Indium tin oxide thin film based saturable absorber for Q-switching in C-band region

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Abstract. An indium tin oxide (ITO) thin film based saturable absorber (SA) is proposed and demonstrated for the operation of Q-switched pulse within the C-band region. The ITO was deposited through DC magnetron sputtering method. The thickness of ITO was 86.40 nm and it was measured using F20 Filmetrics. The deposited fiber ferrule was incorporated in an erbium-doped fiber (EDF) laser cavity for generating a stable Q-switching pulse. The generated output pulses displayed a repetition rate that ranged between 16.74 kHz and 38.03 kHz. The shortest pulse width retrieved was 5.78 µs at the maximum pump power of 165.5mW, while the maximum pulse energy recorded was 12.30 nJ. These results show that ITO has the potential to be used for pulsed laser applications.

1. Introduction
The wide range of applications in Q-switched pulse erbium-doped fiber (EDF) lasers such as optical sensing, telecommunications and material processing [1-3] are attracted much attention due to its own characteristics such as high energy pulses. Q-switched fiber laser presents large pulse energy with low repetition rates and pulse width in the range of microsecond to nanosecond different with mode-locking fiber laser that gives low single energy pulse, but it had high repetition rates and shortest pulse width. In order to modulate the Q-factor for the generation of Q-switched pulse fiber laser, an optical modulator is involved where the saturable absorber (SA) is utilized as efficient optical modulator in passive technique, while in actively Q-switched fiber laser that requires external modulator such as acousto-optics modulator [4] and electro-optic modulator [5]. Usually, passively Q-switched fiber laser has simple in structure and more compact in geometry compared with actively Q-switched that bulky in size and expensive in maintenance.

Semiconductor saturable absorber mirror (SESAMs) are known as commercial SA, but the major challenge in this SA has narrow in bandwidth and expensive in fabrication [6]. Therefore, many researchers are still exploring to find suitable SA that has a few characteristics like low-cost, wideband and high performance in generating pulse fiber laser. Carbon nanotubes (CNTs) and graphene had found as novel SAs and widely investigated in the past few years because of their broad absorption range and good compatibility with optical fiber [7-9]. Yet, they revealed the low modulation depth and limited in applications that needed high output pulse fiber laser [10]. Topological insulators (TIs) (Bi₂Se₃, Sb₂Te₃)
[11,12], transition metal dichalcogenide (TMD) (MoS$_2$, WS$_2$) [13,14], black phosphorus [15], metal nanoparticles [16,17] and platinum [18] are other examples of SAs which are generally due to their advantages such as ultrafast carrier dynamics, easy fabrication, low cost and broadband in operation.

A few reports from the researcher have revealed that indium tin oxide (ITO) can be a good candidate to be selected as SA. This is because ITO has a large energy bandgap about 3.7 eV with unique optical and electrical properties where high transmittance in the visible region and good conductivity. Plus, its exhibit large optical nonlinearity [19], a wide region of saturable absorption [20] and lower carrier density and the plasmon frequencies are placed near-infrared region [21]. There are a few techniques for fabricating ITO thin films such as thermal evaporation [22], chemical vapour deposition [23], sol-gel process [24], pulsed laser deposition [25] and magnetron sputtering [26]. However, the magnetron sputtering technique is more reliable compared to other methods because of low cost, simple and high flexibility.

Therefore, ITO thin film-based SA is proposed and established to generate Q-switched pulse in C-band region. The ITO and DC magnetron sputtering were incorporated for the fabrication of SA by inserting SA into fiber cavity design to induce self-forming Q-switched. Self-started Q-switching at central wavelength 1561.0 nm in the EDF laser pumped by a 980 nm laser diode was obtained for a threshold pump power of 65.60 mW. The generated output pulses showed a repetition rate that ranged between 16.74 kHz and 38.03 kHz. The shortest pulse width retrieved was 5.78 µs at the maximum pump power of 165.5 mW, while the maximum pulse energy recorded was 12.30 nJ. From the results, this SA has the potential to be applied in medical, optical sensing and micromachining.

2. ITO as a saturable absorber

DC magnetron sputtering method was utilized for deposition of ITO thin film onto fiber ferrule and glass substrates. A schematic diagram of the sputtering apparatus (The Quorum-Q 150R S) used in the present study is shown in figure 1. The ITO target was inserted at the negative cathode to be sputtered under conditions of glow discharge using DC power supply. The ITO was sputtered onto glass substrates and fiber ferrule on anode with ($9 \times 10^{-2}$ mBar) plasma vacuum and pressure of the environmental argon gas. Table 1 shows the sputtering parameters setting for deposition of ITO. The thickness of sputtered ITO thin film was measured using F20 Filmetrics which resulted in 86.40 nm.

![Figure 1. Schematic diagram of the sputtering apparatus](image)
Table 1: Sputtering parameters for ITO deposition

| Process parameter            | Values               |
|-----------------------------|----------------------|
| Sputtering gas              | Argon                |
| Power supply                | DC                   |
| Current (mA)                | 80                   |
| Sputtering time (s)         | 600                  |
| Temperature                 | Room temperature     |
| Target                      | ITO                  |
| Plasma vacuum (mBar)        | $9 \times 10^{-2}$   |

The EDS analysis and surface morphology of fiber ferrule of the ITO thin film using Hitachi SU1510 scanning electron microscope together with Horiba EMAX energy-dispersive spectrometer (SEM-EDS) are displayed in figure 2. The analysis shows the presence of indium (In) and tin (Sn) element in the area of fiber core. The EDS also detect the present of silicon (Si) and oxygen (O) due to fiber silica made up of silica ($Si_2O$). There are no elements present means no impurities are affected in this area. Figure 3 portrays the transmission loss of ITO measured using an amplified spontaneous emission (ASE) source. The transmission loss was inclusive of the insertion loss between the fiber ferrules and the ITO itself. Within the wavelength range of 1460 nm to 1600 nm, the ITO has a transmission loss of approximately 1.7 dB. Figure 4 shows the UV–VIS NIR spectra of the ITO thin film in (a) absorption (b) transmittance and (c) reflectance in the wavelength range 300 nm -1700 nm for thickness 86.40 nm of ITO thin film. The ITO thin film exhibits a stronger linear absorption in the wavelength approximately 600 nm. The absorbance of ITO thin film is almost zero in the wavelength range of 900 nm -1700 nm. The trends of transmittance and reflectance spectra were almost the same, where almost 90% of ITO thin film was transmitted and reflected. The AFM images with area 3.0 µm × 3.0 µm of ITO thin film is shown in figure 5. It is observed that the root-mean-square surface roughness is 4.10 nm.

Figure 2. EDS and SEM analysis of ITO thin film.
Figure 3. The transmission loss of ITO.

Figure 4. (a) Absorption, (b) transmittance and (c) reflectance of ITO thin film using UV-VIS-NIR spectrophotometer with thickness of 86.40 nm.
3. Experimental Setup

The experimental setup of Q-switched EDF laser using ITO thin film as SA was illustrated in figure 6. The total length of fiber cavity is 11.5 m. A 5 m long of EDF has an absorption coefficient of 6.43 dB/m peak absorption at 1530 nm and 5.09 dB/m absorption at 979 nm as stated in date sheet was utilized as the gain medium. The EDF was pumped via a 980 nm laser diode. To ensure the unidirectional laser operation, an isolator was incorporated in the laser cavity, meanwhile, to vary the polarization state of intracavity light, polarization controllers (PCs) were utilized. The ITO-based SA was inserted in between PCs and isolator. For signal analysis, a 90:10 optical coupler was applied where the 10% port was tapped out from the coupler while 90% port was connected with 1550 nm port of WDM to complete the ring cavity. An Anritsu MS9740A optical spectrum analyser with a 1.0 nm resolution was used to measure the output spectrum of the generated Q-switched pulse EDF laser. Analysing the pulse train properties and radio frequency spectrum of Q-switched pulsed EDF laser make use of the Tektronix MDO3104 oscilloscope together with 5 GHz InGaAs Biased Detector, DET08CFC/M photodetector.

Figure 5. AFM images of ITO thin film.

Figure 6. Schematic diagram of Q-switched pulse EDF laser using ITO thin film as SA.
4. Results and Discussions
Firstly, the fiber laser cavity was investigated without incorporated the ITO thin film-based SA to observe the possibility of self-Q-switching in EDF laser. However, only the continuous wave (CW) emission was observed even the pump power was increased from the oscillation threshold until the maximum of pump power. The angle of polarizations of PCs also was adjusted from 0 to 360 degree to detect the generation of Q-switched. Then, the ITO thin film was inserted into fiber cavity in between PCs and isolator. Q-switching of fiber laser occurred as pump power at 65.60 mW. The initial repetition rate was 16.74 kHz with an average output power of 0.12 mW. The Q-switched spectrum was analysed using optical spectrum analyser by increasing the pump power until 165.60 mW as shown in figure 7. The Q-switched spectrum has a central wavelength of 1561.0 nm with peak power of -3.37 dBm. The unstable Q-switched fiber laser occurred if further increasing the pump power above the 165.60 mW. The performance of Q-switched was investigated at fix wavelength and changing the pump power.

![Figure 7. The optical spectrum of the Q-switched fiber laser](image)

Figure 8 illustrated the pulse train of Q-switched EDF laser in time domain region at a maximum pump power 165.60 mW by using an oscilloscope with a coupled photodetector. The pulse train gives a repetition rate of 38.03 kHz which corresponding to the time interval of 26.29 µs between the two pulses whereby each pulse measured pulse width of 5.78 µs. Hence, the pulse train adequately stable, where the peak of intensity was constant at around 0.020 V and seemed to maintain uniform in shape. This indicates that no significant amplitudes display in this pulse train. The characteristics of Q-switched EDF laser was further investigated by measuring the RF spectrum at a fixed pump power of 165.60 mW. The fundamental frequency was depicted in figure 9 gives the repetition rate of 38.03 kHz with a signal to noise ratio (SNR) of 56.61 dB. The RF spectrum was measured in a 200 Hz resolution bandwidth (RBW) with a span of 200 kHz. These results show the high stability of the Q-switched EDF laser in this study.
Figure 8. A typical pulse train at the pump power 165.50 mW.

Figure 9. RF spectrum with $f = 38.03$ kHz.

The relationship between pulse width and pulse repetition of Q-switched EDF laser with respect to incident pump power portrayed in figure 10. As predictable, the repetition rate displays a rising trend as the pump power increased from 16.74 kHz at a pump power of 65.60 mW to 38.03 kHz at a maximum
pump power of 165.50 mW. Meanwhile, the pulse width shows a descending order trend with responding to increasing pump power as expected. Initially, the pulse width is longer about 7.76 µs at the lower pump power of 65.60 mW and reduces to 5.78 µs at the maximum pump power of 165.60 mW. The shorter pulse width can be obtained by reducing the length of fiber in the cavity laser [27].

![Graph](image)

**Figure 10.** The pulse repetition rate and pulse width versus pump power

The pulse energy and average output power are summarized in figure 11 with respect to incident pump power. Both the pulse energy average and output power increase almost linearly with pump power, as expected. The pulse energy changed from 7.10 nJ to 12.30 nJ, while the average output power rose from 0.12 mW to 0.47 mW.
5. Conclusion
As conclusions, the generation of passively Q-switched pulse within the C-band region was successfully demonstrated and proposed by using ITO thin film as saturable absorber. The DC magnetron sputtering method was employed for the fabrication of saturable absorber due to the simple and easy method. The deposited fiber ferrule was inserted in fiber laser cavity for generation Q-switched pulse. The Q-switched pulse was worked at a central wavelength of 1561.0 nm with peak power of -3.37 dBm, the highest repetition rate at 38.03 kHz, the shortest pulse width at 5.78 µs and SNR at 56.61 dB. The output pulse energy was attained at 165.60 mW pump power with 12.30 nJ. Based on the outcomes from this experiment, the design can be optimized to generate ultrashort pulse fiber laser to be applied in material processing and spectroscopy applications.

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