Q-switched erbium-doped fiber laser employing gold thin film saturable absorber

Y R Yuzaili, Z Zakaria, N U H H Zalkepalii, N A Awang, A A Latif, A H Ali and N N H E Nik Mahmud.

1Optical Fiber Laser Technology (OpFLAT) Focus Group, Department of Physics and Chemistry, Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, Malaysia.
2Department of Physics, Faculty of Science, Universiti Putra Malaysia, Selangor, Malaysia.

zahariah@uthm.edu.my

Abstract. This research demonstrates an erbium-doped fiber laser (EDFL) which was passively Q-switched by gold thin film saturable absorber (SA). A very simple technique was used to fabricate the SA, in which the gold was directly deposited on the fiber end face through DC magnetron sputtering at 120 mA of sputtering current. The SA was then inserted into the single ring cavity and achieved Q-switching at a threshold pump power of 38.8 mW. By gradually increasing the pump power from 38.8 mW to 119.3 mW, the repetition rate increases from 11.34 kHz to 21.72 kHz. Meanwhile, the pulse duration decreases from 13.91 μs to 7.44 μs. The maximum achievable pulse energy was 13.28 nJ. This research further expands the application of gold thin film SA to the field of Q-switched pulsed fiber laser.

1. Introduction
In recent years, the development of fiber lasers has become a research focus as a possible replacement to the bulky solid-state lasers [1]. Fiber lasers can be developed into pulsed fiber lasers, typically known as Q-switched and mode-locked fiber lasers. These two operations are distinguished by their repetition rates, where kilohertz for Q-switching while megahertz for mode-locking. Q-switching can be achieved by modulating the Q-factor of the laser resonator and its frequency depends on the input power [2]. Meanwhile, mode-locking is achieved by controlling the dispersion and nonlinearity inside the cavity and the repetition rate is influenced by the total cavity length [3].

Q-switched fiber lasers are widely used in the applications that require slower pulse rates but high output powers [4-8], such as 3D optical data storage, tattoo removal and hair removal [9-11]. It emits energetic pulse through active [12] or passive [13] Q-switching techniques. In active Q-switching and mode-locking, some external bulk equipment such as acousto-optics and electro-optics devices are needed to control the absorption wavelength, saturation energy and recovery time. Thus, the passive technique is more preferable since it is simpler, compact and easy to implement.

Passive Q-switching is realized by employing a saturable absorber (SA) inside the laser cavity. The SA plays a vital role in determining the Q-switching performances. Till date, there are several types of saturable absorber have been investigated including carbon nanotubes (CNT) [14-15], graphene [16-18], transition metal dichalcogenides (TMD) such as molybdenum disulphide (MoS2) [19] and molybdenum diselenide (MoSe2) [20] and topological insulators including bismuth selenide [21]. Yet,
only little efforts have been made to discover the potential of metal as saturable absorbers. Recently, platinum has been successfully discovered as saturable absorber to generate Q-switching at 1.5 μm of operating wavelength in our previous work [22]. Ahmad et. al [23] also reported a similar kind of work but using carbon platinum SA on side-polished fiber. Other than platinum, other transition metals such as silver and gold have been explored as Q-switcher due to their unique optical properties in nonlinear optical communications [24]. Besides that, these metals have large third-order nonlinearity and broad absorption governed by localized surface plasmon resonance (SPR) [25].

In this paper, a gold thin film is utilized as SA to induce Q-switching in C-band region. The SA is fabricated by depositing gold on fiber end face via sputtering. It does not need any other materials to act as buffer such as PVA as this technique comprises direct deposition.

2. Experimental details

2.1. Preparation and characterization of gold thin film SA

The fabrication of the gold thin film SA was fully depended on the sputter deposition method. It involves two main processes which are vacuum and deposition. Before depositing the gold target on the fiber end face (substrate), the chamber must be ready in a full vacuum condition. This to allow electrons to strike the Au target in order to eject gold particles. At 5x10^{-3} mBar of vacuum pressure and 120 mA of sputtering current, the deposition process took place. The gold deposited surface is shown in Figure 1(a). The surface was analyzed by SEM and EDS as shown in Figure 1(b) and (c), to ensure the fiber core region was fully covered by the gold thin film. There are 3 peaks of Au element in the EDS graph, confirming the existence of Au at the core area.

![Figure 1](image)

**Figure 1.** (a) Gold thin film on fiber end face (b) SEM image (c) EDS analysis.
2.2. Q-switched fiber laser setup
The experimental setup of the Q-switched fiber laser is illustrated in Figure 2. The setup was constructed as a single ring cavity, consisted of a 5 m long erbium-doped fiber (EDF) as the gain medium, pumped by a 980 nm laser diode (II-VI LC96Z600-74) via 980/1550 nm wavelength division multiplexer (WDM). The absorption coefficient of the EDF is very low, which is only about 5.09 dB/m. To ensure a unidirectional propagation of light, an isolator was inserted into the cavity. The gold thin film SA was employed to realize passive Q-switching. A 90/10 optical coupler was used to extract 10% of the laser output for data collection while leaving the other 90% to oscillate inside the cavity. The 10% output was tapped by a 50/50 optical coupler, in which the 50% was channeled to the optical spectrum analyzer (OSA, Anritsu MS 9740A) while the other half to the oscilloscope (OSC, Tektronix MDO 3104). A 5 GHz photodetector (PD, Thorlabs DET08CFC/M) was preintegrated with the oscilloscope to detect the pulses. The oscilloscope used in this experiment is able to measure both the time and frequency domain.

![Figure 2. Schematic setup of the Q-switched fiber laser employing gold thin film SA.](image)

3. Results and discussions
The experiment started by varying the pump power to determine the threshold of the Q-switching operation. If the energy inside the cavity reaches a certain saturable value, the Q-switching will occur. This is determined by the SA’s recovery time. In this experiment, the Q-switching started to appear at a pump power of 38.8 mW. By further increasing the pump power, the pulse became unstable and disappeared after reaching 119.3 mW. This is because the SA was over-saturated at high incident intensity. Figure 3(a) shows the Q-switched optical spectrum at 119.3 mW of pump power. The peak power and the central wavelength are -7.52 dBm and 1562.4 nm, respectively. The pulse train, which was also taken at the same pump power, is shown in Figure 3(b). The pulse period is measured to be around 46.04 μs, consistent to the repetition rate of 21.72 kHz. The corresponding pulse duration is about 7.44 μs.
Figure 3. Q-switched fiber laser characteristics at pump power of 119.3 mW. (a) Optical spectrum from the OSA (b) Pulse train from the OSC

The performance of the Q-switched pulses are analyzed at various pump power, presented in Figure 4(a) and (b). The dependence of repetition rate and pulse duration on pump power is illustrated in Figure 4(a). It can be seen that the pulse repetition rate (purple dots) escalated from 11.34 kHz to 12.72 kHz as the pump power was increased from 38.8 mW to 119.3 mW. On the other hand, the pulse duration (orange squares) shrunk from 13.91 μs to 7.44 μs within the same range of pump power variations, representing typical Q-switching characteristics. Figure 4(b) shows the trends of average output power (purple triangles) and pulse energy (orange diamonds) which both were increasing with the pump increment. The pulse energy increased from 3.88 nJ to 13.28 nJ, were obtained by dividing the average output power with the pulse repetition rate at each pump power. The pulse energy signifies the total energy available in a single pulse.

Figure 4. (a) The dependence of pulse repetition rate and pulse duration on pump power (b) Average output power and pulse energy as a function of pump power

Figure 5 indicates the radio frequency (RF) spectra of the generated pulse, taken at 200 Hz of resolution bandwidth. There are 9 harmonics lining up over 200 kHz span. It can be seen that the fundamental frequency peaks at 21.3 kHz, which corresponds well with the measured repetition rate at the same pump power. A high signal-to-noise (SNR) value of about 62.41 dB was obtained, signifying a highly stable pulse.
4. Conclusion
A passively Q-switched EDFL using gold thin film SA is demonstrated. The SA was prepared through direct deposition of gold on the end surface of a standard FC/PC fiber connector by using a DC magnetron sputter coater. The proposed Q-switched EDFL operates at 1562.4 nm wavelength. The highest repetition rate and pulse energy are 21.72 kHz and 13.28 nJ, respectively. Meanwhile, the smallest pulse duration obtained is 7.44 µs. The results suggest that the gold thin film can be a promising SA for pulsed fiber laser applications.

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