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# Fiber Lasers and Their Medical Applications

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## Abstract

Advancing of photonics, aided with fruitful and abundant experimental and theoretical studies, over the last four decades has brought about the invention of a large variety of lasers. Among them one of the most popular types is a fiber laser, which is a variation of the standard solid-state laser, with the medium being a clad fiber waveguide structure and different dopants inside core serve as a gain media. They were derived from erbium-doped fiber amplifiers, which are still important component for telecommunications. Since discovery, fiber laser has become a natural choice for many uses, primarily because of the physical characteristics of fiber waveguide structure. Their rapid progress may show how excellent they really are. Although fiber lasers are today widely used in various research and industrial areas, one of the most meaningful applications of fiber laser technology has been through its use in medicine. A wide variety of wavelengths generated by fiber lasers as well as the diversity of physical mechanisms employed in pulse generation also additionally underpins the flexibility of fiber laser technology. This study is devoted to background technology of fiber lasers in the light of medical applications. Basic physics and theories of optical fibers and their important properties are introduced.

**Keywords:** fiber lasers, resonators, pumping, temporal regimes, non-ablative fiber lasers, ablative fiber lasers, host, active media

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## 1. Introduction

From the historical point of view, it can be said that the first working optical fiber laser was developed by Snitzer and his colleagues in the early 1960s [1], as a combination of earlier work on solid-state laser with his novel work on optical fibers [2]. Although this brilliant idea of combining these two then-young technologies was many years ahead of its time, the proving of its substantiality still took a long time. However, it became almost forgotten in

the next several years until 1985, when it was rekindled at Stanford University by Payne and co-workers, who worked on Erbium-doped amplifiers [3].

In the early years, relatively low output powers as well as low brightness of the fiber sources delimited areas of usage, preventing their use in a number of important applications requiring high average or peak powers. Likewise, not only the small diameter but also the small acceptance angle of the fiber core limited these devices and consequently made them convenient just for laboratory work. These limitations were overtaken thanks to the breakthrough technology of the double-cladding concept in 1988 [4]. Despite beginning difficulties, this new laser technology has been adopted swiftly by the relatively conservative laser community, primarily due to promising performance level as well as flexible configuration.

The fiber laser field continued to grow in 1990s, aided with fruitful and abundant experimental and theoretical results, gave rise to a large variety of fiber lasers, not only emitting at different wavelengths and with different pulse duration and energies, but also exploiting different physical mechanisms of pulse generation. The revolution was accelerated after the fabrication of optical fibers doped with rare-earth elements such as Ytterbium, Erbium, Holmium, and Thulium that are used to make amplifiers and lasers [1]. However, major advances in laser performance came to light after discovery of new mode-locking regimes, envisaged mainly for improving its limitations with respect to pulse energy and duration, which led to production of pulses of light with extremely short duration, on the order of picoseconds or femtoseconds [5]. Their biggest drawback was the limitation to peak power by nonlinear effects, which were enforced by the large product of intensity and interaction length inside the fiber core. Although most efforts were focused on weakening these effects, being constrained with an important drawback such as significant reduction of the pulse quality, soon it was become aware of the fact that they can overcome using large-mode-area fiber designs (LMA's) instead of conventional small mode-field diameter fibers. Since LMA's have reduced numerical aperture to maintain single-mode guidance, which is more appropriate for robust power operation, the invention of LMA's was followed by adoption of the technique related to pump-coupling [4]. However, introducing several mode-locking mechanisms such as self-similariton, dispersive soliton, and soliton-similariton regimes, demonstrated in recent years, and idea of managing nonlinearities are likely to surpass many of previously noted limitations in a better way [6].

Considering the ongoing evolution of average output power, which is a key performance parameter determining the applicability on any laser, over the past 25 years it can be said that the ultrafast fiber lasers have been reached from a few mW by 1996 and to almost 1 kW by 2009 [7]. It is to be notified that, being pushed roughly by demand for increasingly shorter pulses, the development in ultrafast fiber laser technology has brought about a variety of temporal output properties that can be encouraged especially in terms of pulse duration and pulse repetition frequency [8]. Otherwise, for continuous-wave fiber lasers, the average output powers would have been reached from just 4 W in the early 1990s to till multi-kilowatt and even more than megawatt today [2].

The revolution established on the desire for inventing a way or ways to guide light has had consequences that no one expected. An increase in the output average power, diversity of mode-locking regimes and active medium as well as highly adaptable design of the fiber lasers have

unlocked their potential usage. Certainly, the major contributor of this intensive progress was the continually growing telecommunication market [9]. However, various intrinsic advantages of fiber lasers, such as excellent beam quality, high efficiency, simplicity of optical cavity construction, micro joule-level energies at high repetition rates that boost processing speed, and above all relatively low cost, have recently brought about set up of a new branch of industry. Nowadays, they are fundamental building blocks of many contemporarily photonic systems, used for scientific researches as well as in a wide range of industrial and medical applications [10].

Especially from the medical point of view, fiber lasers are deployed in almost all spheres of this field, from diagnosis, noninvasive therapeutic procedures and surgery to micro-cutting applications for the medical device industry. Specifically,  $\sim 2\ \mu\text{m}$  pulses have superiority in arthroscopy, urology, and spinal surgery, while  $\sim 3\ \mu\text{m}$  pulses are prospering in brain tissue treatment, bone and cutaneous surgery, and ophthalmology [11]. Likewise, fiber lasers seem to be quite convenient light sources for spectroscopic methods, such as Infrared, Raman, and Photothermal spectroscopies, which are excellent methods for both chemical and biological analyses. In particular, spectroscopy combined with microscopy has become a powerful diagnostic tool in the biomedical applications.

Before specifying the particular applications of fiber lasers in medicine, it is instructive to briefly discuss general concepts common to all-fiber lasers especially, such as the nature of light fundamentals of lasing process, and spectroscopic properties of the prominent rare-earth dopant elements, related ions, and amplification theory for two-, three-, and four-level ions and host media.

## 2. Basic concepts of fiber lasers

### 2.1. Structure and double-clad concept

In the context of laser physics, the active laser medium, also known as gain medium or lasing medium, is a medium in which the power of light can amplified in order to compensate for the resonator losses. The active laser medium is the source of optical gain within a laser the physical origin of which is stimulated emission process and refers to the amount of amplification.

According to classification of lasers with respect to gain media, a fiber laser is a special type of solid-state laser which uses a doped fiber as an active gain medium [12, 13]. An optical fiber is transformed into active by doping its core with one of the rare-earth materials or their mixture, bound up with doped fiber amplifiers, providing light amplification without lasing [11]. That is to say, a fiber-amplifier, which is commonly used to restore optical signals and overcome their transmission losses, can be transformed into a fiber laser by placing it inside the cavity designed to obtain feedback [13, 14].

From a layout standpoint, a fiber laser is a light-guiding strand of silica or a fluoride glass that is only a few times as thin as the thickness of a hair [14]. Its tiny core, just of sub-millimeter diameter, is doped with trivalent rare-earth elements ions [15]. **Figure 1** shows a rudimentary form of the fiber laser. Launching of the pump light into the core of the doped fiber is ensured

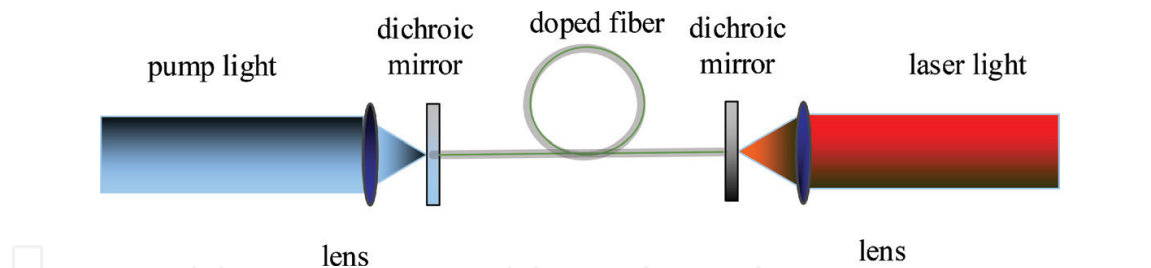


Figure 1. A schematic setup of a basic fiber laser.

via a dichotic mirror placed the left-hand side. Optical pump power is absorbed by dopant ions through the process of stimulated emission at the signal wavelength. Finally, the generated light is extracted on the right-hand side [13, 15].

A huge advancement in fiber lasers technology can be attributed doubtlessly to certain depictive characteristics, coming out by virtue of their waveguide geometry. These are mainly related on double-clad geometry refers to high power fiber lasers. As it is shown in **Figure 2a**, a double-clad fiber is a fiber with a relatively small diameter actively doped core, possessing the highest refractive index, two undoped cladding layers of a large diameter, and polymer coating for protecting from environmental influences [16, 17]. Typically, the single-mode core is surrounded by a second waveguide, called inner cladding. It is highly multimode, refractive index of which is higher than the outer cladding, as shown in **Figure 2b**. This difference between refractive indexes, based on total internal reflection principle, allows the inner cladding to guide light in the same way the core does, provided that wavelength ranges are different. In other words, the inner cladding acts as a waveguide of the pump light concurrently confines the signal light propagating through the core [18].

As the core is located within the inner cladding, it is also a part of the pump waveguide. Thus, it can be deduced that the pump light can also interact with the ions in the core so as to produce optical gain for signal propagation. Besides the various advantages of this configuration, converting a low brightness light source into the high brightness, high power one is, definitely, one

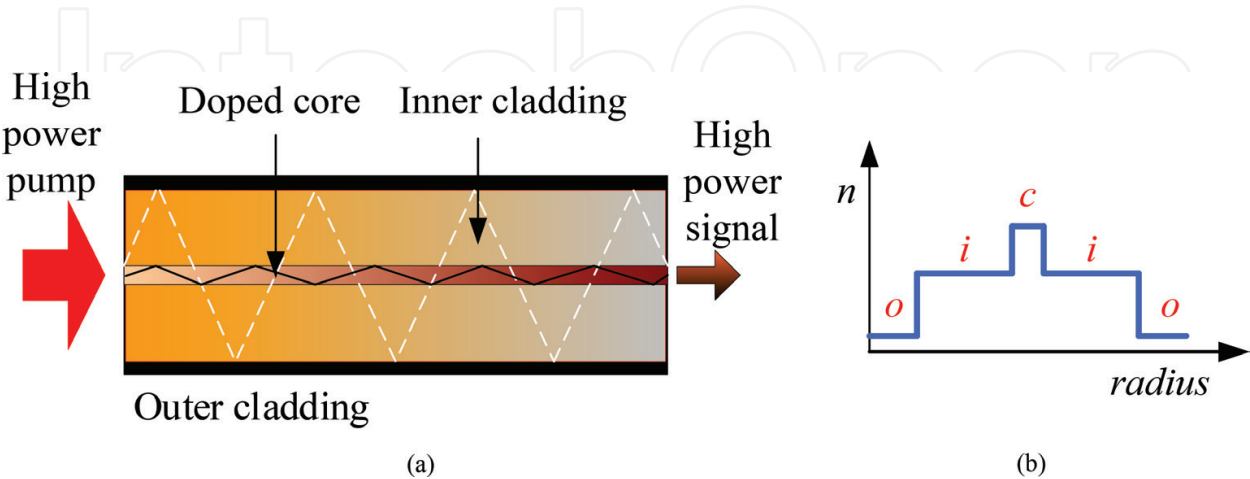


Figure 2. (a) The double-clad fiber concept of high power fiber lasers. (b) Refractive index profile. c: core, i: inner cladding, o: outer cladding.

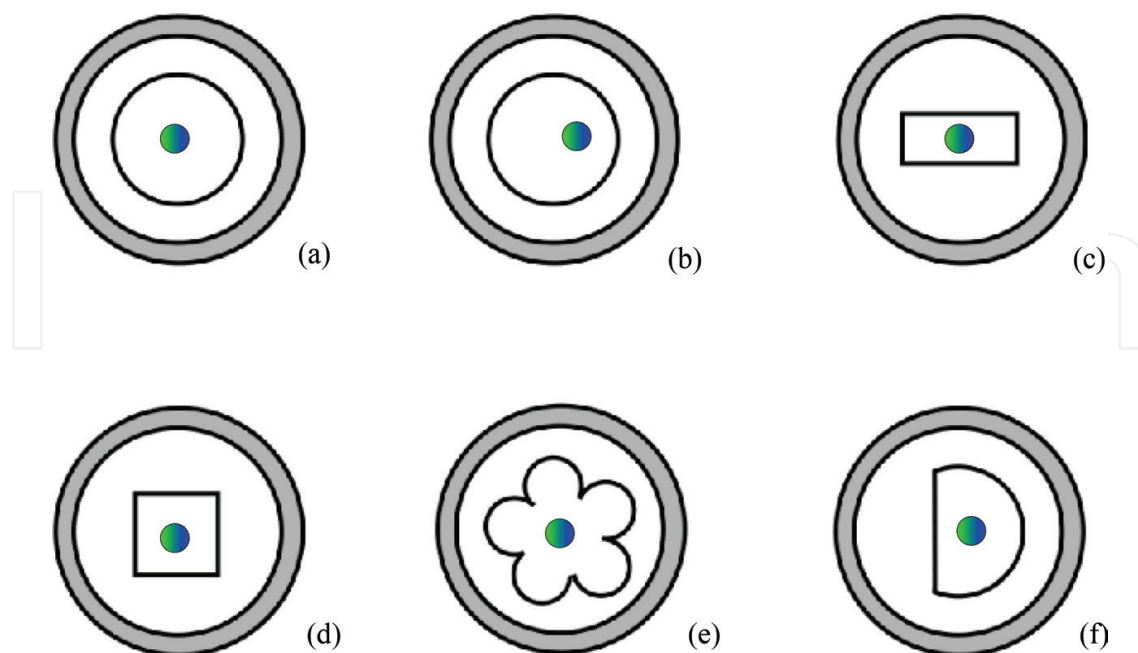


of those to be mentioned separately [16]. In spite of pumping with low beam quality sources such as diode bars or stacks, the output beam guided through the core has the diffraction-limited beam quality. It is to be noted that this very efficient brightness improvement technique together with continuing advancement of pumping technologies has been the primary driving force not only for the increase of fiber laser powers but also for the decrease of the cost per watt [19].

It is to be pointed out that a larger core not only improves the pump absorption but also provides better energy storage that is of especially important for high energy Q switched pulses. However, robust single-mode operation requires the core of a diameter in the range of 2–10  $\mu\text{m}$  [17].

The inner cladding diameter may vary in the range of 200–400  $\mu\text{m}$ . Its circular shape often leads to weak overlap between the core and pump modes due to the fact that the overlap is also different for different modes, resulting in such weak pump absorption that only 10–30% of the power is delivered into the core [20]. Some of these modes have such little overlap that exhibit only very weak pump absorption resulting in substantial pump power may be left no matter whether some of the pump cladding modes are absorbed better than the average [21]. The absorption efficiency can be significantly improved by breaking the cylindrical symmetry when the rays are forced to follow more irregular or even chaotic paths [21]. Noncircular shapes, especially D and rectangular ones are proposed to thwart the propagation of such unwanted intensity distributions. **Figure 3** shows various designs of inner claddings.

Similarly to all solid-state lasers, there are three principal elements inducing the gain in a fiber laser. They are: the dopant ions with their distinctive free-ion electronic configurations and charge states; the host material in terms of its optical, macroscopic, thermal, mechanical, and



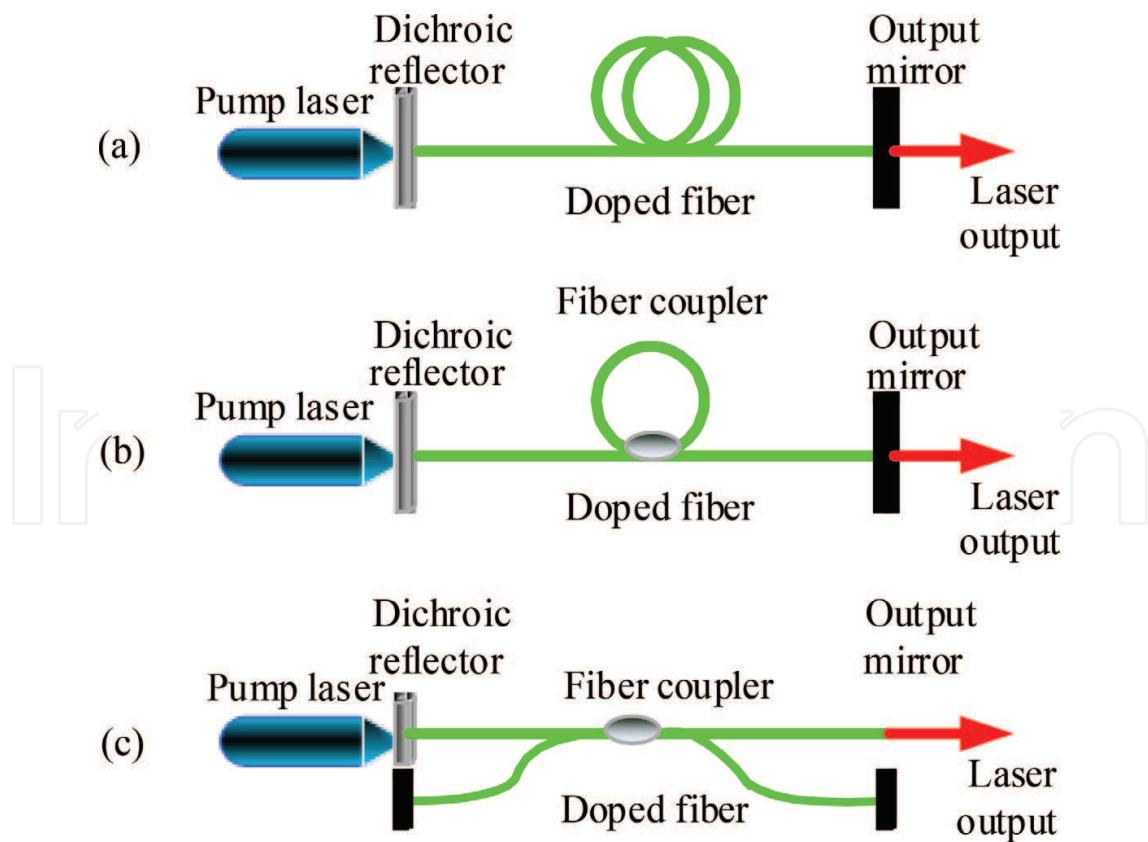
**Figure 3.** Common cladding-pumped structures: (a) centered core, (b) off-centered core, (c) rectangular inner cladding, (d) square inner cladding, (e) flower inner cladding, and (f) D-shape inner cladding [12].

lattice properties; and the optical pump source taking its temporal characteristic into account, spectral irradiance, and particular geometry. These elements are interrelated and have to be chosen self-consistently [22].

2.2. Fiber resonators and pumping process

An optical resonator, an optical counterpart of an electronic resonant circuit, a major component of the laser that surrounds the gain medium, is an arrangement of optical components that allows the laser light to circulate in a closed path forming standing waves for certain resonance frequencies and incorporating feedback for the light. The frequency selectivity is an important property of the optical resonators since it makes them useful as optical filters, spectrum analyzers, or, the most important, confining/storing of light at specific resonant frequencies.

The physics of optical resonators used for fiber lasers is almost similar to the traditional laser resonators with some differences related to the tolerance for optical damages and fiber coupling of the intracavity components and length of the laser medium. Although optical resonators can be made in very different forms to meet many different criteria, this section briefly reviews three fundamental types that have been exploited in fiber laser technology, taking to account some important advantages and disadvantages. These are: linear laser resonator, all-fiber ring resonator, and Fox–Smith resonator, illustrated in **Figure 4**.



**Figure 4.** Resonator types: (a) Fabry-Perot with dielectric reflectors; (b) all-fiber resonator; and (c) Fox-Smith resonator.

Pumping is a process that is utilized in lasers and amplifiers with doped gain media, an example of which are fiber lasers for energy transfer from the external source into the active medium. The energy which is can be provided in the form of light, electric current, or as result of chemical or nuclear reactions, is absorbed by the medium directs its atoms to get through excited states and when the majority of the atoms are in excited states population inversion is achieved and the medium acts as a laser or an optical amplifier. It is to be noted that common of all implemented pump power must be higher than the threshold power essential for lasing process of the media.

Fiber lasers utilize optical pumping, generally used for lasers possessing transparent active medium. The most widely used optical pump sources for CW fiber lasers are arc lamps, lasers diodes, or more often some other fiber laser. Depending on required power, the laser diode sources used in pumping process can be fabricated as single-emitter diodes, broad area laser diodes, diode bars, diode laser stack of bars, or fiber-coupled diode laser [22, 23]. To achieve high pumping efficiency and avoid high thermal load, characteristic for high power fiber lasers, the laser diode sources have the spectrum that is as narrow as to be mostly within the absorption region of the gain medium. Furthermore, for the same reason, the wavelength is also kept near the absorption peak of the gain medium over the operation temperature and condition [24]. Several different types of diode lasers are illustrated in **Figure 12**. Single-emitter diodes are very compact battery-powered systems, whose output power does not exceed 1 watt. Broad area laser diodes, which can be treated as very efficient laser light sources due to their electro-optical efficiency, exceed 70%, typically generate several watts and are suitable for pumping solid-state lasers. Diode bars are formed with multiple emitters side by side in a single substrate that can provide tens of watts [25]. Laser stack of bars are often used for the highest powers and emit multiple kilowatts. In contrast to the previous types of laser diode, fiber-coupled diode lasers can be treated as a different kind of pump optics, which provide separation of the actual laser head from another package containing the pump diodes, so that the laser head can become very compact [26].

Fiber lasers are optically pumped not only with diode sources but also with other fiber lasers and this pumping method is known as tandem pumping [27]. In tandem pumping method, the output of several double-clad fiber lasers is combined into a single high brightness beam to pump the main amplifier fiber. This strategy provides pumping closer to the emission wavelength, which reduces the quantum defect heating what in turn reduces thermal load. In addition, the high brightness of this pump source can also allow the length of the main amplifier fiber to be reduced, therefore helping to mitigate one of the main limitations of fiber lasers systems nonlinear effects [10]. Although tandem pumping allows for the highest output powers, the vast majority of fiber lasers are pumped directly by laser diodes as they are simpler, cheaper, and also have higher wall plug efficiency [23].

However, the output beam quality and the brightness of the source decrease with increasing power, which can sometimes result in very strong asymmetric and fairly poor beam quality followed by brightness that is much lower than some lower power diodes that requires the use of beam shapers. Although they are utilized to symmetrize the beam quality, they make it easier either to pump a bulk laser or to couple the light into the fiber [17].

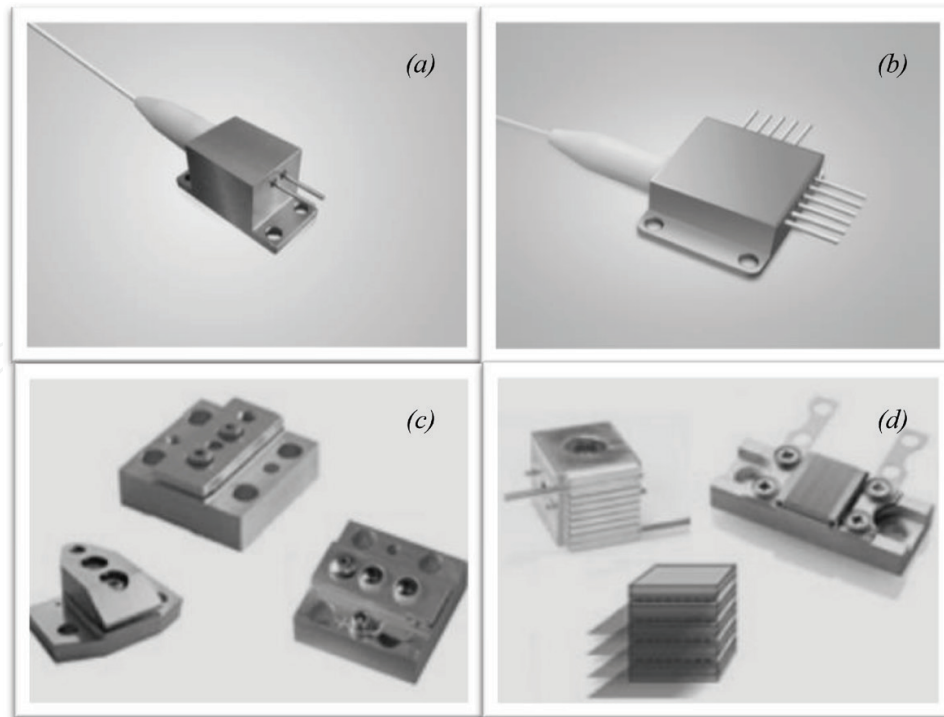


Double-clad fiber lasers are conventionally categorized as being either end-pumped or side pumped and both of techniques are illustrated in **Figure 5** [28, 29]. In end-pumping, the light from one or many pump sources is coupled via an optical coupling system through a front surface. Additionally, end-pumping can be provided by pumping through either backward surface or both end sides of the fiber laser. On the other hand, in side-pumping the pump source is connected through a side surface.

### 2.3. Temporal regimes of fiber lasers

On the basis of temporal regimes, radiation of fiber lasers may be provided in continuous-wave (CW) or ultrashort optical pulse form depending of temporal regime used [30]. There are three main temporal regimes to provide laser action: continuous-wave and free-running, mode-locking, and Q-switching.

Even though laser light is perhaps the purest form of light, it is not of a single, pure wavelength, but of some natural bandwidth or range of frequencies, which is determined by the gain of laser medium as well as optical cavity or resonant cavity of the laser. Bounced between the mirrors of the cavity, the light constructively and destructively interferes with itself, which leads to the formation of standing waves of discrete set of frequencies between the mirrors. These discrete set of frequencies, known as the longitudinal modes, are self-regenerating and allowed to oscillate by the resonant cavity. Each of these modes oscillates independently, with no fixed relationship between each other. Consequently, the laser acts as a set of independent



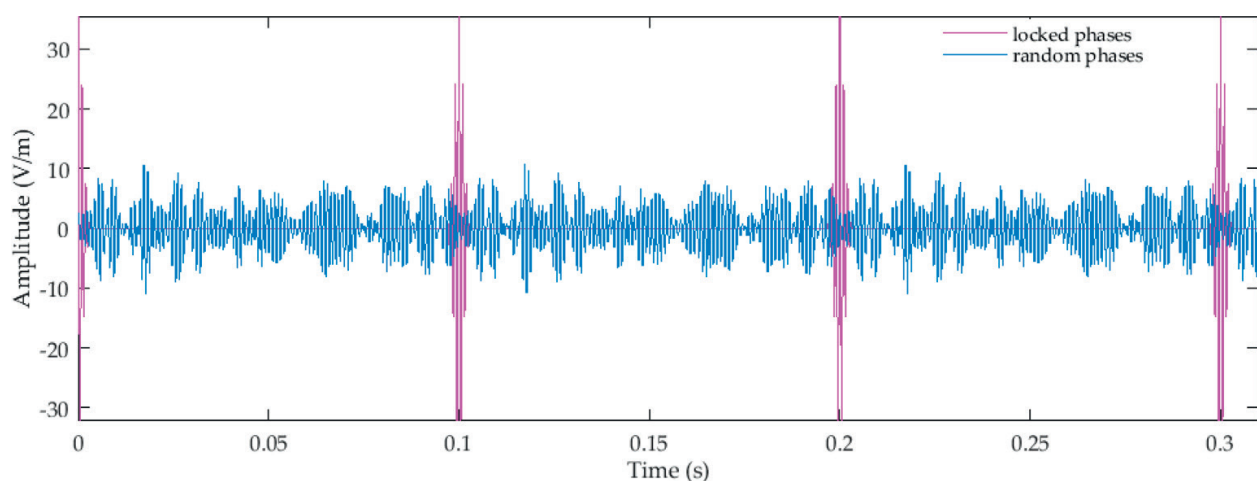
**Figure 5.** Different types of diode lasers: (a) Fiber-coupled diode laser; (b) 808 nm 4 W single-emitter diode laser; (c) power diode bars; (d) high power vertical diode laser Stac.

lasers, all emitting light at slightly different frequencies. An increase in the number of modes causes near-constant output intensity because interference effects tend to average, and, then, the laser is said to operate as continuous wave [31].

Instead of oscillating independently, each mode can operate with a fixed interconnected phase. In other words, the phase relations among a large number of neighboring longitudinal modes of the laser cavity are locked. As a result, the modes of the laser will mutually interfere, producing a periodic variation in the laser output in form of intense burst or pulse of light of extremely short duration ( $10^{-12}$ – $10^{-15}$  s), having a significantly larger peak power than the average power of the laser. Such a laser is said to be mode-locked or phase-locked [8]. These pulses occur separated in time by  $\Delta t = 2L/c$ , where  $\Delta t$  is the time taken for the light to make exactly one round trip of the laser cavity and  $L$  is the cavity length (**Figure 6**).

Refers to the way of gain modulation, mode-locking methods can be classified as active and passive. Active methods typically involve using an external signal to induce a modulation of the intracavity light, but, rely on placing some element into the laser cavity which causes self-modulation of the light. Passive methods, on the other hand, do not need any external signal to produce pulses. Rather, they use the light in the cavity to cause a change in some intracavity element, which will then itself produce a change in the intracavity light [8]. A saturable absorber is an optical device that exhibits an intensity-dependent transmission. What this means is that the device behaves differently depending on the intensity of the light passing through it. For passive mode-locking, ideally a saturable absorber will selectively absorb low intensity light, and transmit light which is of sufficiently high intensity.

There are also passive mode-locking schemes that do not rely on materials that directly display an intensity-dependent absorption. In these methods, nonlinear optical effects in intracavity components are used to provide a method of selectively amplifying high intensity light in the cavity, and attenuation of low intensity light. One of the most successful schemes is called Kerr-lens mode-locking (KLM), also sometimes called “self mode-locking” [22]. This uses a nonlinear optical process, the optical Kerr effect, which results in high intensity light



**Figure 6.** Mode-locking technique. Temporal evolution in a laser with random and locked phases.

being focused differently than low intensity light. By careful arrangement of an aperture in the laser cavity, this effect can be exploited to produce the equivalent of an ultrafast response time saturable absorber.

Q-switching is widely used technique in generating of energetic pulses in the picosecond to nanosecond regime [10]. These short pulses are achieved by rapidly increasing and decreasing of the laser resonator Q factor. In a low Q state, the cavity loss, controlled by intracavity loss modulators, is such a high that lasing cannot be inhibited. Consequently, pump power builds up the inversion population, pumped several times above the threshold inversion up to its peak value, when the laser cavity Q factor switches to its high value. Because of removed intracavity loss, manifesting itself by the large gain, a high energy pulse is quickly produced and in the meantime the population is drained by the pulse [32].

The resonator losses can be switched in different ways: actively, by an active control element driven by an external electrical generator, typically either an electro-optic or an acousto-optic modulator [33], or passively [34] by some kind of saturable absorber, such as semiconductor saturable absorber mirrors (SESAM), graphene [35], quantum dots [36], carbon nanotubes (CNT) [37], and topological insulator [38].

Q switched fiber lasers are widely applied in microsurgery of soft biological tissues [34], biomedical diagnostics [35], surgery [36], and chemical bond spectroscopy [39]. Short and ultrashort pulses possess specific advantages over continuous-wave (cw) operation, enabling cleaner ablation of materials in medical surgeries.

It should also be pointed out that creating of ever-shorter optical pulses has been a topic of extensive research since the advent of pulsed laser sources. However, motivated primarily by scientific curiosity, ultrashort pulses have been put forward because of some important benefits for technical and industrial applications. For now, passive mode locking is one of the key methods of ultrashort pulse generation. Today's ultrafast light sources devices produce pulses of peak output powers on the order of a megawatt, directly from a simple laser. For many experiments, however, a peak power of a megawatt is not sufficient, making it necessary to increase the energy of these pulses. On the other hand, achieving short duration and high energy of the pulses, at the same time, is undoubtedly more striving than improving one of these parameters independently because both of those are associated with high field intensity that often makes physical system nonlinear [8]. One of the challenging ways to obtain the higher energy levels of these pulses is Q switched mode-locked (QML) method. QML is the combined Q-switching and mode locking in one cavity and it has also been successfully employed for generation of high energy pulses.

### 3. Classification of fiber lasers for medical purposes

As it was pointed out before, medicine is an eminent consumer of fiber laser technology from surgery and therapy to diagnostics and imaging. Driven by the huge demand, based primarily on the recognition of the need for better healthcare, fiber laser technology has shown

tremendous growth in advancement and innovations in recent years. Nowadays, fiber lasers are widely recognized as unique light sources for many medical applications due to advanced features such as high beam quality, superior performance, and extreme power efficiency concurrently with low cost of ownership.

Broad-scale research has led to a wide diversification of fiber lasers in their operating modes, wavelengths, and energy levels. Consequently, in medical science, fiber lasers are no longer in their initial stages of development. They should be rather considered as promising tools for modernization in medicine, because every invention in this field may be a valuable step toward achieving less invasive or less painful medical technologies.

Medical fiber lasers can be classified according to several criteria, such as, output characteristics, safety, the reaction of the organic tissue, host media, gain media, emission wavelength, etc. The first classification refers to temporary regimes, which have been adequately explained in the previous section, while the second one categorizes fiber lasers according to potential risk of adverse health effects and it can be quite helpful in selection of appropriate control measures to minimize the risks [40]. However, it is to be pointed out that, in practice, the risk also depends upon the conditions of use, exposure time, and the environment.

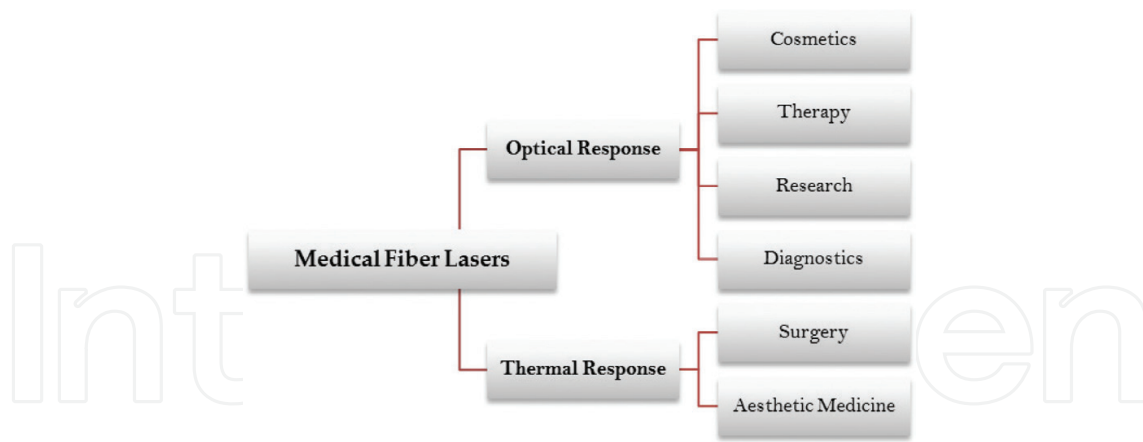
3.1. Ablative versus non-ablative fiber lasers

The interaction of the laser beam with leaving tissue is manifested through several important effects, which are summarized in **Table 1**.

In this context, fiber lasers can be categorized in the basis of those effects. In spite of a far greater number of groups, for practical reasons, two groups, referring to the optical and the thermal responses, are widely accepted by medical authorities. According to the categorization is shown in **Diagram 1**, the first group of fiber lasers employs optical processes such as selective resonant absorption, fluorescence, reflection, elastic scattering, inelastic scattering, and transmission. In subsequent studies, the fiber lasers are designated with a term non-ablative. The thermal effect of laser irradiation is so small that could not damage or destroy the irradiated tissue. Such fiber

| Temperature                   | 37–60°C                          | 60–65°C  | 90–100°C             | 37–60°C                        | ~100°C       | Beyond 100°C             |                   |
|-------------------------------|----------------------------------|--|----------------------|--------------------------------|--------------|--------------------------|-------------------|
| Chemical and physical effects | Heat/ increased diffusion        | Denaturisation Coagulation                     | Phase change         | Carbonization                  |              | Vaporization Verbrennung | Shockwave plasma  |
| Optical effects               | Scattering refraction reversible | whitening Scattering Destruction of structures | Scattering Shrinking | Darkening Increased Absorption |              | Gases vapor              | Vapor debris      |
| Biological results            | Stimulation                      | Damage   | Shrinking            |                                | Heavy damage |                          | Mechanical Damage |

**Table 1.** Effects of the interaction of the laser beam with leaving tissue.



**Diagram 1.** A classification of fiber lasers depending upon the reaction of the tissue.

lasers are widely used in therapy [41–43], diagnostics [44–46], cosmetics [40, 42], and research [47, 48]. The second group refers to the thermal response and members of this group are often called ablative fiber lasers. According to applications, the group is sub-divided into two classes: the first one is used in various types of surgery [49–51], while the second one is used in esthetic medicine such as skin rejuvenation or resurfacing [52, 53].

Before classifying fiber lasers, according to active medium, the chapter will be continued with discussion of most prominent host media, which has an important role in medical applications. In this context, it could be very helpful to explain what the host media is as well as what the criteria for selecting appropriate host media are.

**3.2. Host media**

As the chapter will be continued with discussion of most prominent rare-earth elements and prominent host media, which are of crucial role in medical applications, it could be very helpful to explain what the host media is as well as what the criteria for selecting appropriate host media are.

As it is said before, the population inversion that is essential for the stimulated emission of photons cannot be produced without presence of the dopant atoms placed in some of host media. The host media can be defined as a laser gain media doped with rare-earth ions. In the host medium, the rare-earth ions replace host ions which have a similar size and the same valence. The pump and laser transitions of all rare-earth-doped gain media have fairly small oscillator strength and are known as weakly allowed transitions. So, the host media removes the limits regarding the stabilization or the coherence of the pumping source what means that the pumping source does not need to be of a single frequency [25]. Their upper state lifetime, which provides the storage of the substantial amounts of energy in some media, is consequently long. This distinguishing property makes rare-earth-doped media convenient for mode-locking and Q-switching.

The strong demand in optical communication has triggered the successful development of the host materials and increased their diversity. Nowadays, the most challenging host media



are crystals or glasses, and there is ongoing development in testing and fabrications of new ones. Although silicate glasses remain the most prosper media, the majority of silicate glasses seem to be unsuitable for lasing at long wavelengths. Tellurite, Chalcogenide, and Fluoride (especially ZBLAN) glass are largely employed in the field of optical sources could in the mid-infrared region [9].

### 3.3. Active media

An understanding of a laser and optical amplification process is closely related to understanding of the nature of light and the interaction between electromagnetic radiation and matter, which is the basis for studies of more complex quantum mechanical systems, including those of fiber lasers [54]. The operation of laser process is based on amplification of light stems from absorption, spontaneous, and stimulated emission of radiation as the fundamental mechanisms common for all laser actions. During the lasing process, stimulated photons promote further stimulated photons in a cascade, resulting in sustained gain, if several conditions are met. The first condition is achieved at population inversion, which is an important term closely related to the operation of laser. Under thermal equilibrium conditions, emission process which competes with stimulated absorption so weak that it cannot provide amplification of a beam of light is stimulated. Amplification is carried out when the rate of the stimulated emission is so increased that the number of atoms in the upper level is larger than that of atoms in the ground level. The requirement for population inversion imposes other two conditions: adequate pumping process by an external energy source, which has higher energy than the upper energy level, and minimum two participating energy levels where the process can take place. Although the two-level system appears as the most simple and straight-forward method to establish the population inversion, it is not useful as it does not lead to laser action [31]. Consequently, the other pumping schemes become more important and widely employed. According to the arrangement of those energy levels within dopant ions, lasing schemes are typically classified as a two, three, quasi-three, and four-level schemes [55].

Fiber lasers can amplify incident light via stimulated emission, provided by the optically pumping in order to obtain population inversion that caters for the optical gain. The population inversion, essential for the stimulated emission of photons, can be brought forth by electrons of the dopant atoms, obtained from one or more luminescent rare-earth metals [12]. Attractiveness of those elements lies in their distinguishable optical characteristics refers to emitting and absorbing processes over narrow wavelength ranges, which are relatively insensitive to host material, longer lifetime of metastable states, and higher quantum efficiencies. Although the rare-earth group consists of 2 groups of 14 elements each, the rare-earth ions referred to as lanthanides that fill the 4f shell and occupy the atomic number 58–71 of the periodic table. The most common rare-earth elements with some of its basic atomic properties, common host media, and important operating wavelengths are explained in short below.

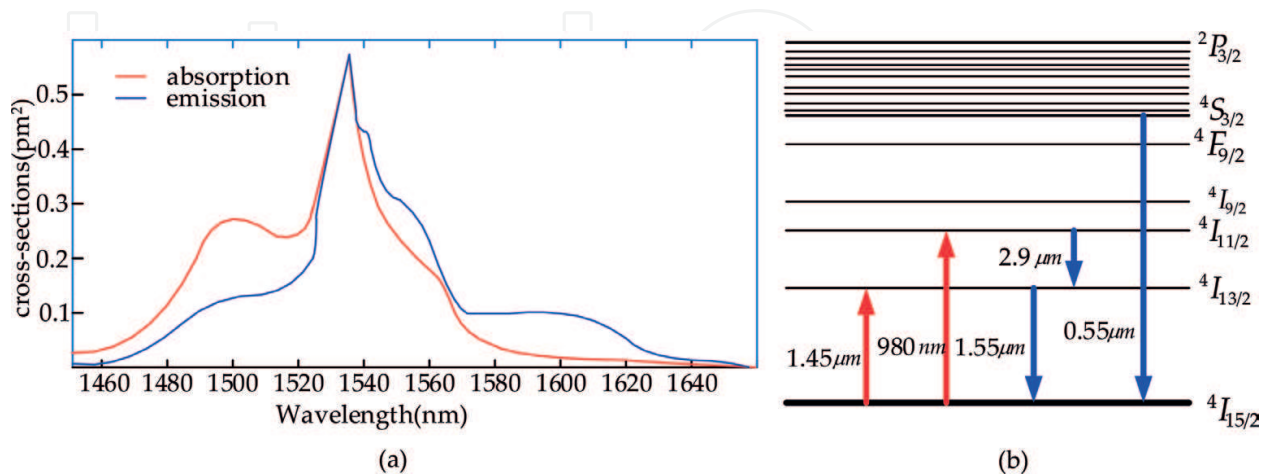
#### 3.3.1. Erbium-doped fiber lasers

Erbium, mainly involved by  $\text{Er}^{3+}$  ions, has optical fluorescent properties that are particularly convenient for some laser applications. Er-doped fiber laser application technology has seen

substantial progress since its invention in the late 1980s. Refers to hosting media, it can be said that different glass hosts are preferable for different purposes. Silica glass is the most widely used host material in telecom, while Tellurite and ZBLAN glasses, are preferable in mid-IR region, where  $\text{Er}^{3+}$ -doped fiber lasers utilized in the field of optical sources, applied in various areas among of which is an optical coherence tomography [9]. Similarly, absorption region between 2.5 and 4  $\mu\text{m}$ , where Er-doped fiber lasers have sparked a huge interest, due to evident opportunities for sensing and the highly precise modification of biomedical and industrial material [56, 57]. There are some evidences that Er-doped fiber lasers at used in medical endoscopy [58] and surgery [58, 59]. Phosphate glasses also regarded as better ones due to their higher phonon energy and better solubility of  $\text{Er}^{3+}$  ions [60].

Emission and absorption cross sections for erbium in phosphate glass host media [15] are illustrated in **Figure 7a**, while an energy level diagram of some common optical transitions of  $\text{Er}^{3+}$  is shown in **Figure 7b** [12, 13]. In the optical amplification media, made from erbium-doped crystals or glasses, electrons of  $\text{Er}^{3+}$  ions are optically pumped at the vicinity of 980 or 1480 nm and excites into the  $^4\text{I}_{11/2}$  or  $^4\text{I}_{13/2}$  states, respectively. Then, light can be amplified in ranges from 1530 to 1560 nm, via stimulated emission, where the ions show strong three-level state behavior and the maximum gain is reached [61].

It is to be noted that it is difficult to realize an efficient pump absorption on the  $^4\text{I}_{15/2} \rightarrow ^4\text{I}_{11/2}$  transition due to relatively small absorption cross sections and limited doping concentration that is confined by quenching processes. This problem is commonly solved by co-doping with  $\text{Yb}^{3+}$  sensitizer ions. In those co-doped systems, pumping is absorbed via  $\text{Yb}^{3+}$  ions that provide subsequent energy transfer to  $\text{Er}^{3+}$  ions that support stimulated emission in 1520–1650 nm spectral range [11, 23]. It is to be pointed out that 1550 nm wavelength, which is of especially importance for optical communications as loss of the standard single mode for optical fibers is minimal at this particular wavelength [27], is also used for the removal of café-au-lait macules (CALMs) for darker skin phototypes [62] as well as fractional resurfacing [63]. Moreover, 2000–3000 nm range seems very encouraging for microsurgery applications such as glaucoma surgery, vitreoretinal surgery, and myringotomies [64]. Microjoule femtosecond fiber laser at



**Figure 7.** (a) Emission and absorption cross section for erbium in phosphate glass host media [61]. (b) Energy level structure of  $\text{Er}^{3+}$  ions and some of the common optical transitions.

1600 nm are used in corneal surgery [65]. Er-doped fiber lasers at 1565 nm wavelength can be used for cosmetic treatments. Particularly, they are appropriate for effective treatment of facial wrinkles [66].

There are two important particular wavelengths for medical proposes at 2800 nm, which is useful for spectroscopy applications [67], and 2940 nm emission, where the erbium ions that is highly absorbed in water [68]. On the other hand, CW and pulsed Er,Pr-ZBLAN and a coupled Yb,Er-silica fiber lasers have been widely researched as a short-coherence-length light source for optical coherence tomography (OCT) between the range of 1000–3000 nm [64].

### 3.3.2. Thulium-doped fiber lasers

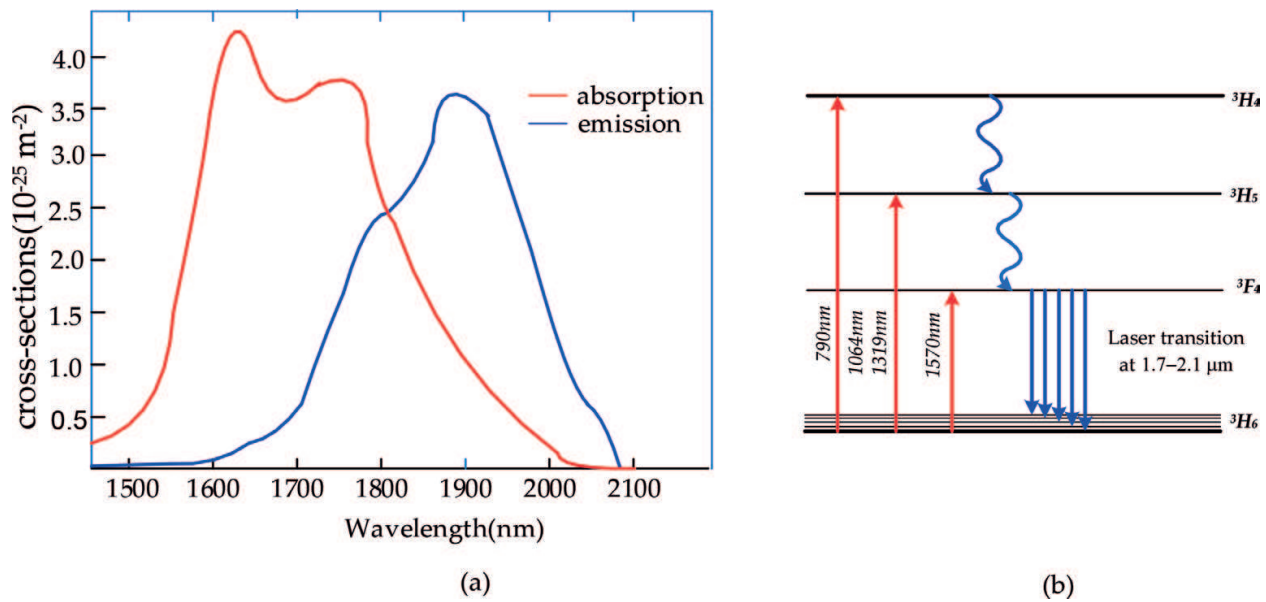
There are several important reasons why Tm-doped fibers lasers are more promising at present. One of them is the possibility of pumping the  $\text{Tm}^{3+}$  ions at around 790 nm or at 915–975 nm, where efficient high brightness diodes are readily available. Another advantage is the laser operation between 1470 and 1800 nm among wide gain spectrum ranging from 1400 to 2700 nm, which is so-called eye-safe spectral range of optical wavelengths as it can be highly absorbed by water in the eye before reaching the retina [69].

Tm-doped fiber lasers, operating beyond 2  $\mu\text{m}$  would benefit diverse applications. They are good candidates for spectroscopy in mid-IR region, often labeled the molecular fingerprint region, containing the spectral signature of many molecules. For this reason, this spectral region is important for many applications that require high quality laser cutting and welding, such as remote sensing and specific surgical procedures known generically as microsurgery [13, 70]. Although there are a lot of emission bands of  $\text{Nd}^{3+}$  and  $\text{Er}^{3+}$  in the same gain spectrum, much of the interest in  $\text{Tm}^{3+}$  stems from its emission that occurs in the gaps of these bends.

**Figure 8a** shows an energy level diagram of the most important optical transitions of  $\text{Tm}^{3+}$ , while its absorption spectra in fluoro-tellurite bulk glass is shown in **Figure 8b** [71]. It is to be noted that around 1900 nm  $^3\text{F}_4 \rightarrow ^3\text{H}_4$  transition is a quasi-three-level transition but as wavelength draws close 2100 nm transition is turned to a four-level one [23].

Tm has three important extremely broad absorption bands:  $^3\text{H}_6 \rightarrow ^3\text{F}_4$ ,  $^3\text{H}_6 \rightarrow ^3\text{H}_4$ , and  $^3\text{H}_6 \rightarrow ^3\text{F}_4$ . 790 nm pump sources, which are more widely used, pump  $\text{Tm}^{3+}$  ions from  $^3\text{H}_6$  to  $^3\text{H}_4$  state, 1064 and 1319 nm pump sources are used for  $^3\text{H}_5$  band pumping, while 1570 nm pump sources excite  $\text{Tm}^{3+}$  ions to  $^3\text{F}_4$  the main metastable level. Although the highest theoretical slope efficiency, with respect to absorbed power, is expected for 1570 nm sources due to the lower quantum defect, the reality is quite different. That is to say, 790 nm pump sources have much higher theoretical slope efficiency, of 82%, due to doubling through a cross-relaxation process. This phenomenon, known as “two-for-one” occurs as a result of one pumping photon excites two Tm ions [23].

All Tm-doped silica fibers, yet reported, have been utilizing  $^3\text{H}_4 \rightarrow ^3\text{F}_4$  at transitions at 1487 nm followed by  $^3\text{F}_4 \rightarrow ^3\text{H}_6$  at 1800 nm. The first transition is of special importance for resonant pumping of Er-doped lasers and amplifiers. Tm has enormous bandwidth with wavelength between 1700 and 2100 nm ranges that makes Tm good candidate for source for generation



**Figure 8.** (a) Measured absorption and emission cross-section spectra of the Tm<sup>3+</sup>-doped silicate fiber. (b) Energy level structure of Tm<sup>3+</sup> ions and some of the common optical transitions [71].

of femtosecond pulses [72]. Emission band around 1900 nm is not only appropriate for spectroscopic and chemical sensing applications but it is also very attractive in tissue welding and ablation [73], while 1940 nm is thought to be a good scalpel for precise soft tissue surgery [74].

The power output and efficiency of the fiber lasers steadily have risen since 1998. Moreover, this progress has been speeded up with the realization that the Tm doping level could be increased with the addition of Al co-doping of the core. Although the efficiency of Tm-doped lasers not yet compete with the efficiency of Yb-doped lasers, applications at mid-IR wavelengths as well as pulsed applications appear to be key advantages for further improvements.

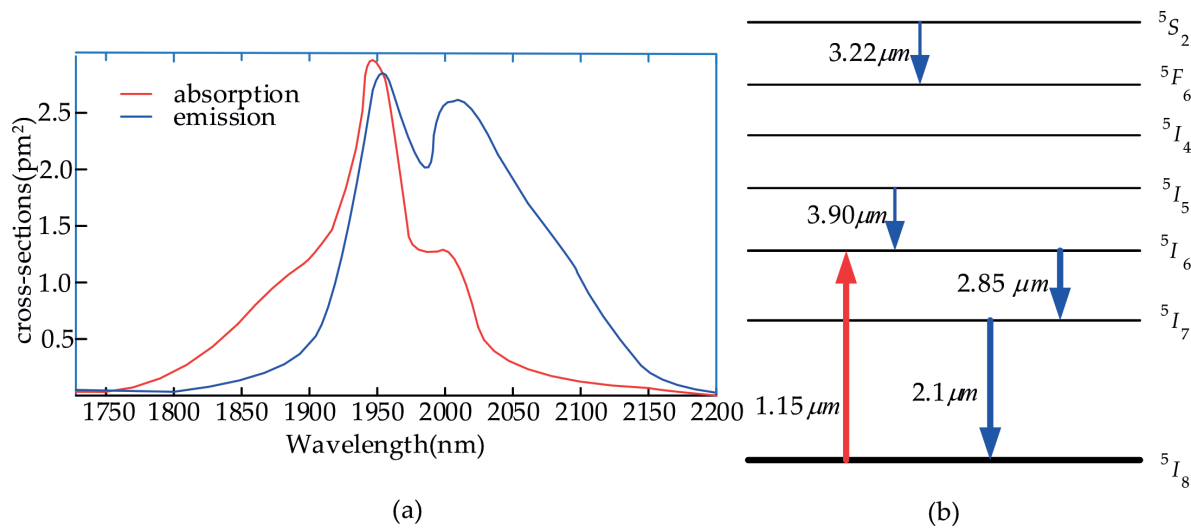
### 3.3.3. Holmium-doped fiber lasers

Holmium (Ho) and Ho-doped fiber lasers have attracted tremendous interests in scientific community due to potential operation with high power levels at wavelengths beyond 2.1 μm in addition to wide spectral tunability, which make them an ideal choice for a variety of medical lasers and promising tools for applications in spectroscopy [75].

The effective gain cross section as a function of inversion and relevant energy levels of Ho<sup>3+</sup>-doped silica are illustrated in **Figure 9a** and **b**, respectively [76]. The most commonly used pump bands are: 1.15 μm, and 2.046 μm, and 2.1 μm, which are absorbed  $^5I_8 \rightarrow ^5I_6$ ,  $^5I_8 \rightarrow ^5I_7$ , and  $^5I_8 \rightarrow ^5I_6$  transitions, respectively. Important emission transitions are labeled in **Figure 8a**. The two of them deserve special attention. These are:  $^5I_7 \rightarrow ^5I_8$  and  $^5I_6 \rightarrow ^5I_7$  transitions produce radiation in the range of 2050–2850 nm, respectively. At 2860 nm Ho<sup>3+</sup>-doped fiber lasers overlap more strongly than their counterparts. Hence, they are thought to be a more practical tool for interaction with biological tissues [77].

Comparing to  $^5I_7$  level, short lifetime of  $^5I_6$  level is considerable obstacle for population inversion. According to research, the stimulated emission from this transition state can be achieved in two ways: by simultaneously allowing the lower transition ( $^5I_7 \rightarrow ^5I_8$ ) at 2.1 μm to also





**Figure 9.** (a) Measured absorption and emission cross-section spectra of the  $\text{Ho}^{3+}$ -ions. (b) Energy level structure of  $\text{Ho}^{3+}$  ions and some of the common optical transitions [3].

emit light or by co-doping by another dopant (typically  $\text{Pr}^{3+}$ ) to hold the  $^5\text{I}_7$  level depopulated through energy transfer processes. The first one provides the possibility of dual wavelength pulsing in  $\sim 2 \mu\text{m}$  and  $\sim 3 \mu\text{m}$  emission bands [76].

Besides that, Ho-doped fiber lasers are appropriate for ureteroscopy and stone treatment because of quite efficient stone fragmenting regardless of the composition [78]. About  $2\text{-}\mu\text{m}$  CW Ho-doped fiber lasers are proposed for surgery because of using the contact method [79].

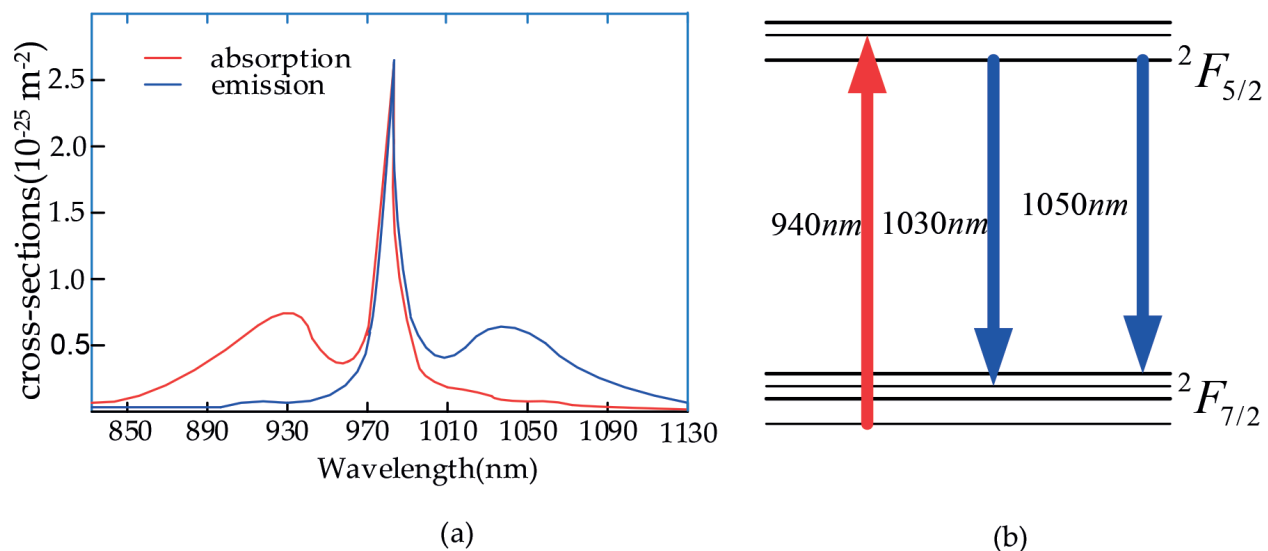
### 3.3.4. Ytterbium-doped fiber lasers

The absorption and emission cross sections and spectra of  $\text{Yb}^{3+}$  for silica host media are illustrated in **Figure 10a**, while pumping and amplification involve transitions between different sublevels of the manifolds are shown in **Figure 10b**. An abnormally high emission cross section, combined with diversity of the available pumping sources, resulting from broad absorption band and especially the narrow absorption peak at 975 nm, provides generation of many wavelengths of general interest. Exciting of the electrons to the higher energy achieved by interaction with near-infrared or visible photons [81]. Another advantage of  $\text{Yb}^{3+}$  ions is a remarkable simplicity of the electronic level structure, in comparison with other rare-earth ions.  $\text{Yb}^{3+}$  ions have two relevant manifolds: a ground-state,  $^2\text{F}_{7/2}$ , with four sublevels, and a metastable state,  $^2\text{F}_{5/2}$ , consists of three sublevel [82].

For short wavelengths around 990 nm,  $\text{Yb}^{3+}$  ions show three-level system behavior, whereas, at wavelengths between 1000 and 1200 nm, they behave as nearly pure quasi-four-level systems [15]. These combined features are of crucial importance for very short fiber lasers with high pump absorption. Some research show that, at 1070 nm, pulsed fiber laser could be very useful in oral surgery due to superiority related to thermal elevation in the irradiated tissues [83].

In regard to medical applications, although its usage in femtosecond laser micromachining, from waveguide fabrication to cell ablation, should not be underestimated, it is rather utilized as a sensitizer in co-doping of  $\text{Er}^{3+}$ -,  $\text{Tm}^{3+}$ -, or  $\text{Ho}^{3+}$ -doped fiber lasers to demonstrate near and





**Figure 10.** (a) Ground-state absorption and emission cross-sections and spectra of Yb³⁺ in silica. (b) some common optical transitions of Yb³⁺ ions [80].

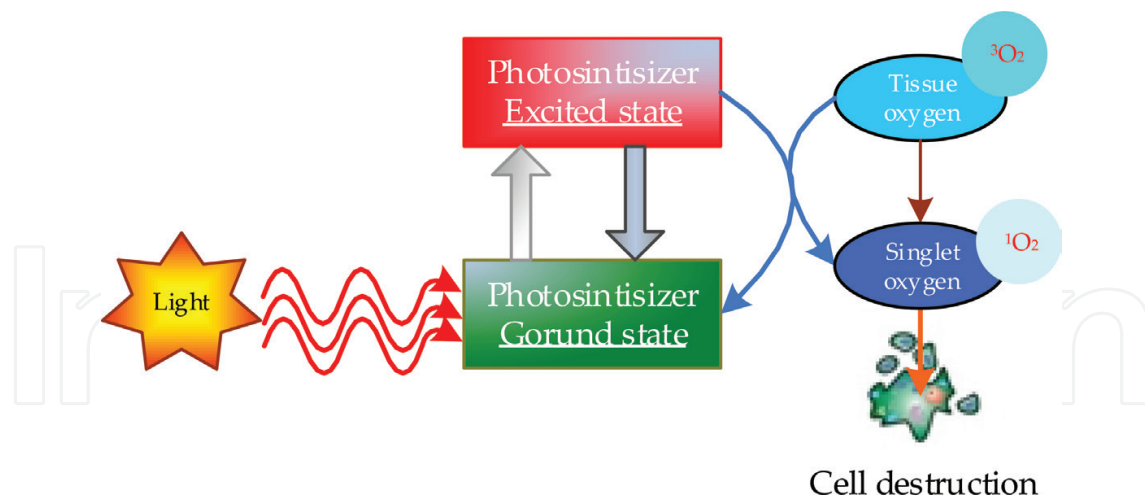
mid-infrared emissions at around 1.545, 2.05 and 2.9  $\mu\text{m}$  wavelengths, respectively, appropriate for chemical sensing [2]. Moreover, there is some evidence that, at a wavelength of around 1000 nm, Yb³⁺-doped fiber lasers can be used as short coherence light sources in optical coherent tomography, used for ophthalmology [84]. Additionally, according to reports by scientists from Ultrafast Optics & Lasers Laboratory, Bilkent, there are some already developed Yb-doped fiber laser configurations, appropriate for high precision processing of both hard and soft tissue. The hard tissue experiments were performed on dentine (human tooth sample), while the soft tissue experiments were focused on brain tissue removal and corneal flap cutting. It has been pointed out that the operation of the custom-developed fiber laser is provided through either uniform repetition rate pulse or ultrafast burst-mode regimes [85].

In the recent years, Yb-doped fiber lasers have been also widely used in MOPA configuration with various pulse duration and repetition rates for creating novel laser configurations, which can be attractive solutions for many medical applications, such as fluorescence analysis of biological molecules [86] and photoacoustic microscopy [87]. It is to be pointed out that MOPA configurations have been also under research for photoacoustic imaging (PAI), in order to substitute currently available Nd:YAG laser, targeting 150 times faster imaging [88]. Femtosecond Yb-fiber laser with MOPA configuration at 1035 nm can be a part of widely tunable Cherenkov fiber lasers used in both confocal and super-resolution microscopy [89].

## 4. Some examples of medical applications

### 4.1. Fiber lasers in photodynamic therapy

Photodynamic therapy (PDT), a simple scheme of which is illustrated in **Figure 11**, also referred to as blue light therapy, is a treatment modality that utilizes light sensitive molecules, photosensitizers, activated by adequate kind of light, commonly generated by laser



**Figure 11.** Photodynamic therapy.

sources, to cause the formation of singlet oxygen, producing peroxidative reactions that can cause damage and death of abnormal or neoplastic cells [90]. In addition, PDT is currently used in cosmetic surgery, oncology, oral medicine, and ophthalmology [91]. Although being primarily developed for cancer treatment, at the outset, usage in oncology usage was confined to a few specific cancer kinds, such as non-small cell lung cancer and esophageal cancer. However, further investigation has revealed that PDT can be quite convenient for general oncology for conditions including cancers of the peritoneal cavity, prostate gland, cervix, and brain [92].

PDT is a noninvasive or minimal invasive alternative techniques for conventional, more systematic, treatment of tumors, consists of surgical resection, radiotherapy and/or chemotherapy, which is developed to target tumor itself by light-induced activation of a photosensitizer that selectively accumulates within neoplastic tissue. As a promising treatment for selective tissue destruction, PDT has attracted widespread attention from the entire scientific community since, comparing to radiation therapy, it offers more patient-comfortable cancer treatment without cumulative long-term complications. PTD is a dynamic process, which requires careful administration of interaction of all principal components. The distribution of light, determined by the light source characteristics and the tissue optical properties, is in interaction with photosensitizer and oxygen concentrations since they influence the tissue optical properties. On the other hand, the distribution of oxygen is in closely relation with the photodynamic process since the photodynamic process is an oxygen consumer, which is, in turn, influenced by the distribution of photosensitizer. That is to say, well-administrated PTD requires optimal photosensitizers, smart transport strategies, and activation by adequate light source [93].

Over the last several decades, research focused on better understanding of the basic biophysical mechanisms of light transport and delivery in tissue, has led to diversification of photosensitizing agents, and light sources as well, which in turn has brought about a valuable progress in PDT in terms of the light penetration depth in the skin tissue. Hence, it seems that poor skin penetration depth of around 1 cm that diminish ability of the light to target deeper cells could be overcome.

In PDT, light sources, which are used as a spatially and temporally precise stimulus, typically operate in the 600–800 nm range. This visible and NIR spectral zone, also known as the therapeutic window, has the advantages in light transport and delivery in tissue. The other superiorities of aforementioned region are reducing pain, inflammation, and edemas as well as preventing tissue damage. Although nowadays there is diversified amount of light sources that can be used, lasers are quite prominent ones because obtained monochromatic light could be easily coupled into optical fibers in order to get up to deeper regions. At this point, practical advantages that fiber lasers offer over other types of lasers, such as inherently more efficient coupling, compactness, flexibility, and high beam quality as well as lower running costs, may overcome key clinical limitations of PDT related to delivery of optical energy and afford new opportunities for PDT. It is to be pointed out that early lasers were based on argon laser, gas vapor laser-pumped dye laser, or Nd:YAG solid-state lasers. Nowadays, they are replaced by diode-pumped fiber lasers, 1540 nm non-ablative fractional erbium-doped fiber laser [94, 95], 1927-nm thulium fiber lasers, and quantum dot (QD) fiber laser [43, 96, 97].

#### **4.2. Fiber lasers in biomedical sensing—mid-infrared spectroscopy**

Quite a few diseases can be detected by monitoring consequential metabolic abnormalities through the quantification of the serum biochemical components, such as urea, globulins, enzymes, glucose, cholesterol, triglyceride, and albumin. Hence, numerous biochemical methods have been developed to quantify, and more rarely characterize, specific serum components. However, most of those offer information on a particular component rather than a combination of several biochemical parameters. In this context, identifying serum fingerprints via MIR spectroscopy, from a rather small amount of sample, can provide more extensive view on the serum biochemical species levels, which, in turn, can facilitate diagnostic procedure.

The middle-infrared (MIR) region spanning 2500–10,000 nm of electromagnetic spectrum is proved to be very useful in spectroscopy, for quantification of the composition of the sample by means of light, particularly in clinical chemistry [98]. Broad spectral coverage of the region provides opportunity for sensing a great deal of molecules, including molecules of biological tissues, where they can be recognized with great sensitivity. Until recently, challenges, such as poor coherence of light sources, troublesome sensing due to highly attenuated backscattered sign as well as a lack of low noise MIR detectors were insurmountable obstacles especially in vivo spectroscopy [99]. However, over the last few years, advances in material science, in addition to diversifying and miniaturizing of photonic components have paved the way for enhancing novel light sources, with previously unattainable performance capabilities, which have improved accuracy of measurements to a great extent. As result, MIR spectroscopy has been consolidated and put on center stage again.

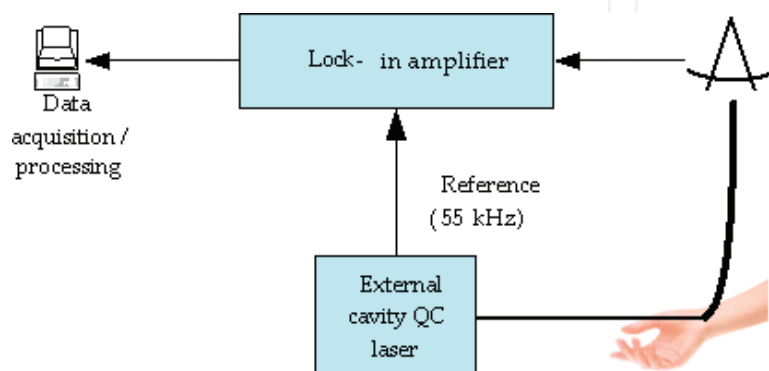
Refers to the physical principle, MIR spectroscopy utilizes fundamental molecular vibrations, such as bending and stretching, of a specific bond or bonds within the molecule under study generally caused by matching quantized energy difference of transitions between the ground state and the first excited state. Its high sensitivity to polar groups is the result of the same oscillation frequency of the molecular dipole moment and electric field vector of the source light [147]. Furthermore, the “fingerprint” region has a quite strong absorbance, with numerous and well resolved absorbance peaks, differing in position, width, and

intensity providing unique absorption patterns for each constituent, which enable direct constituent identification at a molecular level. The MIR region is quite suitable for identifying C-C, C-O-H, and C-H groups for asymmetrical and symmetrical stretching's [100]. However, MIR light only penetrates up to 100  $\mu\text{m}$  into human skin due to the strong water absorption [97]. Problem of limited penetration has been partially avoided by application of multivariate data-analysis techniques.

The basic setup of the MIR measuring instrument consists of a light source, an optical assembly and a light detector unit. A high spectral brightness, tight focusing characteristic for a spatially coherent, laser-like beam as well as high average power is common requirement for the all spectroscopy schemes. Until the last decade, the most preferred laser sources were  $\text{CO}_2$  laser and vertical-cavity semiconductor laser (VCSEL) [101]. However, their complexity and high costs got research to change direction toward tunable semiconductor lasers, such as: quantum cascade laser (QCL) and external cavity quantum cascade laser (Eq-QCL) [102]. In the last years, in several researches, it has been pointed out that supercontinuum generation light sources and some mode-locked oscillators can be quite encouraging as they span exceedingly MIR region [103]. Refers to light detection unit, there are several kinds of photodetectors widely used in this region, chosen depending on measuring technique. Lately, the most remarkable sensor types have been small fiber-based on attenuated total reflectance (ATR), and photoacoustic sensors. ATR has still been a monopoly technique in analyzing the sample.

**Figure 12** shows example setup used by Liakat and colleagues, where glucose MIR spectra are collected from wrist skin. Hollow core fiber, particularly suited for delivery of picosecond pulses with high average and high peak power, is used for both delivery of QC laser light and collection of backscattered light, coupled directly to a MCT detector. The lock-in amplifier, which provides amplifying and measuring of phase and frequency locked output, has reference frequency of 55 kHz. Finally, the output of lock-in amplifier is recorded by computer, where data is processed.

Up to now, most of drawbacks refer to MIR spectroscopy have been in large part overcome. Although some of them, such as high sensitivity to external factors and sudden drop in available energy with increasing wavelength, still remain important challenges keeping ahead more strongly reconsideration and practical implementation, there is a strong believe that MIR spectroscopic techniques is one of the forefront candidates for a viable future solution



**Figure 12.** Setup used for collecting data from human skin [104].

with a few advancements and adaptations. In this sense, it has been pointed out that possible step toward could lay in fortifying MIR spectroscopy with some other technique or using alternative measuring technique with MIR light source.

### 4.3. Fiber lasers in dentistry

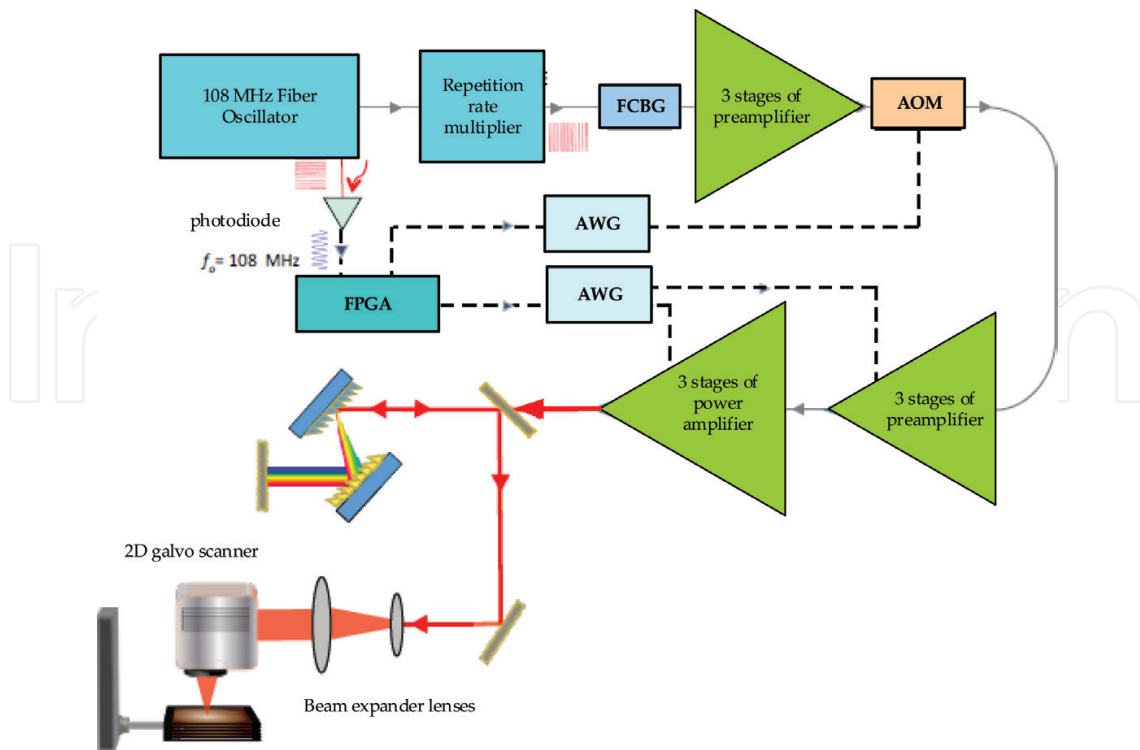
Comparing to other areas of medicine, the introduction of lasers into dentistry lagged mainly due to some skepticism by a majority of dentists and correspondingly predominance of long-standing clinical dogma of clinical techniques. Hence, although the original Nd:YAG was launched as a soft tissue laser primarily for dental purposes, the real expansion in laser usage began when professionals began recognizing a need for a hard tissue laser, so that, the laser technology in dentistry emerged with introduction of the Er: YAG laser, as an alternative to the rotary drill.

In the last decades, lasers have become more and more important in dentistry. From a patient point of view, the treatment performed by lasers are very beneficial primarily because of quicker and more efficient dental care accompanied with notably reduced pain during the treatment, less need of anesthesia, reduced post-treatment pain, and shorter post-treatment recovery period. Refers to the practitioner, one of the main arguments in favor of laser-assisted dental surgery is better efficiency due to generally shorter treatment procedures as well as less complex and time consuming pre and post-procedure protocols. The requirements of the output from lasers used for dental applications are manifold. Besides the essential attributes such as the pulse energy, output power, and wavelength, laser must have some other practical qualities such as the size, input power, tightness of the focus of the output, and maintenance level.

Lasers used in dental practice are usually classified according to tissue applicability into: hard tissue and soft tissue lasers. Er: YAG and diode lasers have proven their value for many dental procedures, both as surgical and therapy tools, with added benefits in a wide range of applications. In spite of high price, the Er:YAG is still one step ahead because of its elevated absorption in water, which makes it adequate for both treatment of dental hard tissues and soft tissue ablation. On the other hand, diode lasers having several advantages, such as reduced size, reduced cost, and possibility to beam delivering by optical fibers, are more appropriate for the soft tissue treatments.

According to research, fiber laser technology has been trying to break up Er:YAG and diode lasers' monopolies in the dentistry market, for almost two decades. In spite of is a growing trend in usage of fiber lasers in oral surgery, expected outcome has not been reached yet. However, there is no depth that benefits, such as compactness, high reliability, low cost, high beam quality, and power efficiency could pave the way for fiber lasers to compete with Er:YAG and diode lasers in terms of pulse energy. In this context, ex vivo study for 1070 nm fiber lasers, carried out on both tissues and materials, could be one of the promising results due to reduced thermal elevation in the irradiated tissues, thanks to the possibility of emission in ns pulse duration, limiting the collateral damage due to the overheating of the target [41]. Custom-developed laser system, developed by UFOLAB, Bilkent, illustrated in **Figure 13**, is another encouraging





**Figure 13.** Laser, optical scanning, and sample positioning setup custom-built for the hard tissue and piezoelectric ceramic cutting experiments [105].

study, in which an in-house developed Yb-doped fiber burst-mode laser amplifier system with an adjustable in-burst repetition rate is seeded by an all-normal dispersion laser oscillator generating a mode-locked signal at a repetition rate of 108 MHz as the seed source. The system with central wavelength of 1035 nm is set up for hard and soft tissue treatment [106].

However, it is to be pointed that usage of lasers in daily dentistry is not confined to tissue treatment; it is also extended to anti-bacterial applications as well as surface texturing or coating for modification of surface properties of various materials, such as titanium-based dental implants and disilicate ceramics. Although the dental industry is not the largest industry to be using fiber lasers, their biggest impact on this industry might be the way in which the tools and equipment used by dental surgeries can be manufactured.

## 5. Conclusion

The purpose of this chapter is not only to provide an overview on theoretical basis but also revise existing classification schemes of fiber laser technology for medical purposes. It is to be stressed that our theoretical framework is concerned with basic concepts that are relevant for fiber laser technology in medical field. The second part of the chapter is devoted to classification of medical fiber lasers according to several criteria, the most prominent of which is host media and with relevant emitting wavelengths of special proposes.

The idea of using light in therapeutic purposes is not a new one. It is widely believed that sunlight was used as a therapy by the ancient Greeks and Egyptians. However, the idea has become reality since laser invention. In the past two decades, lasers have gradually found a place in the practice in many areas of medicine and biomedical research. Recently, they have already found their way into cosmetic surgery and oncology. Now, they are becoming important tools for a large number of applications with microscale accuracy, in branches such as nanosurgery and ophthalmology. Fiber lasers have also unique places in family of coherent light sources and they make their presence felt in vivo sensing. As example, applications of mid-IR light to noninvasive in vivo sensing systems yield robust and clinically accurate ones that got rid of boundaries set in the past. It has been highlighted that in near future it will be possible to achieve immense amount of cellular-related information. Recently, improved cancer diagnosis via lasers that illuminate cellular activity has been reported. Additionally, in near future, light will play a very important role in solving energy life sciences challenges. Fiber laser technology seems to come to take medical market share away from their merged counterparts.

## Thanks

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