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Chapter 2

Cladding Pumped Thulium-Ytterbium Short Pulse Fiber Lasers

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Abstract

This chapter describes double clad fiber along with cladding pump technique in which pump light is coupled in the inner cladding of fiber thereby interacting with doped core through total internal reflection. Lasers operating in continuous wave mode have limited output power. Their output power can be enhanced to a great extent by concentrating the available energy in a single or in a periodic sequence of optical pulses. This is achieved by Q-switch and modelock techniques. Q-switched and modelocked lasers can be realized by active and passive means. Active technique is based on active loss modulation by using mechanical, electro-optic or acousto-optic based modulators. However, such techniques require complicated electronic circuits and have limited gain bandwidth. The attention then moves towards the passive technique which is low cost, compact in size, gives reliable operation without high voltages and provides simple cavity design without need for external electronics. Passive technique employs a saturable absorber, based on materials like carbon nanotubes, graphene, molybdenum di-sulfide etc. A brief description of pulsed fiber lasers and solitons in view of modelocking are described in the text. Moreover examples of Q-switched and modelocked lasers are also presented by using Thulium-Ytterbium co-doped double clad fiber. A cladding pump technique is employed for the purpose.

Keywords: fiber laser, double clad fiber, cladding pump, Q-switched, modelocked

1. Introduction

Fiber laser is a mature technology that has become an essential tool facilitating a wide range of scientific, medical, and industrial applications. Fiber lasers are advancing rapidly due to their ability to generate stable, efficient, and diffraction-limited beams with significant peak and average powers.

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In fiber optics, optical signals travel in hair thin strands of glass or plastic fiber [10]. The light propagates in the core at the center of the fiber, surrounded by an optical material called cladding that confines the light in the core employing the phenomenon of total internal reflection. There are two basic types of fibers: single-mode and multi-mode fibers. Single-mode fiber has a core diameter of 8.3–10 microns and supports only one mode of transmission. Multi-mode fiber has a core diameter of either 50 or 62.5 microns. Multimode fibers support multiple modes as shown in **Figure 1**. Due to their smaller core size, these fibers cannot support high power pump sources and therefore cannot generate high output power.

To overcome the three limitations (small core radius, larger attenuation, and dispersion) of high speed transmission, a new type of optical fiber called double clad optical fiber is proposed [2]. It consists of three layers of optical material instead of the usual two as shown in **Figure 2**. The inner-most layer is called the core, surrounded by the inner cladding, while the inner cladding is surrounded by the outer cladding. All the three layers are made of materials with different refractive indices. The typical refractive index profiles are shown in **Figure 3**. Generally, the outer cladding is made of a polymer material rather than glass. Refractive index of inner cladding is higher than the outer cladding. This enables the inner cladding to guide light by total internal reflection, but for a different range of wavelengths than the core. Also, the inner cladding has larger area and higher numerical aperture so that it can support large number of modes. This allows multi-mode laser diodes to be used as the pump source, which possess high power but low brightness.

1.1. Cladding pump

The pump light can be easily coupled into the large inner cladding and propagates through the inner cladding, while the signal propagates in the smaller core as shown in **Figure 4**. The

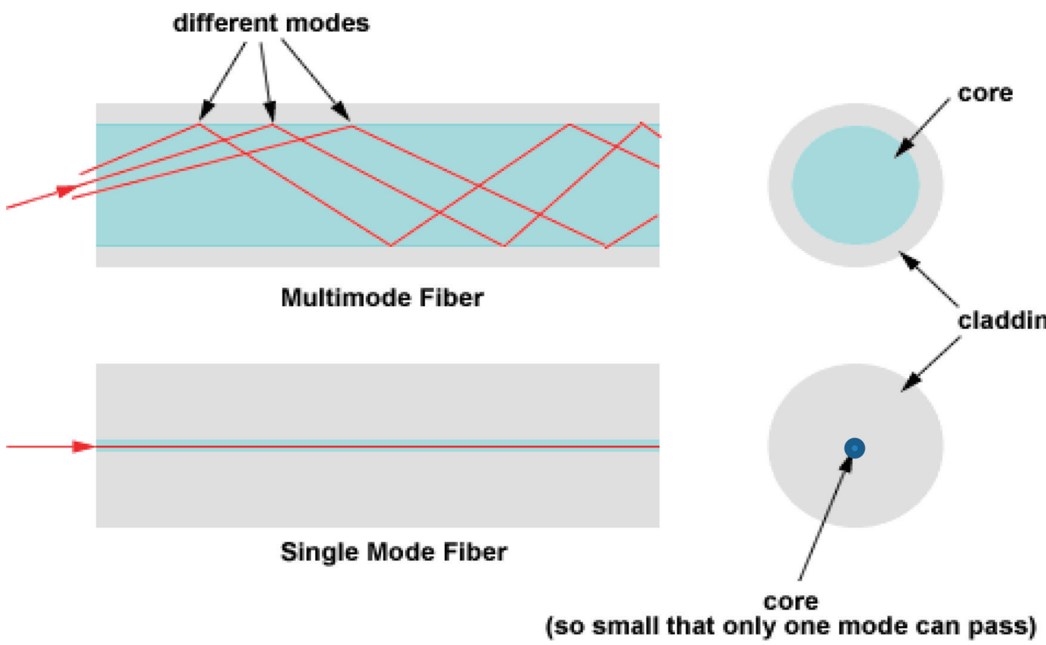

Figure 1. Mode propagation in single- and multi-mode fibers [1].

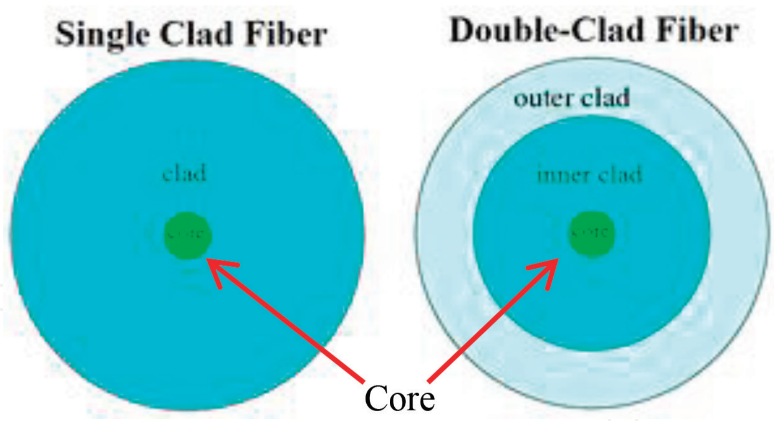

Figure 2. Structure of single and double clad fibers.

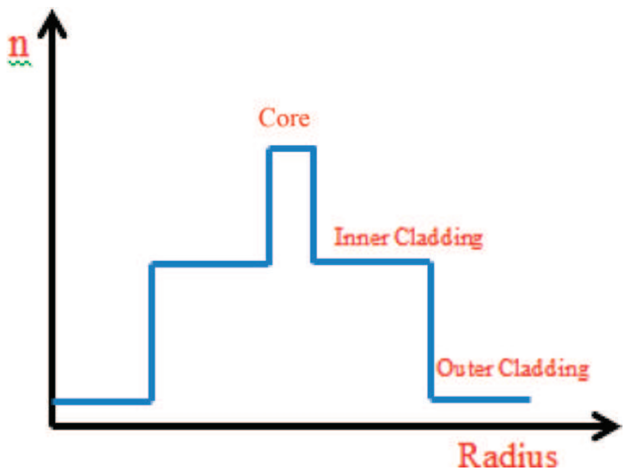

Figure 3. Typical refractive index profile of double clad optical fiber.

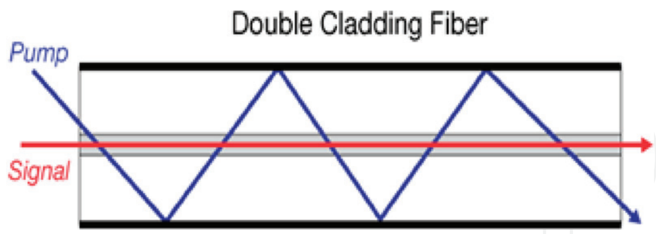

Figure 4. Cladding pump scheme.

doped core gradually absorbs light from the cladding as it propagates through the core and amplifies it [4]. This type of pumping scheme is referred as cladding pumping, an alternate scheme to the conventional core pumping, where the pump light is coupled into the small core. Cladding pumping has revolutionized the design of fiber amplifiers and fiber lasers [3]. Using this technique, contemporary fiber lasers can generate continuous power up to several kilowatts, besides allowing the signal light to maintain near diffraction limited beam quality [4].

In a double clad fiber, cladding shape is of extreme importance, particularly in case of small core diameter compared to the cladding size. Circular symmetry is considered the worst in a double clad fiber, because many modes of light in the cladding missed the core, therefore cannot pump the core [5]. Normally, claddings are noncircular, which enhance the absorption of the pump light in the doped core [7]. Different shapes of inner cladding are shown in **Figure 5** for rare earth doped fibers.

Hence, double clad cladding pumped fiber lasers are regarded as devices that can generate diffraction limited single-mode laser light using multi-mode laser diodes as the pump. Due to large size of inner cladding, high pump powers can be injected in a double clad fiber. However, the core size puts limits on the output power due to the danger of optical damage and thermal effects [7].

Different lasers operating in continuous wave or quasi-continuous wave mode have limited optical output power, linked with the maximum available pump power [10]. The peak output power of a laser can be enhanced by concentrating the available energy in a single, short optical pulse, or in a periodic sequence of optical pulses as in Q-switched and modelocked fiber lasers.

1.2. Q-switched lasers

Q-switching, also known as giant pulse formation or Q-spoiling, [8] is a powerful technique by which a laser can be made to produce a pulsed output beam. This technique is capable of producing light pulses with extremely high (gigawatt) peak power, much higher than the continuous wave mode (constant output) operation of the laser. As compared to modelocking, another technique for pulse generation with lasers, Q-switching leads to much lower pulse repetition rates, much higher pulse energies, and much longer pulse durations than it. It was in 1958 when Q-switching was proposed by Gordon Gould [9]. Practically, it was achieved in 1961 or 1962 by Hellwarth and McClung using Kerr cell shutters in a ruby laser, and these require electricity for switching [10].

A variable attenuator is required inside the laser's optical resonator to produce Q-switched laser light. When the attenuator is functioning, light which leaves the gain medium does not

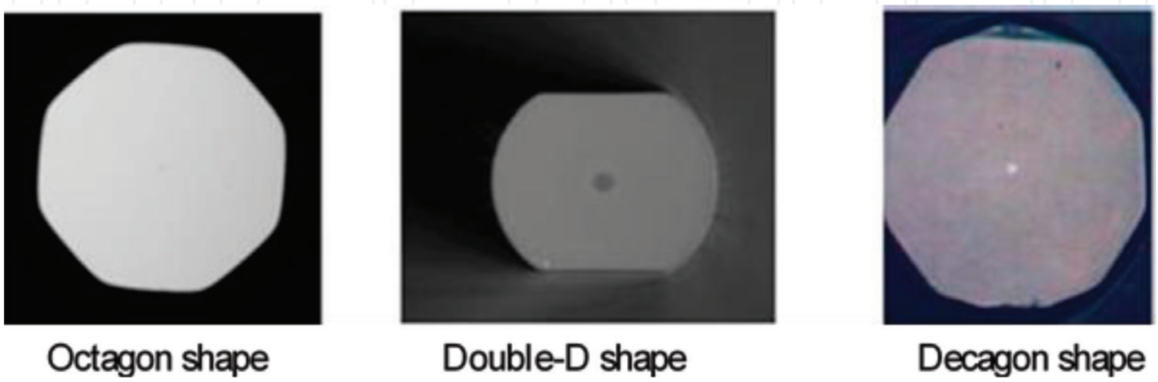

Figure 5. Cross-sectional images of a few inner cladding shapes used in double clad fiber lasers (a) octagon (b) double-D (c) decagon [6].

return or cannot travel back and forth, this restricts the lasing, putting the optical cavity in low Q factor or high loss condition. A high Q factor represents low resonator losses per round trip. The variable attenuator is commonly known as "Q-switch."

First, the laser medium is pumped, while the Q-switch is set to prevent feedback of light into the gain medium (producing an optical resonator with low Q factor). This produces a population inversion by losing pump energy through absorption by electrons, thus pumping electrons to higher energy level; this accumulates energy in the gain medium. However, the laser operation cannot yet begin, because there is no feedback from the resonator [3]. As the rate of stimulated emission depends on the amount of light entering the medium, therefore, the amount of energy stored in the gain medium increases as the medium is pumped. Due to losses from spontaneous emission along with other processes, the stored energy takes some time to reach some maximum level; the medium is said to be gain saturated. At this point, Q-switch rapidly changes from low to high Q, allowing feedback and the process of optical amplification by stimulated emission to begin [3]. Since a large amount of energy is already stored in the gain medium, the intensity of light in the laser resonator builds up very quickly; this also causes the energy stored in the medium to be depleted almost as quickly. This develops a short pulse of light output from the laser, known as a giant pulse, which may have very high peak intensity. Generally, several round trips are needed to completely depopulate the upper energy level and several more round trips to empty the optical cavity, so the duration of the pulse is greater than one round trip. The peak power (the pulse energy divided by its duration) of these lasers can be in the megawatt range or even higher. There are two main techniques for Q-switching: active and passive.

1.2.1. Active Q-switching

In active Q-switching, the losses are modulated with an active control element so-called active Q-switcher, either by using an acousto-optic or electro-optic modulator, which requires an external electrical signal to operate. The pulse is formed shortly after an electrical trigger signal arrives. There is also mechanical type Q-switchers such as spinning mirrors, used as end mirrors of laser resonators. The pulse repetition rate can be controlled by the active modulator in an actively Q-switched laser. Higher repetition rates lead to lower pulse energies.

1.2.2. Passive Q-switching

In passive Q-switching, the losses are modulated or controlled by optical cavity light, rather than some external electrical source. A saturable absorber device is normally used as a Q-switcher in this technique. The transmission of this device increases when the intensity of light exceeds some threshold. The material may be an ion-doped crystal like Cr:YAG (chromium-doped Yttrium-Aluminum garnet), which is used for Q-switching of Nd:YAG (neodymium-doped Yttrium-Aluminum garnet) lasers, a bleachable dye, graphene mechanical exfoliation and PVA thin film, semiconductor saturable absorber mirrors (SESAM), and carbon nanotubes embedded in PVA thin films. Initially, the loss of the absorber is high, once a large amount of energy is stored in the gain medium, the laser power increases, and it saturates the absorber, and light can pass through as there are no electrons in the ground state to absorb pumped energy. As soon as the energy is depleted in the resonator, the absorber recovers to its high loss state before the gain recovers, so that the next pulse is delayed until the energy in the gain medium is fully replenished. In this way, it works as an on-off optical switch to generate pulses. The pulse repetition rate can only be controlled indirectly by varying the laser's pump power and the amount of saturable absorber in the cavity. For direct control of the repetition rate, a pulsed pump source is needed.

Passive Q switching is simpler and cost effective as compared to the active one. It eliminates the modulator and its electronics. Moreover, it is suitable for very high pulse repetition rates, but with lower pulse energies. External triggering of the pulses is not possible (except with an optical pulse from another source), and also pulse energy and duration are often more or less independent of the pump power, which only determines the pulse repetition rate [11, 12].

1.3. Modelocked lasers

In laser technology, modelocking refers to a technique by which a laser can be made to generate pulses of extremely short duration, of the order of picoseconds (10^{-12} s) or femtoseconds (10^{-15} s). This is achieved by establishing a fixed-phase relationship between the longitudinal modes of the laser's resonant cavity. The laser is then referred as phaselocked or modelocked. Interference between these modes causes the laser light to be produced as a train of pulses. In a simple laser, different modes oscillate independently, without a fixed relationship between each other, like a set of independent lasers all emitting light at slightly different frequencies. In lasers with few oscillating modes, interference between the modes produces beats in the laser output, leading to fluctuations in intensity; whereas in lasers with many thousands of modes, interference between modes tend to average to a near-constant output intensity. **Figure 6** shows the electric fields of five modes with random phase and the power of the total signal distributed in a random fashion.

On the other hand, if each mode operates with a fixed phase relationship between it and the other modes, all modes of the laser will periodically constructively interfere with one another, generating an intense burst or pulse of light instead of random or constant output intensity as shown in **Figure 7**. Such a laser is termed as modelocked or phaselocked laser. These pulses are separated in time by $\tau = 2L/c$, where τ is the time taken for the light to make exactly one round trip of the laser cavity, L is the length of laser cavity, and c is the speed of light. The frequency is exactly equal to the mode spacing of the laser, $\Delta\nu = 1/\tau$. The duration of each pulse is determined by the number of modes which are oscillating in phase. Suppose there are N modes locked with a frequency separation $\Delta\nu$, the overall modelocked bandwidth is $N\Delta\nu$, and the wider the bandwidth, the shorter the pulse duration of the laser [5].

The actual pulse duration is determined by the shape of each pulse, which is measured by the amplitude and phase relationship of each longitudinal mode. As an example, a laser producing pulses with a Gaussian temporal shape, the minimum possible pulse duration Δt is given by the equation

$$\Delta t = \frac{0.441}{N\Delta\nu} \tag{1}$$

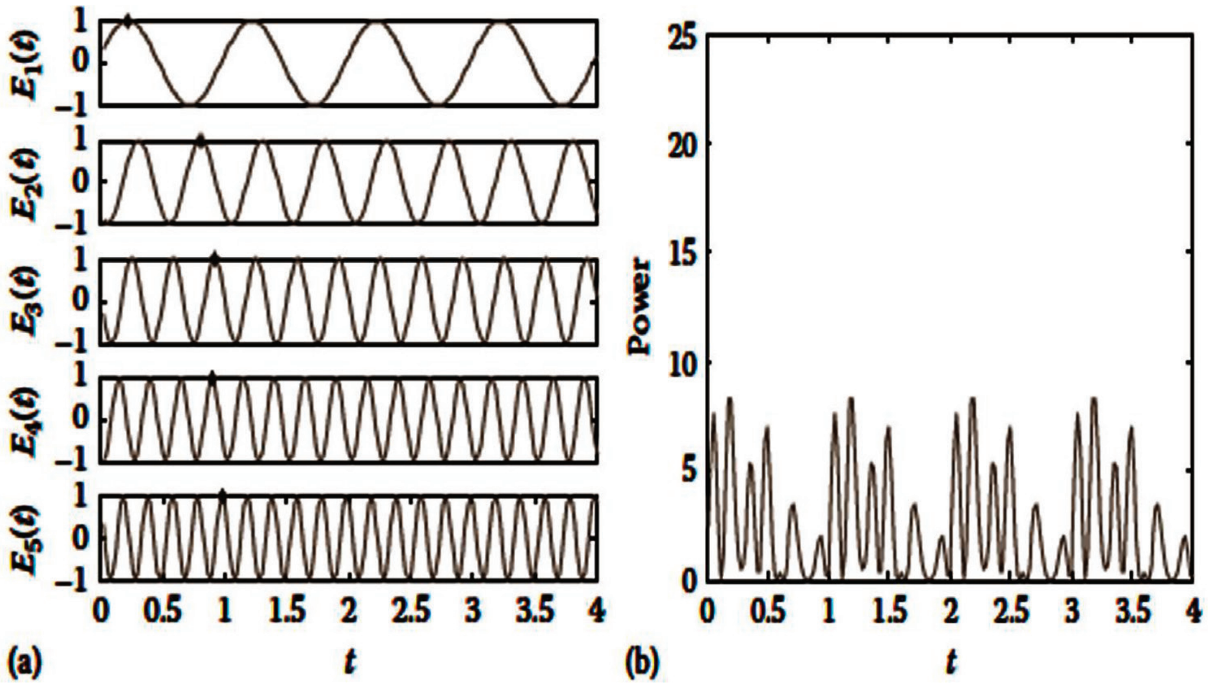

Figure 6. Plots of (a) electric field amplitudes of five individual modes of randomly distributed phases and (b) power of the total signal of a multi-longitudinal mode laser [13].

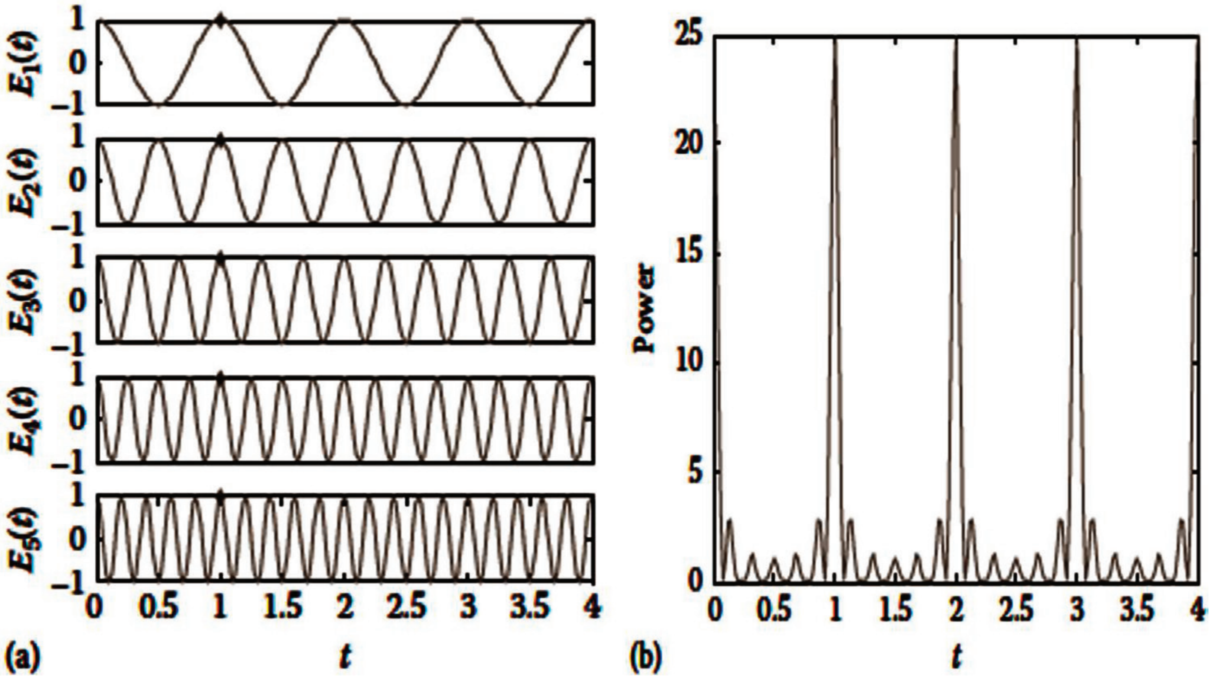

Figure 7. Plots of (a) electrical field amplitudes of five in-phase individual modes and (b) the total power of a periodic pulse train [13].

The value 0.441 is known as the "time-bandwidth product" of the pulse and varies depending on the pulse shape. Generally for ultra-short pulse lasers, a hyperbolic-secant-squared ($sech^2$) pulse shape is considered, giving a time-bandwidth product of 0.315. Using this equation, the minimum pulse duration can be calculated consistent with the measured laser spectral width [13].

Modelocked fiber lasers are capable of producing pulses with widths from close to 30 fs to 1 ns at repetition rates, ranging from less than 1 MHz to 100 GHz. This broad range along with a compact size of optical fiber lasers is quite unique in laser technology, making them feasible for a large range of applications. As modelocked fiber laser technology was developed and these lasers became commercially available, they have been used in various fields, such as laser radar, all-optical scanning delay lines, THz generation, injection-seeding, two-photon microscopes, optical telecommunications, and nonlinear frequency conversion, just to mention the most widely publicized areas [12]. Surely, modelocked fiber lasers are a premier source of short optical pulses sharing an equal position with semiconductor and solid-state lasers [14].

1.3.1. Modelocking methods

Modelocked lasers can be produced by using either active or passive methods. In active modelocking, the optical modulator such as acousto-optic modulator is used with the help of an external electrical signal, as a modelocker. On the other hand, passive modelocking does not need an external signal to operate [15]. The modelocking is achieved by modulating an intra-cavity light using some intra-cavity elements, such as nonlinear polarization rotation and saturable absorber. Most of the passively modelocked lasers are achieved using a saturable absorber since it allows the generation of much shorter (femtosecond) pulses. This is attributed to the saturable absorber used, which can adjust the resonator losses much faster than an electronic modulator: the shorter the pulse becomes, the faster the loss modulation, if the absorber has a sufficiently short recovery time [14]. The pulse width can be even smaller than the recovery time of the absorber [6].

In addition, there are some passive modelocking schemes that do not require materials that directly display an intensity dependent absorption. These methods use nonlinear optical effects in intra-cavity components to provide a method of selectively amplify high intensity light in the cavity and attenuate low intensity light in the cavity. Among them, the most successful scheme is Kerr-lens modelocking (KLM), also sometimes referred to as “self-modelocking.” This technique uses a nonlinear optical process, the optical Kerr effect, which results in high intensity light being focused differently from low intensity light. By careful arrangement of an aperture in the laser cavity, this effect can be made to produce the equivalent of an ultra-fast response time saturable absorber.

1.4. Optical solitons

A fascinating manifestation of the fiber nonlinearity is the development of optical solitons, created due to the balance between dispersive and nonlinear effects [8]. Solitons are a unique type of wave packets, capable of propagating unaltered over long distances inside a fiber.

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Solitons have been discovered in many branches of physics. In the field of photonics, especially in fiber optics, solitons not only are of fundamental interest, but they have also found practical applications in the field of fiber-optic communications [16].

The pulse maintains the shape and width, along the entire length of the fiber, if the effects of SPM and GVD cancel out with each other. Such a pulse is called solitary wave pulse or soliton. The pulse that has the above property is the sech profile pulse, which is a solution of the nonlinear Schrodinger equation NLSE [13].

Figure 8 shows the spectrum of different types of modelocked fiber lasers. The conventional soliton and stretched pulse are obtained in anomalous dispersion fiber laser setup, where the pulse shaping is mainly due to the natural balance between the anomalous dispersion and the fiber nonlinearity. On the other hand, dissipative solitons (DSs) are obtained in the normal dispersion region as a result of the combined effects among the fiber nonlinearity, cavity dispersion, gain and loss, and spectral filtering [13]. Moreover, the soliton shaping is strongly dependent on the dissipative effects. Consequently, dissipative solitons have a wider pulse duration and lower peak power, compared to conventional solitons and stretched solitons [17].

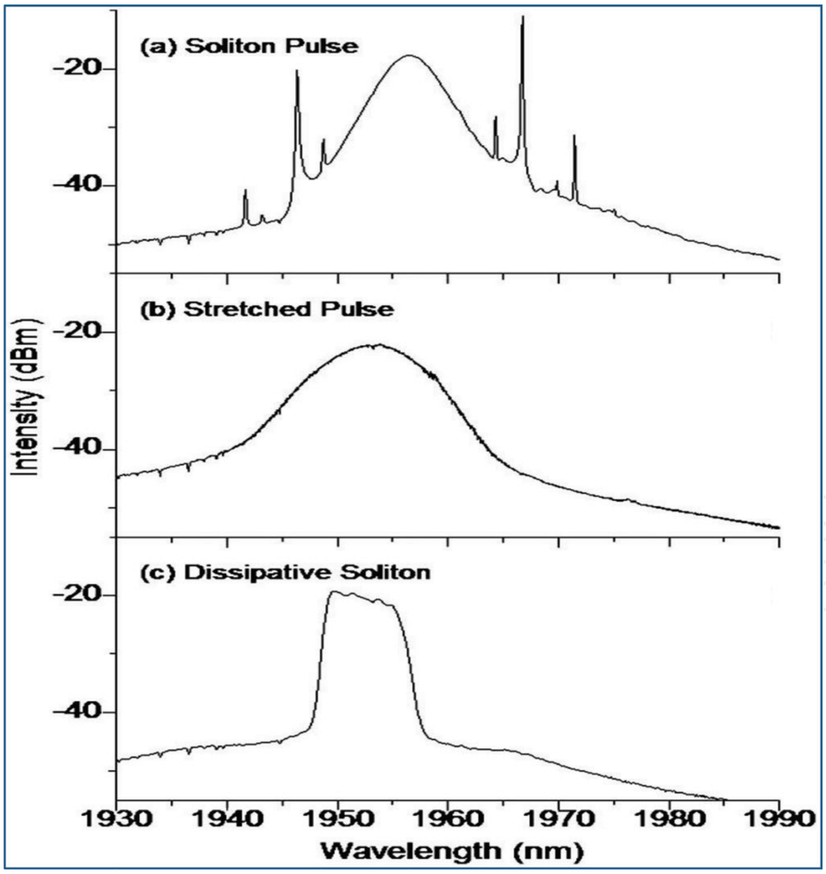

Figure 8. Different types of solitons [17].

2. Q-switched TYDFL using multi-walled carbon nanotubes passive saturable absorber

There are growing interests in compact Q-switched laser sources that operate in the mid-infrared spectral region around 2 microns. This is mainly driven by the applications in spectroscopy, communication, material processing, manufacturing, sensing, medicine, and nonlinear optical research [18, 19]. Nowadays, another type of nanotube called multi-walled carbon nanotubes (MWCNT) has been examined in the field of nonlinear optics because its production cost is 50–80% lower than SWNTs [9]. MWCNTs also have higher mechanical strength, higher photon absorption per nanotube, and higher mass density which leads to better stability [20].

We successfully demonstrated, a Thulium-Ytterbium co-doped fiber (TYDF) Q-switched laser using a laboratory made saturable absorber based on MWCNTs implanted in polyvinyl alcohol (PVA) composite for the first time [2]. A homemade double clad Thulium-Ytterbium co-doped fiber (TYDF) drawn from a preform which was manufactured based on the modified chemical vapor deposition (MCVD) and solution doping processes is used as a lasing medium. The fabricated MWCNT-PVA film (SA) is attached within the laser cavity by sandwiching it between two fiber connectors. Similarly, a modelocked TYDFL is also demonstrated using graphene PVA film as a saturable absorber.

2.1. Configuration of the Q-switched TYDFL

The schematic of the proposed Q-switched TYDFL is shown in **Figure 9**. It is constructed using a simple ring cavity, in which a 15-m long laboratory made TYDF is used for the active medium. An indigenously developed MWCNT-PVA-based SA was used as a Q-switcher. The double clad TYDF was forward pumped by a 905-nm multi-mode laser diode via a MMC.

2.2. Q-switching performance of Thulium-Ytterbium co-doped fiber laser

Initially, the continuous wave (CW) TYDFL was investigated without using the SA, and the laser threshold was found to be at 1.0 W pump power. When SA is inserted in the cavity, stable and self-starting Q-switching operation is obtained just by adjusting the pump power at a threshold value of 1.6 W, which is higher than that of the CW TYDFL because of the presence of SA in the cavity which increases the loss [2]. **Figure 10** shows the output spectrum of the Q-switched TYDFL at the threshold (1.6 W) pump power. As seen in the figure, the laser operates at 1977.5 nm with an optical to signal noise ratio (OSNR) of around 30 dB.

Figure 11(a) and **(b)** shows the temporal analysis and the corresponding single pulse envelop of a typical Q-switched pulse train, respectively, at a pump power of 1.6 W [2]. The spacing between two pulses in **Figure 11(a)** is around 53 μs, which can be translated to a repetition rate of 18.8 kHz. The corresponding pulse width is around 8.6 μs as shown in **Figure 11(b)**.

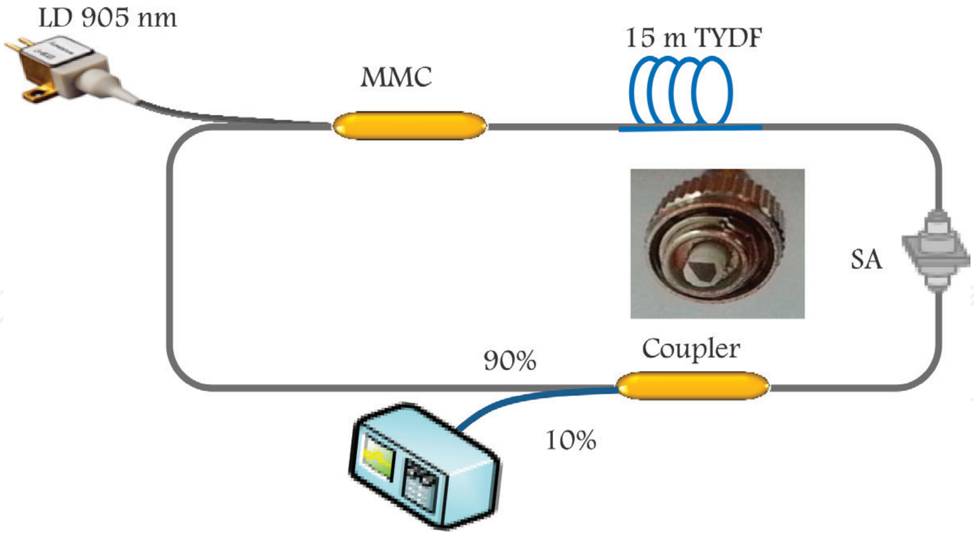

Figure 9. Setup of the proposed Q-switched TYDFL with MWCNT-PVA-based SA. Inset shows the image of the film attached onto a fiber ferule.

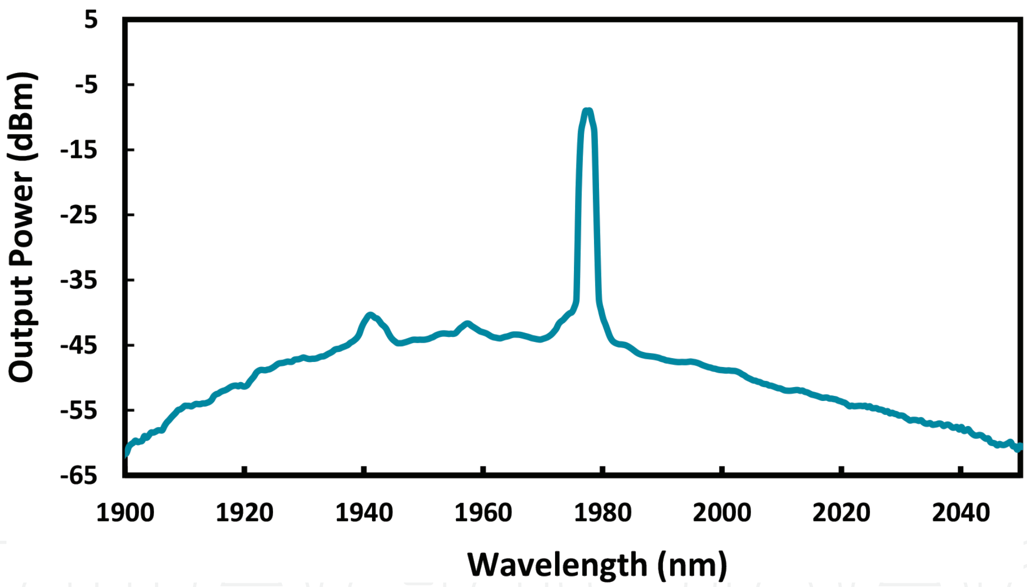

Figure 10. Output spectrum of the Q-switched TYDFL at pump power 1.6 W.

Figure 12 shows the pulse repetition rate and pulse width as a function of the pump power. As the pump power increases from 1.6 to 2.3 W, the repetition rate of the Q-switched pulses grows from 18.8 to 50.6 kHz. At the same time, the pulse duration significantly reduces from 8.6 to 1.0 μs as expected. The pulse duration could be further narrowed by optimizing the parameters, including shortening the cavity length, and improving the modulation depth of the MWCNT Q-switcher. An anomalous increase in the pulse width is observed at 1862 mW pumping, attributed to fiber nonlinearities [21].

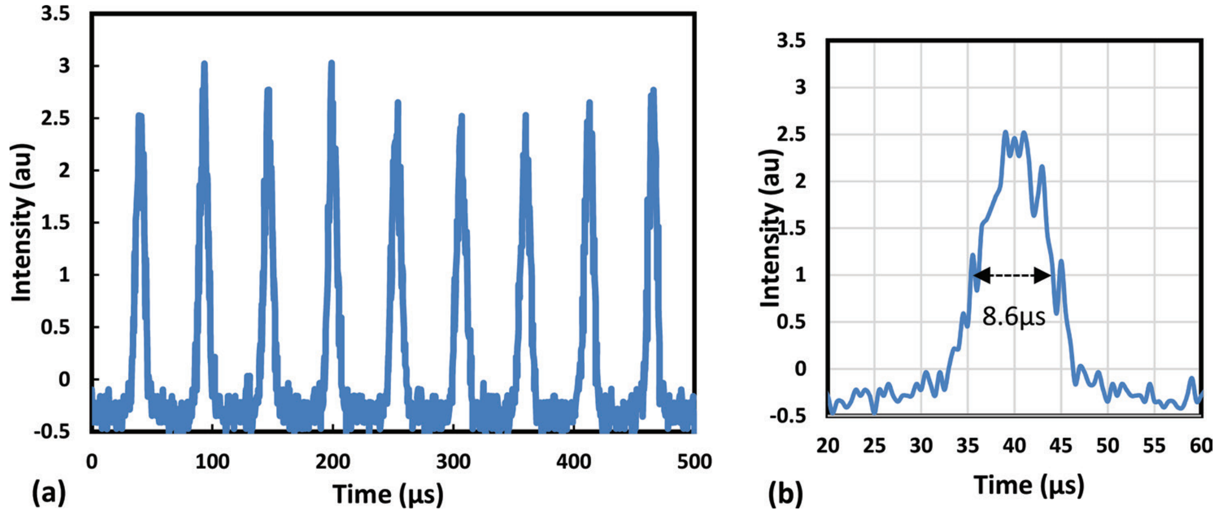

Figure 11. (a) A typical pulse trains and (b) a single pulse envelop of the proposed Q-switched TYFL at a pump power of 1.6 W. It shows a repetition rate of 18.8 kHz and a pulse width of 8.6 µs.

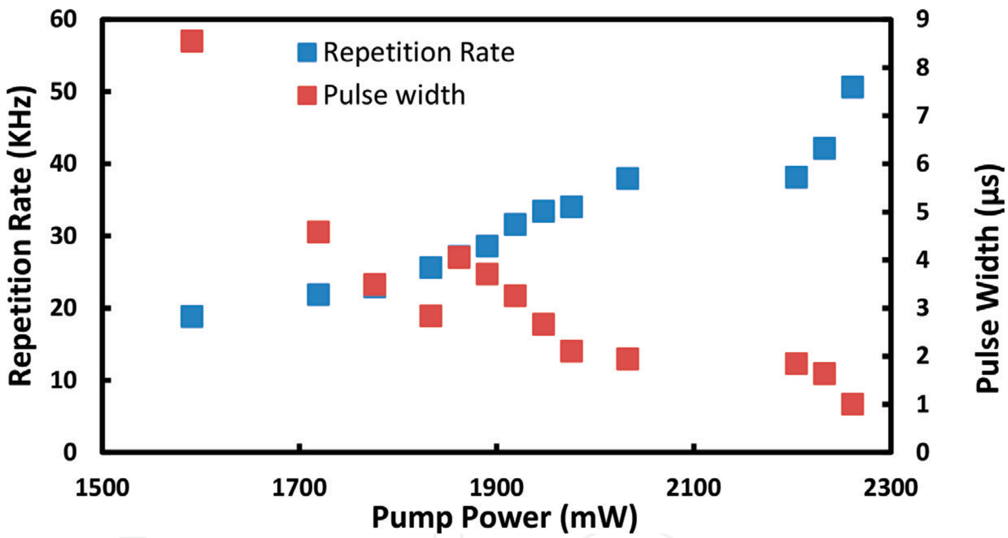

Figure 12. Repetition rate and pulse width as a function of 905-nm pump power.

3. Modelocked TYDFL using graphene PVA film as a saturable absorber

Modelocked Thulium-doped fiber lasers (TDFLs) have attracted intense interest in recent years for a number of potential applications, including atmospheric measurements, material processing, communication, laser radar, biomedical and medical applications, and longer-wavelength laser pumping [22–24]. The graphene PVA film was prepared by mixing the graphene solution in PVA solution. The graphene solution was obtained from the flakes produced using electrochemical exfoliation process. A free-standing graphene PVA film was obtained after drying in an oven and is used as SA.

3.1. Configuration of the proposed modelocked TYDFL

Experimental setup for the Thulium-Ytterbium co-doped fiber laser (TYDFL) is shown in **Figure 13** [1]. It uses a double clad Thulium-Ytterbium co-doped fiber (TYDF) as the lasing medium in ring cavity configuration. The TYDF has an octagonal inner cladding to enhance the pump light interaction with the doped core. The core has 5.96-nm diameter with an NA of 0.23. The selected fiber length of 10 m provides more than 90% pump absorption. The fiber type SA device was constructed by inserting graphene PVA film between two ferules. The length of total cavity is set at around 17 m, so that the net cavity dispersion is anomalous for facilitating self-starting mode locked laser.

3.2. Modelocking performance of the TYDFL

Modelocking was self-started by increasing the pump power above the threshold of 1487 mW. The modelocked operation was maintained as the pump power is increased up to the maximum power of 1964 mW. **Figure 14** shows the output spectrum of the modelocked pulse train when the pump power is fixed at 1610 mW.

As shown in the figure, the spectrum was centered at 1942.95 nm with a 3-dB bandwidth of 0.08 nm. Without SA, the CW laser operates at 1943.50 nm. This shift of the operating wavelength toward the shorter wavelength is caused by the change in cavity loss by the insertion of SA [1]. Usually, lasers shift toward the shorter wavelength to acquire more gain to compensate for the insertion loss of SA. Moreover, the presence of weak sideband at 1942.5 nm confirms the existence of soliton as shown in **Figure 14**. The presence of conventional soliton confirms that the laser is operating in anomalous dispersion regime.

The typical pulse train of the passively mode-locked TYDFL at pump power of 1627 mW is shown in **Figure 15** [1]. The observed repetition rate is 11.76 MHz with a pulse-to-pulse

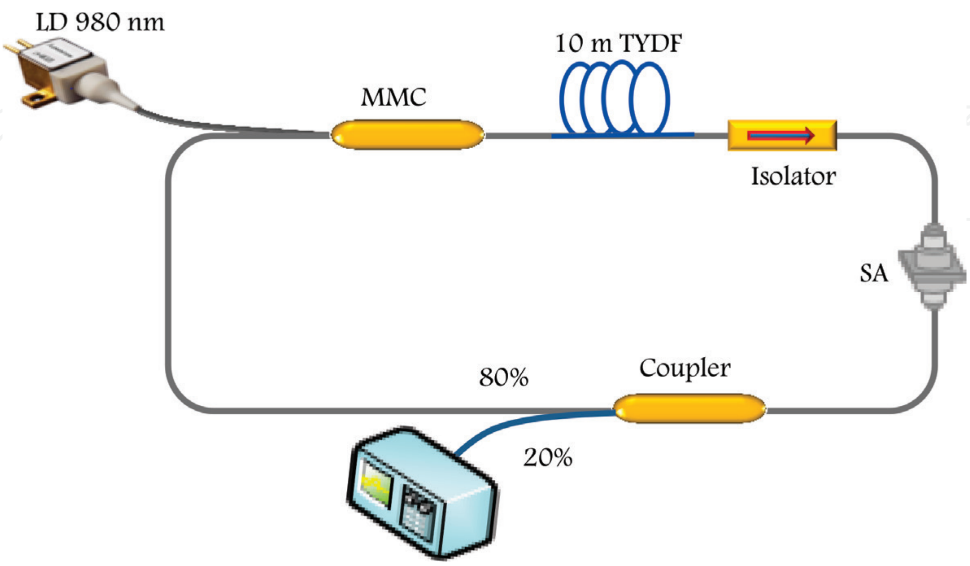

Figure 13. The schematic setup of the modelocked TYDFL employing the fabricated graphene PVA film-based SA.

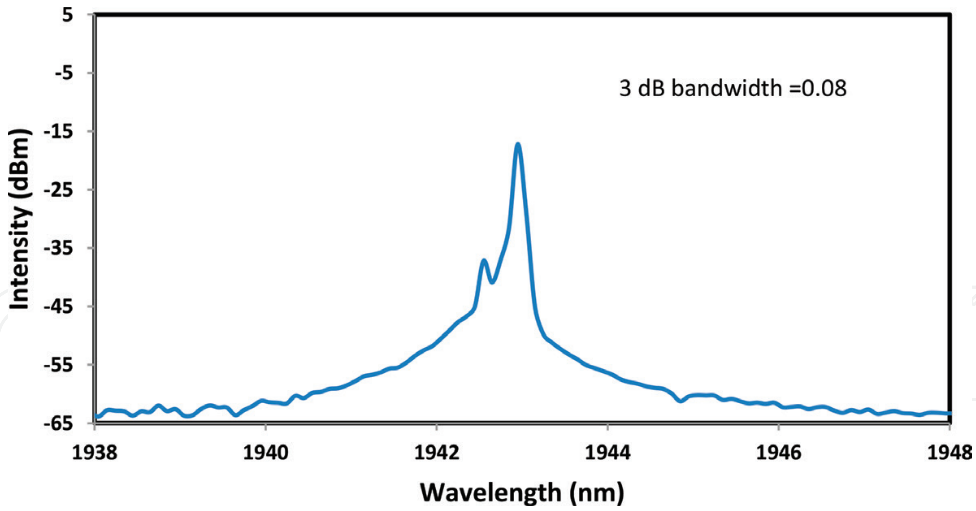

Figure 14. Output spectrum of the modelocked TYDFL.

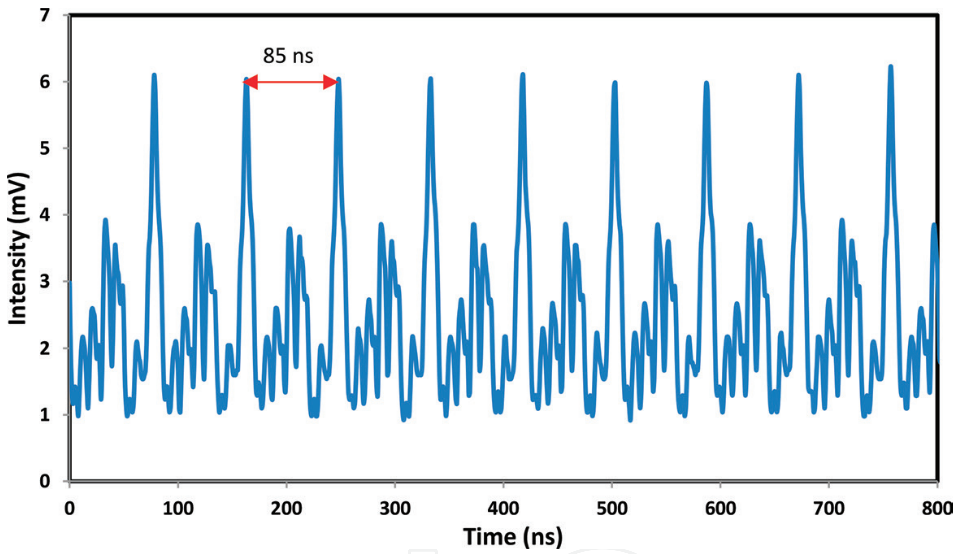

Figure 15. Typical pulse train for the modelocked TYDFL at a pump power of 1627 mW.

separation of 85 ns, which is in accordance with the cavity round trip time of a cavity length of 17 m. Thus, the well dispersed graphene in the PVA film exhibits sufficient saturable absorption for modelocking operation.

Figure 16 shows the repetition rate against the pump power. It is found that the repetition rate remained fixed at 11.76 MHz as the pump power increases from 1487 to 1964 mW [1]. The temporal analysis shows that the pulse width of the laser should be less than 9 ns. It is expected that the actual pulse width is much smaller than 9 ns, but due to the limitations of the oscilloscope resolution, it could not be accurately measured.

The total length of the laser cavity is about 17 m, and it consists of 10 m long TYDF and 7 m long single mode fiber (SMF) [1]. The estimated dispersions for TYDF and SMF are −0.083 and −0.034 ps^2/m, respectively, at 1943 nm. Therefore, it is expected that this modelocked

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fiber laser operates in an anomalous dispersion regime. Moreover, the pulse width can be measured using an autocorrelator or can be calculated mathematically using time bandwidth product (TBP). Since an autocorrelator in the 2-μm range is not available, it is calculated mathematically by considering TBP of about 0.315 for $sech^2$ pulse profile. Since the 3 dB bandwidth of the optical spectrum is about 0.075 nm (5.96 GHz), the minimum possible pulse width is estimated about 52.85 ps. In addition, the repetition rate of the pulsed laser is also calculated by using the formula c/1.5 L, which gives a value of 11.76 MHz. This is in agreement with the observed repetition rate of this laser as shown in **Figure 16**. Single pulse energy is also calculated at various pump powers by using the measured values of output power of the laser. A maximum output power of 14 mW is observed at 1750-mW pump power. A linear increase in pulse energy is observed up to a pump power of 1750 mW, and with further increase in pump power, it decreases because of energy converted to noise as shown in **Figure 17**. The calculated pulse energy is in the range of 756.048–1190.476 pJ.

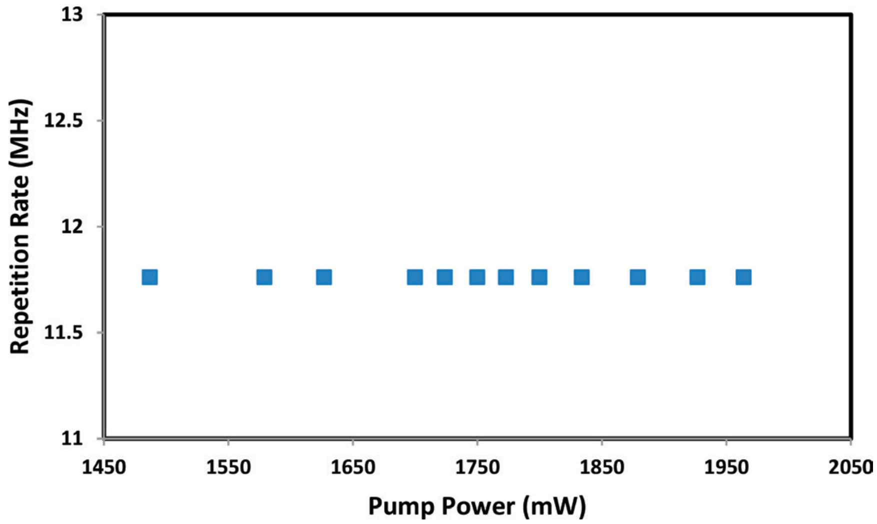

Figure 16. Repetition rate of the modelocked laser at various pump powers.

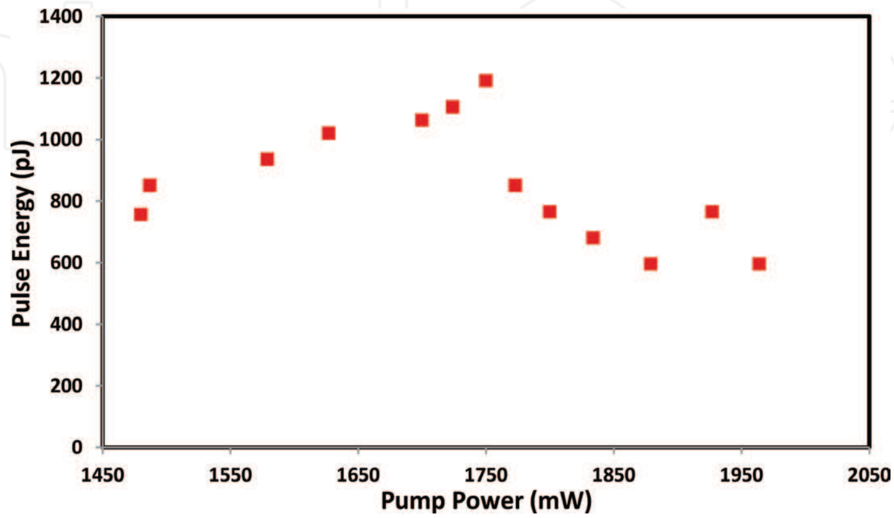

Figure 17. The calculated pulse energy against the input pump power.

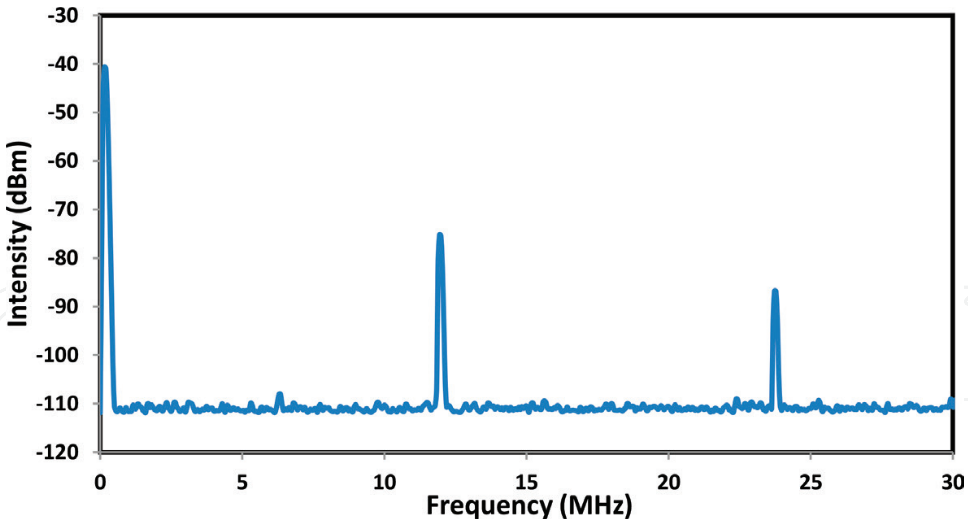

Figure 18. RF spectrum of the modelocked TYDFL.

The RF spectrum of the modelocked pulses is also measured, and the result is shown in **Figure 18**. Its fundamental mode peak locates at a frequency of 11.76 MHz and has an SNR of 36.5 dB, which confirms the stability of the modelocking operation [25].

4. Summary

This chapter describes some of the basic concepts regarding optical fibers and dynamics of Q-switched and modelocked fiber lasers with the help of the existing literature. It includes the description of double clad fiber structure and cladding pump technique. Later, it presents some details about Q-switching and its types. It also includes a detailed description of modelocked lasers, especially, passive modelocked lasers along with a brief introduction of solitons, which are an integral part of the most modelocked fiber lasers. Moreover, examples of Q-switched and modelocked fiber lasers are presented by using double clad Thulium-Ytterbium co-doped fiber. A cladding pump technique is employed with a 980-nm multi-mode laser diode. The Q-switched pulses are produced by using a saturable absorber fabricated with MWCNT-PVA film, while modelocked pulses are generated with the help of graphene-PVA film. The Q-switched laser is produced with a repetition rate in the range 18.8–50.6 kHz, whereas the modelocked laser generates pulses with a repetition rate of 11.76 MHz.

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