 *nm* (Fig.4.4). This showed that suppressing backreflection from the straight-cleaved is key, as Fresnel reflection continued to allow the oscillation of higher wavelengths.

With the information gathered from the previous setups, a third system was setup employing both 30% OCFBG and an angle-cleaved output end as demonstrated in Fig.4.5. The output end was cleaved to 8° using the VYTRAN cleaver. The angle cleaving was done so as to suppress the backreflection as highly as possible. With this setup, efficient lasing was observed around 1018 *nm* (Fig.4.5). ASE was also sufficiently suppressed as the peak-to-peak suppression ratio (laser to ASE) was more than 40 *dB*. The YDFL was pumped up to a maximum power of 176.8 *W* yielding 140 *W* output. Efficiency was 79.2% and the linewidth of the output beam was around a very narrow 0.2952 *nm* (Fig.4.5).

In order to get rid of the unwanted pump and ASE around 1030 *nm*, a CLS was implemented into the system. A cascaded CLS was developed (thanks to Elif Uzcengiz-Şimşek) and characterized in terms of power stripped and temperature. The schematic of the new system is illustrated in Fig.4.6. The CLS implementation resulted a spectrum free of both unwanted ASE and reduced unabsorbed power (Fig.4.6). However, the efficiency of the system reduced by more than 10%, as a pump power of 176.8 *W* yielded an output of 117.5 *W*. The output beam linewidth remained narrow at 0.3163 *nm*.

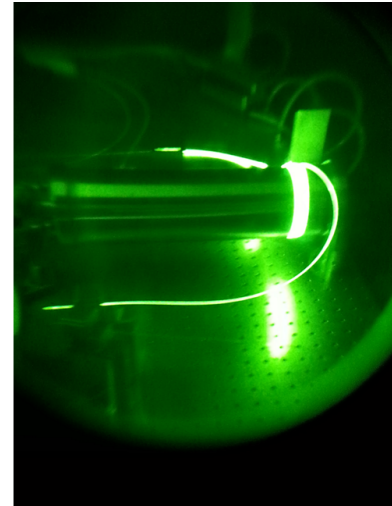
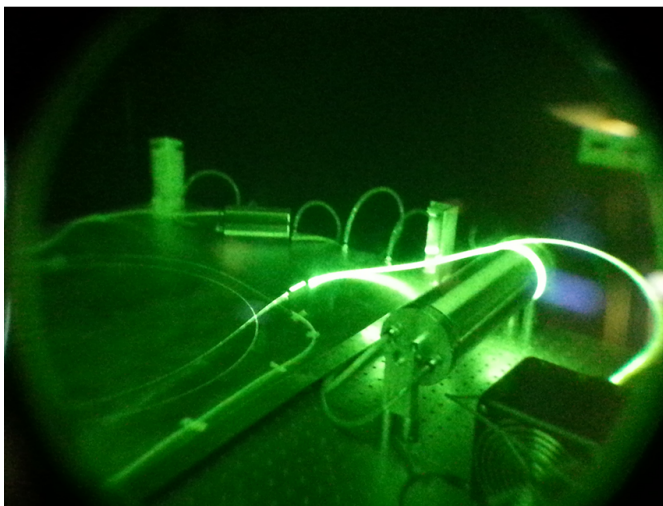
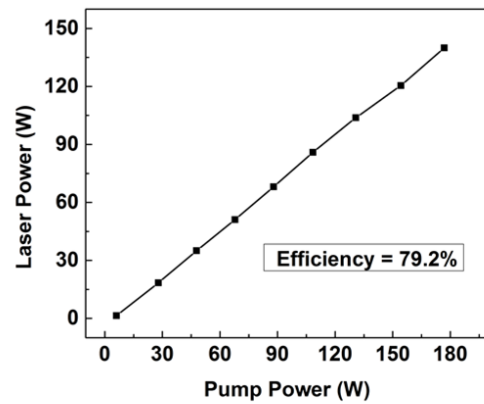
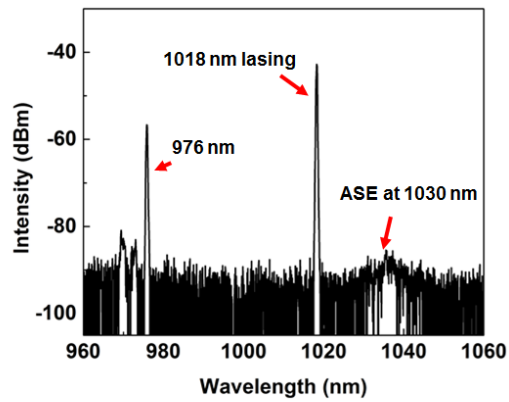
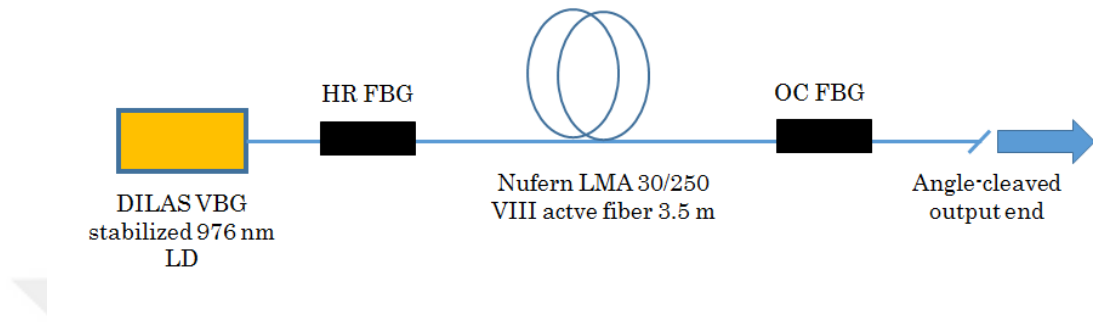


Figure 4.5: System configuration of the successful attempt, spectrum and efficiency obtained from output laser. The system as seen from an Infra-red viewer during lasing at low power

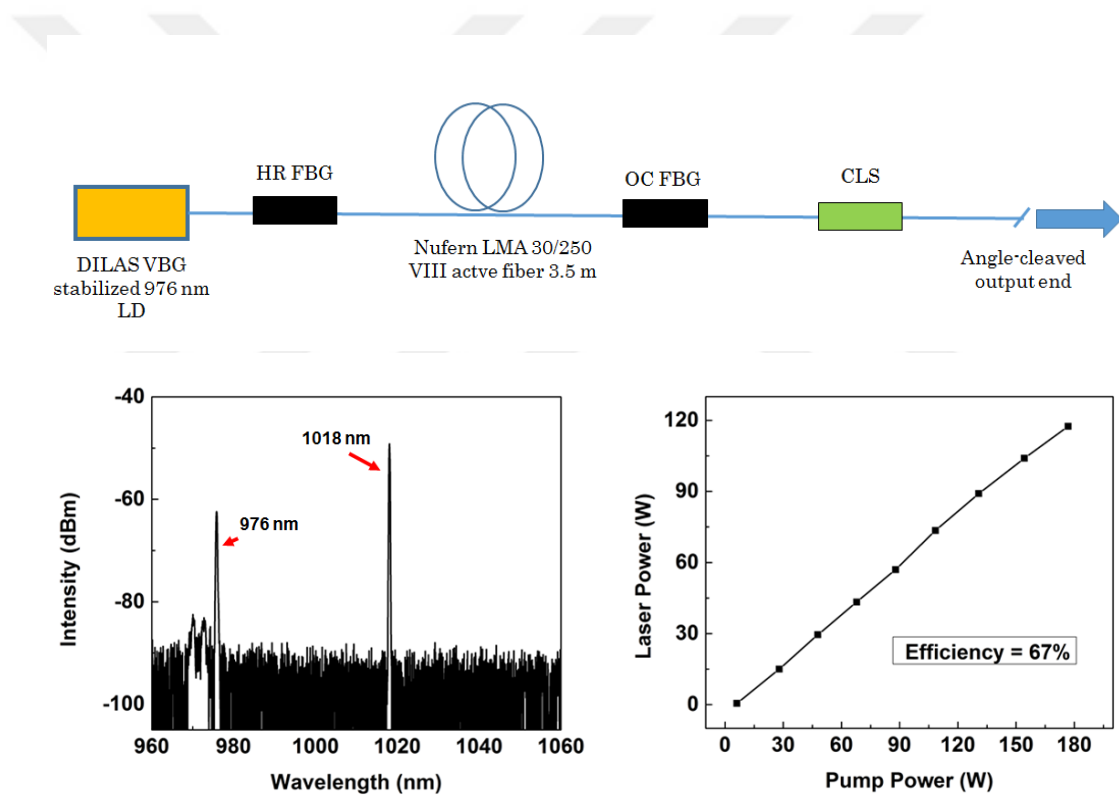


Figure 4.6: System configuration of the with CLS implemeted, spectrum and efficiency obtained from output laser.

After the successful attempts with the 30% OCFBG, the 10% OCFBG was tested as well. In this case, the active fiber length was shortened to 3 *m* as both ASE and lasing were observed in the spectrum. Reducing the fiber length prevented reabsorption thus reducing the probability of ASE generation in the system. The YDFL developed using 10% OCFBG showed similar spectrum results as with the ones developed when using the 30% OCFBG. The system was run with and without the CLS. Without the CLS, an efficiency of 79% was obtained from a pump power 176.8 *W*, while with the CLS, efficiency dropped to 66% with pump power remaining the same.

4.3 Tunable Pumping for 1018 nm YDFLs

The broad absorption cross-section of Yb-doped silica glass around 915 *nm* gives an interesting prospect as tunable pump sources for pumping 1018 *nm* YDFLs. Yb-doped fibers have two pronounced absorption regions (Fig.2.10); the narrow region with relatively high absorption cross-section around 976 *nm* and the broad region with lower absorption cross-section around 915 *nm*. For these reasons, almost all 1018 *nm* YDFL pump sources employ the use of pump sources around the 976 *nm* region. Although pump sources around 915 *nm* have been used for pumping YDFLs operating in the 1050 *nm* to 1090 *nm* range, there is no mention of the use these pump sources for 1018 *nm* YDFLs.

One of the main challenges with using 976 *nm* sources is ensuring the wavelength stability of pump sources during laser operation. This arises due to the narrowness of the absorption region around 976 *nm* in the spectrum ytterbium ion. Parameters such as operating temperature and electrical requirement affect the output center wavelength of the pump diodes. Thus, a careful thermal stability management is required for the pump diodes to facilitate optimal pumping of 1018 *nm* YDFLs. Even with good thermal management and cooling of the pump diodes, the output spectrum of the pump diodes may broaden at high power application due to increased driving current. Narrowing the linewidth of the pump diode output spectrum is also a challenging issue for pump sources operating at

976 *nm*. This situation can be overcome through the use of wavelength-stabilized diode lasers. Wavelength stabilization can be achieved by several approaches including the use of volume Bragg gratings (VBG) [17]. VBG stabilization reduces the sensitivity of the laser diodes to temperature variance and increasing driving current. In the literature, VBG wavelength stabilization was also shown to narrow the diode linewidth from 10 *nm* to 1 *nm* [17]. In spite of all these advantages, the use of VBG stabilization has its drawbacks. Firstly, the use of VBG stabilized diodes is not a cost effective approach and due to the pump laser diode being an aggregated stacks of smaller diodes coupled together, non-uniform cooling these individual diodes stacks can broaden the output linewidth and also make wavelength stabilization challenging [17]. Nevertheless, the low absorption spectral cross-section region around 915 *nm* offers a broad range of wavelengths usable for pumping 1018 *nm* YDFs.

Although, utilizing these wavelengths for pumping 1018 *nm* YDFs will yield lower efficiency due to the lower absorption cross-section for Yb-ions compared to the region 976 *nm*. However the efficiency drops from pumping wavelength shifts -due to temperature rise or increase in diode driving current- can be overcome using the 915 *nm* broad region. In this study, the motivation is from the hypothesis that, the pumping wavelength range around 915 *nm*, coupled with well optimized parameters -such as active Yb ion doping concentrations, the length of the active fiber, and output coupler reflectivity- can offer a robust tunable pumping scheme for 1018 *nm* YDFs.

The numerical simulations showed that an active fiber length of 5 *m* would be optimal, however upon experimental analysis, the optimal length was shown to be around 4 *m*. Fiber length shorter than 4 *m* (around 3.5 *m* or less) resulted in lasing at 1018 *nm*, but inadequate power absorption and high unabsorbed pump power was present in the output spectrum. Fiber lengths significantly longer than 4 *m* (5 *m* or more) did not favor any lasing action at the desired 1018 *nm*. We observed parasitic lasing at around 1030 *nm* for longer active fiber length. The output end of the laser system was definitely angle cleaved to 8° to prevent back reflection. It should also be noted that, there was no lasing observed around 1018 *nm* when the output end was straight cleaved.

4.3.1 Results

From the assessment of the information obtained from simulation, and the capabilities of the pump diodes, pump wavelengths from 904 *nm* to 922 *nm* were tested to pump 1018 *nm* YDFL. The center wavelengths of both nLight and JDSU diodes can be tuned by varying the operating temperatures of individual diodes. This allows the operating temperature of the diode to increase steadily even at a fixed input driving diode current. The diodes were characterized with respect to the pump center wavelength and pump power at each temperature value. In the characterization study depicted in Fig.4.7a, it was observed that varying the operating temperature (within safety limits) of the diodes, causes the pumping power of the diodes to slightly vary. Due to this reason, the optical-to-optical efficiencies of the laser system at each pump center wavelength are displayed instead of the laser output powers realized during the experiment. The increase in the operating temperature of the diode due to limited cooling causes a red shift in the center wavelength of the diode (Fig.4.7a). The nLight diode presented an initial operation wavelength of 904 *nm* and 30.3 *W* at about 22°C operating temperature. When its operating temperature was run up to about 34°C, the center wavelength shifted to 910 *nm* and the diode output power dropped to 28.8 *W*. The JDSU diode presented an initial operation wavelength of 914 *nm* and power of 30.3 *W* at 24°C, ended up with a center wavelength of 922 *nm* and 29.7 *W* at 36°C when its operating temperature was allowed to rise. The wavelength range obtained from the characterization study formed the tunable viable wavelength span used in the experiments.

The center wavelengths from both pump diodes have linewidths between 1.2 *nm* and 1.3 *nm* for all operation temperatures, which are narrow enough linewidths for pumping the laser systems. Pumping the laser system through 904 *nm* - 922 *nm* from the experiments yielded an almost constant optical-to-optical efficiency of around 59% - 63%. This result agrees with the simulation data, as depicted Fig.4.8. The simulation data used for comparison in Fig.4.8 are chosen from the earlier simulation in Fig.3.3c to match relevant in points with the experimental data. The results obtained from experiments indeed show the tunability

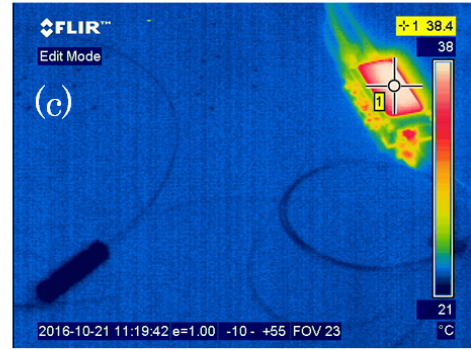
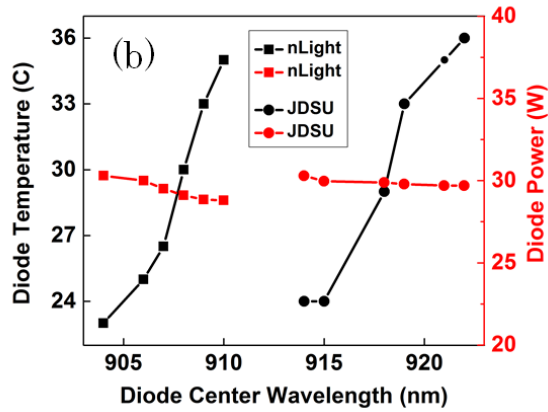
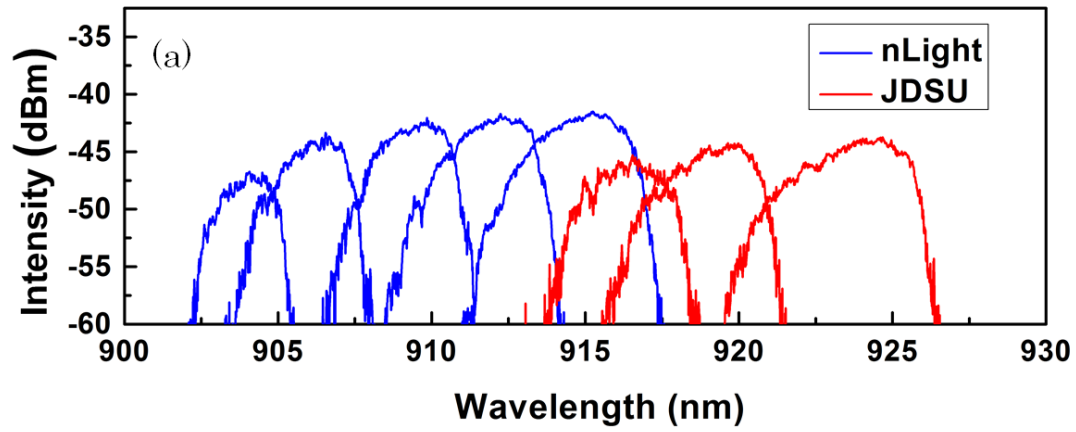


Figure 4.7: (a) Red-shifting of diode center wavelength due to increasing temperature (b) nLight and JDSU diode characterization data for center wavelength versus diode temperature and diode output power.(c) Temperature monitoring from an thermal infra-red camera.

of the pump sources used in the configuration.

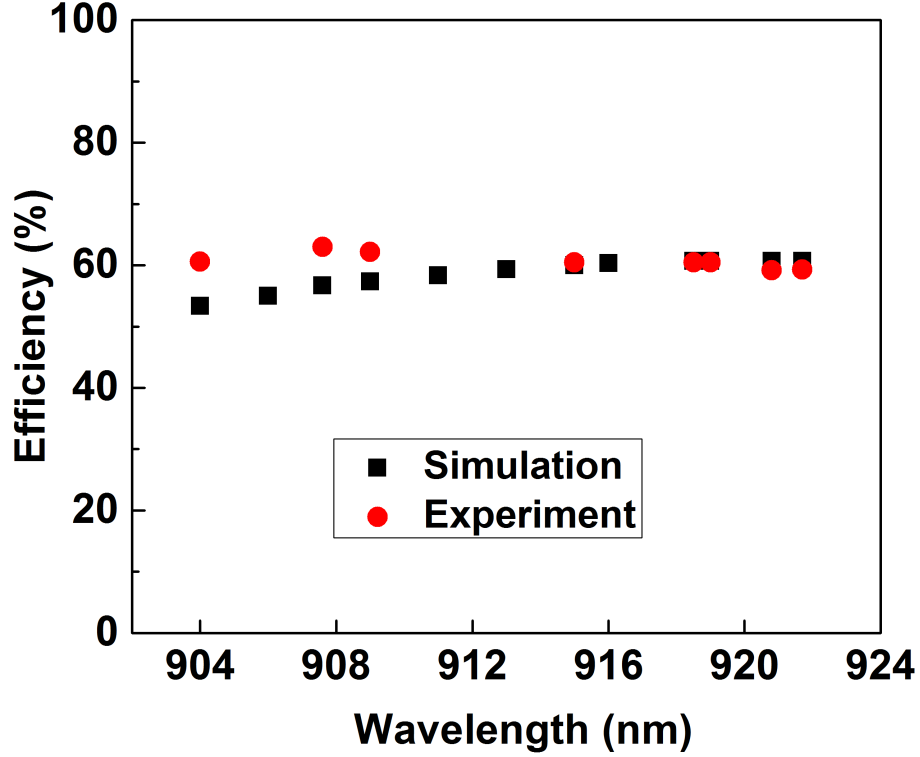


Figure 4.8: Experimental and simulation results of the optical-to-optical efficiencies for pumping configurations from 904 *nm* to 922 *nm*.

The laser system was further tested for high power experiment. The laser system was pumped with the nLight diode at operating central wavelength of 911 *nm* with a linewidth of 2.5 *nm*. There was an uncertainty about the in-built protection window against backreflection from HRFBG of the pump diode. Due to this a new system configuration was devised. A combiner acting as an adapter was implemented between the diode laser and the HRFBG. The combiner minimizes the amount of backreflection that goes into the fiber by attenuation (Fig.4.9. The length of the active fiber was also shortened to 3 *m* so as to prevent any rise of ASE in the system during lasing at high powers (although 3.5 *m* would have been optimal.

The output laser yielded an optical-to-optical efficiency of 67.3% and a slope

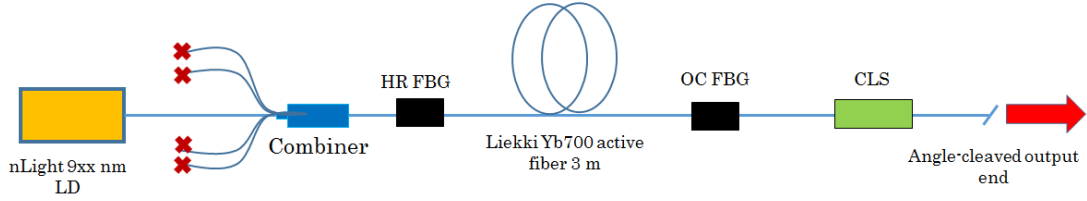


Figure 4.9: Schematic of the laser system used to test high power for the nLight diode.

efficiency of 69% with a spectral linewidth of 0.27 nm when the total pump power was 167 W with the absorbed power be (see Fig.4.10). The peak-to-peak difference between laser output and onset of ASE was about 45 dB. No parasitic lasing nor ASE was observed in the output spectrum of the system as shown in Fig.4.10 (inset). In order to calculate the total power resulting from unwanted power, the area under-the-curve from around 915 nm was evaluated. On the linear scale, the output laser was more than ten times higher than the unabsorbed pump.

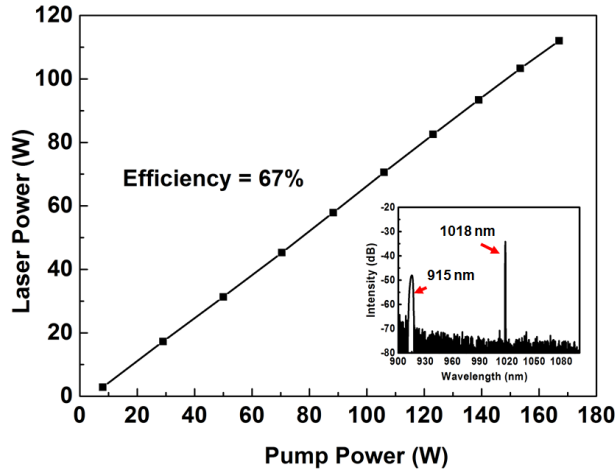


Figure 4.10: Efficiency plot and spectrum (inset) of the output laser.

Chapter 5

Outlook and Conclusion

As discussed extensively in Chapter 2 and Chapter 4, 1018 *nm* YDFs have great potential as use for pump sources for lasers operating at longer wavelengths. The challenges that come with development of 1018 *nm* YDFs are well known. As suggested in some citations [13, 15, 16, 51] in this work, using lowly doped Yb-ion to decrease excess gain in the cavity is beneficial. However, this situation is also tied to the length of the active fiber. A compromise in this case will be to have a fiber with adequate length to compensate reduction of unabsorbed pump and reabsorption, while maintaining a gain threshold in the cavity. The importance of core-cladding ratio as well as the cross-sectional geometry must also be considered. In this work, the geometries of the fibers are 30 μm core diameter, and 250 μm inner cladding diameter. With this geometry, single mode output lasers is not possible as the diameter of the core is not narrow enough to allow single mode propagation in the cavity. Development of single mode 1018 *nm* poses even more challenge since the diameter selection of the core of the fiber is restricted. Thus the core-cladding ratio choice is limited. Nevertheless as demonstrated by IPG, very high powers are achievable.

While pump sources for 1018 *nm* are usually around 976 *nm*, -for reasons such as high absorption cross-section and lower quantum defect- pump source around

915 *nm* propose an interesting prospect. Because of the broad absorption cross-section around 915 *nm*, there is a myriad of wavelengths to pump the YDFL without significant loss in output power and efficiency. This is particularly useful when pumping at higher power where red-shifting occur due to increased driving current of the diodes. Even with all of these advantages, pump sources around 915 *nm* are not favorable due to the low absorption cross-section compared to 976 *nm*. However, as shown in this thesis, these pump sources are capable of producing high power and narrow linewidth lasers with good efficiency, while negating the costs of the use of VBG-stabilized diodes. Improvements can be realized in the system by using highly doped active fiber lasers. While it has been reported that using low doped fibers is beneficial (by preventing excess gain), pumping from a low absorption region should facilitate a similar single pass gain in the cavity.

The need for a very good CLS is paramount. CLS implemented in the system, ensures both unabsorbed pump power and ASE are stripped off the output. In this work, the CLS employed reduced the efficiency by 15% which was a lot more than the efficiency loss calculated by integrating for the contribution from unabsorbed pump and ASE. This shows that, useful power was stripped from the system as well. While this loss of useful power is probably inevitable, optimizing the CLS so as minimize this loss is of importance.

The end goal of the 1018 *nm* YDFLs developed in this thesis is for use as pump sources for longer wavelengths, particularly around 1080 *nm* in tandem pumping configuration. The final 10180 *nm* YDFL can be either as tandem-pumped amplifiers or oscillators. While high power tandem-pumped amplifiers have been reported, there are very scarce reports of tandem pumped oscillators. A step in the right direction will be to develop and investigate tandem-pumped oscillators taking into account of all the optimization parameters discussed. Since 1080 *nm* YDFLs are very ubiquitous and widely studied, there should be enough information not to make this task arduous.

In this thesis, the history, research and development of 1018 *nm* YDFLs have been examined. The challenges that arise from this work, such as parameter optimization, and ASE suppression have also been discussed. With information

gathered from the research, and simulations, two sets of 1018 *nm* YDFLs have been developed with respect to the pump sources.

The first YDFL developed consisted of a VBG stabilized DILAS laser diode with an output at 976 *nm* to pump a 3.5 *m* long NUFERN LMA 30/250 active fiber. The HRFBG and OCFBG were 99% and 26% respectively. In the initial configuration, no CLS was used and an output power of 140 *W* was obtained from a pump power of 176.8 *W* marking a 79.2% efficiency. Upon the implementation of a CLS, the output power dropped to 117.5 *W*. As discussed in Chapter 5, there is a need for the optimization of the CLS as it is clear the CLS also stripped some useful light. The 10% OCFBG was also tested. The configuration remained the same, except this time, the fiber length was reduced to 3 *m* as excess gain occurred in the cavity when the fiber length was 3.5 *m*. Very similar results were obtained, when the system was tested without CLS (139.7 *W* output) and with CLS (117 *W* output).

A different approach for pumping YDFL with 1018 *nm* output was implemented taking advantage of the wide absorption spectrum of Yb-doped fibers around 915 *nm*. Two YDFLs were developed, one with pump source ranging from 904 *nm* to 914 *nm* and the other from 915 *nm* to 922 *nm*. HRFBG of 99% and OCFBG of 26% were used with LIEKKI 30/250 Yb-doped active fiber with absorption of 2.2 *dB/m* around 920 *nm*. This configuration utilizing these wavelengths as pump sources for 1018 *nm* YDFLs is first implemented in this work, as there no other detailed sources in literature. The novelty of this research lies in the fact that, with this pumping scheme, the temperature effects such as red-shifting of pump center are greatly reduced; while still maintaining a very good efficiency. With the tunable spectrum pumping scheme, it was demonstrated that there was minimal efficiency drop when pumping within the aforementioned spectral range. Optical-to-optical efficiencies of around 60% were obtained across the spectrum used for pumping. The obtained laser outputs also showed good ASE suppression. From the high power experiments diodes, and have obtained an optical-to-optical efficiency of 67.1% and a slope efficiency of 69% when pumping at 911 *nm*. The laser output showed ASE absorption, with a suppression ratio

of 45 dB . The results obtained from the high power experiment show an agreement with our results when the tunable pump sources are implemented. This further shows the scalability when employing the broad spectrum around 915 nm as pump sources for 1018 nm YDFLs.



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