Q-switching Zirconia-Erbium-doped Pulsed Fiber Laser with MWCNTs-PEO as Saturable Absorber

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Abstract. Q-switched pulses provide a significant contribution to recent biomedical applications such as laser treatment, medical imaging, biomedical diagnoses and spectroscopy due to high efficiency, compact device, less footprint, flexibility and cost effective. A successful generation of Q-switched pulsed fiber laser by using a homemade fiber of zirconia-based erbium-doped fiber (Zr-EDF) with the utilization multi-walled carbon nanotubes-polyethylene oxide (MWCNTs-PEO) as saturable absorber is reported. The active medium is 1 meter length of Zr-EDF with ~0.6 ps² group delay dispersion (GDD) for overall setup arrangement. At maximum pump power 126 mW, the repetition rate, pulse duration, output power and pulse energy are 17.3 kHz, 7.57 μs, 1.13 mW and 65.03 nJ, respectively.

1. Introduction

Q-switching pulsed fiber lasers are frequently used for developing applications with high energy pulses at low repetition rate. It have been applied in many fields especially in biomedical technologies such as laser treatment, medical imaging, biomedical diagnoses and spectroscopy due to efficiency, compactness, simple, flexible to design, high safety and low cost [1-2]. Recently, Q-switching laser treatment is gained significant attention including removal hair, unwanted brown spots, sun freckles, spider veins, and tattoos as well as skin resurfacing for anti-aging faces [3-6]. The energy pulsed laser releases the pigment into the skin, thus naturally it can reabsorbed and disposed to the body without harm. Medical imaging provides high resolution and deepest in vivo imaging with broadest tuning using laser ultrasound Q-switching together with baby development, tumour progression and electrography that maps elastic properties and stiffness of soft tissue [7-9]. Biomedical diagnosis help so much people especially for early detection such as tumour, cancer and fungal infection [10-11]. Finally spectroscopy where radiation intensity measurement such as toxic compound in blood samples and optical fiber cure monitoring [12-13].
The most popular rare earth material that used as active medium is Erbium for more than 70 years. However, this material is saturated technology and leads to unfavourable effect to collect optical gain, yet the material has outstanding optical properties. It is also stuck at C-band transmission and need help with various complicated structure of experiment to enhance the transmission to the L-band to open wide opportunity for many applications, nowadays. Therefore, a homemade optical fiber of zirconia-yttria-aluminium co-doped erbium-doped (Zr-EDF) with a massive erbium concentration of 4000 ppm is develop to create a simple experiment structure of pulsed generation. Moreover, our aim is to achieve pulsed creation with using a minimum length of active medium to realize a compact devices compared to 2 m to 5 m for normal Erbium fiber.

The development of Q-switching pulsed fiber laser is preferable by using passive method where saturable absorber (SA) as the key element. Commonly, SA is a piece of thin film material whose absorptions decline as increasing irradiances. When useful light go through the SA, the process of molecules absorption become stronger and push significant number of atoms excite to the upper levels. The absorption becomes very small when the ground and excited level from population inversion are almost equivalent, and thus the material of SA is understood to be saturated [14]. An increasing irradiance creates to the further saturating until the material is changed from absorbing to transmitting, and cause the generation of intense and short (in range micro to nanoseconds) pulse duration. In this experiment, the SA used is multi-walled carbon nanotubes (MWCNTs) due to excellent throwbacks that proven in many researches in optical fiber lasers [15-17]. This MWCNTs is then mixed with polyethylene oxide (PEO) polymer compound because it easily dispersed in water and make it simple and easier for the fabrication process.

2. Methodology
The saturable absorber (SA) was named as multi-walled carbon nanotubes - polyethylene oxide (MWCNTs-PEO). About 10 to 20 nm mean diameter and 1to 2 μm length distribution were used for SA preparation. To improve liquid solubility, 400 ml pre-dissolved Sodium Dodecyl Sulphate (SDS) solution (0.01g/ml) is homogenized with 250 mg MWCNTs which were stirred in 50 W ultrasonic cleaner for one hour. Then, the undispersed MWCNTs were detached by using centrifugation (1000 rpm). Next, to form MWCNTs-PEO compound mixture, the dispersed MWCNTs solution was sonicated at about one hour after poured with 10.1 wt % concentration of PEO solution. At last, in room temperature for seven days were used to dry the MWCNTs-PEO compound and successfully to fabricate 50 μm thickness of thin film. The Raman spectrum of the MWCNTs-PEO thin film as shown in Figure 1. The D-band at 1356 cm\(^{-1}\) defines for multi-layer of walls whereas G\(^+\) and G\(^-\) bands were formed at 1579 cm\(^{-1}\) and 2719 cm\(^{-1}\) due to extending tangential carbon-carbon bonds within graphene sheet.

![Raman spectroscopy of MWCNTs-PEO thin film.](image)

**Figure 1.** Raman spectroscopy of MWCNTs-PEO thin film.
Figure 2 demonstrates the arrangement setup of the proposed Zr-EDFL where it consists a 1 m Zr-EDF as active medium, 980/1550 nm wavelength division multiplexer to multiplex the optical signal carrier to the two different wavelengths of 980 nm and 1550 nm in the optical fiber, polarization controller (PC) used to alter the polarization of light, isolator to enable only one direction of light transmission and a coupler 95/5 to divide 5 % to observe the output while the balance will be back to the setup arrangement to produce pulsed fiber laser. While fabricated MWCNTs-PEO SA was cut to a small piece of 2 x 2 mm and inserted between two fiber ferrules with the aid of index-matching gel. Finally, a 3 dB coupler was used to divide each 50 % to observe the output of pulsed fiber laser and optical spectrum by using Oscilloscope (OSC) and optical spectrum analyzer (OSA), respectively. Besides, the 2 m length of Zr-EDF had -56 ps²/km for group velocity dispersion (GVD), the 4 m length of WDM had -38 ps²/km GVD and remaining single mode fiber (SMF) from PC, isolator and coupler had -21 ps²/km GVD. Thus, the total length arrangement setup was 21.7 m and obtained -0.6 ps² group delay dispersion (GDD). This small amount of GDD contributes in normal Q-switching pulsed fiber laser which defines in anomalous dispersion.

![Figure 2. Arrangement setup for Zr-EDFL.](image)

### 3. Results and Discussion

Optical spectrum with and without SA were illustrated in Figure 3 (a). The threshold laser without SA was 57 mW as it expanded from 1540 nm to 1640 nm with the peak power of – 43.4 dBm at 1568.8 nm. Meanwhile the threshold laser with SA was 87.2 mW as the wideband spectrum from 1520 nm to 1640 nm with the peak power of – 30.9 dBm at 1560.8 nm wavelength. The result shows with the aid of SA, the spectrum of fiber laser was able to develop a wideband transmission and sharp lasing due to intra-cavity losses by the added the SA. Moreover, with MWCNTs-PEO SA, a stable and self-stating pulsed train Q-switching was developed at the threshold pump power. The fundamental behind Q-switching theory was the initial loss cavity at the top whereas Q factor was sat at the ground level. As the pump power was slowly increased, the optical gain also increased due to the population inversion in the active medium until the loss is surpassed by the accumulated optical gain. This phenomena activates a high Q factor and develop pulsed fiber laser of Q-Switching.
Figure 3. (a) Optical spectrum. (b) Q-Switching pulse train at pump power of 121 mW.

Figure 4. (a) Repetition rate and pulse width against pump power. (b) Output power and pulse energy against pump power.

Figure 5. Optical signal to noise ratio (OSNR) at repetition rate of 17 kHz.

Figure 3 (b) shows the pulse train of normal Q-switching at pump power of 121 mW which was obtained 15.82 kHz and 7.89 μm for repetition rate and pulse duration. The repetition rate and the pulse duration generation were caused by the active medium of Zr-EDF with high erbium concentration about 4000 ppm. The Zr-EDF is allows to activate population inversion and thus generate optical gain with the increasing pump power. Therefore, with the increasing pump power that varied from 102 mW to 126 mW, the Q-switching repetition rate was consistently increased from 12.94 kHz until 17.30 kHz as illustrated in Figure 4 (a). Meanwhile the pulse duration was inversely proportional with the pump powers started by 10.34 μm until 7.57 μm. The trends of Q-switching were increasing repetition rate and decreasing pulse duration against increment pump power.

Figure 4 (b) shows output power and pulse energy against pump power. The pulse energy was increases as increasing pump power from 33.77 nJ to the highest of 65.03 nJ. This pulse energy was
defined by multiplication of pulse duration with peak power for each pump power increment. Then, the output power increases from 0.44 mW until 1.13 mW at maximum pump power and calculated by multiply the pulse energy with the repetition rate. Both of the calculation was actually affected by the length of Zr-EDF and the thicker layer of MWCNTs-PEO where more atoms stored at energy level were stimulated to create coherent photons of useful light fiber laser. Besides, Figure 5 shows the OSNR at repetition rate of 17 kHz with 67 dB, which translates the high stability of the Q-switching pulsed fiber laser.

Table 1 shows the optical gain characteristics for three different length of Zr-EDF using simple double pass arrangement of experiment. 1 m length shows the highest gain of 40.3 dB compared to 0.5 m and 2 m with only 32.7 dB and 34.0 dB, respectively. Again, 1 m shows the highest and consistent uniform gain of 38.6 dB with a small fluctuation of 1.1 dB from 1525 nm to 1560 nm. Meanwhile 0.5 m and 2 m show lower and almost similar results for uniform gain around 27 dB with specific wavelength as detailed in the table. The fluctuations are also large with 7.2 dB and 32.5 dB for 0.5 m and 2 m that leads to huge loss and noise for real device applications.

Table 2 is the comparison between this Zr-EDF with a commercial Erbium-doped fiber (EDF) which is done by F. Ahmad et. al by using the same length of 1 m active medium and the same SA of multiwall CNT-PEO [16]. Both results are Q-switching pulsed fiber lasers. Zr-EDF shows excellent candidate as alternative optical fiber with a better results for pulse duration, pulse energy and output power. This is with the help of zirconia-yttria-aluminium doping with erbium element that successfully to increase high and uniform optical gain to create a better Q-switched pulsed fiber laser. However, the repetition rate has a slight low due to loss in experiment arrangement.

4. Conclusion
The development Q-switching pulsed fiber laser was successfully using zirconia-yttria-aluminium co-doped erbium-doped fiber with 4000 ppm erbium concentration without any detrimental effect. Together with the use of MWCNTs-PEO saturable absorber, the majority population inversion was achieved and thus provides 17.3 kHz repetition rate, 7.57 μs pulse duration and 65.03 nJ pulse energy at maximum pump power of 126 mW.

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