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Silver nanoparticle-film based saturable absorber for passively Q-switched erbium-doped fiber laser (EDFL) in ring cavity configuration

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Abstract
We report a passive Q-switched erbium-doped fiber laser based on silver (Ag) nanoparticle thin-film saturable absorber (SA). The thin film was sandwiched between two fiber ferrules, which offer flexibility and easy integration into the ring cavity. Self-started and stable Q-switching is achieved at a central wavelength of 1558.7 nm; within the C-band region. The repetition rate and pulse duration shows a typical Q-switched laser profile as we increase the pump power; the repetition rate increases from 19.471 – 74.074 kHz while pulse duration decreases from 8.88 – 3.2 µs. A signal-to-noise ratio value of 35 dB was obtained at 100 mW pump power. By using a balanced twin-detector method, the modulation depth and saturation intensity of the Ag nanoparticle thin film were measured to be 31.6% and 0.54 MW cm⁻² respectively. This result offers another alternative to the existing SA materials.

Keywords: Q-switching, fiber laser, silver nanoparticle-film, saturable absorber, erbium-doped fiber laser

(Some figures may appear in colour only in the online journal)

1. Introduction

Q-switched lasers at a wavelength of 1.5 µs holds several highly potential and interesting field applications such as micromachining, telecommunication, medicine, fiber optical sensing, remote sensing, range finding, material processing, biomedical diagnostics and metrology [1–7]. Q-switching is a simple modulation method of the Q-factor of a laser oscillator to generate higher pulse energy and peak power. Q-switched fiber lasers can be generated by active or passive means. Generally, active modulation requires electrically powered equipment such as electro-optics and acoustic-optics modulators, which can produce high loss in the cavity as well as add more complexity compared to the passive modulation [8]. There are many methods to achieve passively Q-switched laser, such as using nonlinear polarization rotation (NPR), transition metal-doped bulk crystals [9], semiconductor saturable absorber mirrors (SESAMs) [10], single-walled carbon nanotubes (SWCNT) [11, 12] and graphene [13, 14] saturable absorbers (SA). Passive modulation using SA is more attractive due to its simplicity as opposed to the active method.

Over the past few years, the success of graphene SA in generating passive Q-switched and mode-locked lasers has attracted significant research on 2D materials [15]. Amongst the 2D materials examined are transition metal dichalcogenides (TMDs) such as molybdenum disulfide (MoS₂) [16],...
molybdenum diselenide (MoSe₂) [17], tungsten disulfide (WS₂) and tungsten diselenide (WSe₂) [17–20], a topological insulator such as bismuth diselenide (Bi₂Se₃) [21, 22] and black phosphorus (BP) [23–25]. Of these materials, Bi₂Se₃ has the highest performance, with a modulation depth of approximately 95.3% and a repetition rate and pulse width of 1.21 MHz and 1.21 ps, respectively, making it by far the highest performing material as an SA. Ag nanoparticles and BP both also perform admirably, with modulation depths of approximately 18.5% as well as repetition rates of about 17.9–59.5 kHz and 7.0–15.8 kHz respectively. Similarly, MoS₂ and MoSe₂ also can perform as SAs, although at much lower performance parameters compared to the other aforementioned SA materials.

It must be noted, however, that while the performance characteristics of each material vary greatly, consideration must also be given to other aspects of the SA, such as ease of fabrication and cost. In this sense, Ag nanoparticles hold the advantage, as they are the most easily obtainable and cost-effective candidate of those listed in table 1.

Very recently, a new type of nanomaterial such as metal nanoparticles such as gold and silver nanoparticles (SNPs) has garnered great interest amongst scientific researchers because of their unique optical properties such as large third-order nonlinearity, broadband surface plasmon resonance (SPR) absorption and fast response time [26–29]. However, more research focuses on gold-based SAs rather than Ag-based SAs. Nanostructures of SNPs show interesting optical properties, which are also present in molecules and bulk metals. They exhibit absorption in the visible light region due to surface-plasmon oscillation modes of conducting electrons, which are coupled through the surface to the external electromagnetic fields. Furthermore, silver has the highest electrical and thermal conductivities among metals [30–32]. The band gap of bulk silver is zero eV and 2.6 eV in silver dimer particles [32, 33]. Hao et al deposited SNPs at the end of a fiber ferrule using a photodeposition technique to create a fiber-compatible SA. Their self-started Q-switched fiber laser operated in the C-band region with their modulation depth calculated to be approximately 18.5% [26].

In this paper, a passively Q-switched fiber laser based on SNP thin-film SA is demonstrated. The SA was sandwiched between two fiber ferrules, which offer simplicity, flexibility and easy integration into the laser cavity. The results show a self-started, typical Q-switched fiber laser profile at 1558.7 nm central wavelength. As the pump power was increased from 20–220 mW, the repetition rate also increased from 19.471–74.074 kHz, while the pulse duration decreased from 19.417–3.2 μs.

### 2. Preparation and characterization of SNPs-film SA

#### 2.1. Preparation of the Ag SA

In this experiment, the Ag nanostructures used were obtained from Sigma Aldrich (Malaysia) Sdn. Bhd. and used without further purification. The sizes of the nanostructures estimated by particle size distribution were in the range of 20–50 nm. The performance of Ag as an SA was tested by embedding it into a polymer methyltrimethoxysilane (MTMS)-based thin film. The thin film was developed by mixing the Ag powder (5% wt) into a mixture of silane and ethanol. The ratio of MTMS and ethanol was 1:1 by weight. The mixture was then ultrasonicated for 15 min before the upper part of the mixture was separated and put into another beaker. Subsequently, sulfuric acid (10% wt) was added into the beaker and ultrasonicated for 5 min. The mixture was then poured into a plastic mould and dried in 27 °C environment for 3 d. The thickness of the thin film was measured to be 0.15 ± 0.01 mm.

Figure 1 shows the Raman spectra of the thin film without and with SNPs, respectively. As can be seen in figure 1(a), the dominant peaks of 248, 2913 and 2979 cm⁻¹ contribute to the characteristics of the host material, which is MTMS. These results are in good agreement with those studies of similar compounds [34]. However, figure 1(b) shows the Raman spectrum after the SNPs were added to the host material. It can be seen that the Raman spectrum of added SNPs displays a group of strong bands in the region of 1300–1700 cm⁻¹. There are two well-defined prominent peaks located at 1385 and 1588 cm⁻¹ generally assigned by the SNPs. The result is in good agreement with the reported work by Ghinwa et al [32]. Other peaks are assigned to the characteristics of the host material (MTMS). Therefore, it is confirmed that the SNPs are present in the thin film.

#### 2.2. Nonlinear absorption properties of Ag-film SA

The investigation of the nonlinear absorption properties of SNPs thin-film SA was performed using the balanced twin-detector measurement method. The mode-locked pulse seed has a central wavelength of 1560 nm with a repetition rate of 27.7 MHz and pulse duration of 0.53 ps; which was subsequently connected to the low-dispersion optical amplifier, optical attenuator and 50/50 output coupler. After the optical amplifier, the pulse duration from the pulse seed expands to 0.96 ps. The output power was measured using two identical optical power meters (OPMs) connected with a 50/50 output

| Table 1. Comparison of performance of various SA candidates. |
|----------------|----------------|----------------|----------------|----------------|----------------|
| SA             | Modulation depth (%) | Saturation intensity (MW cm⁻²) | Repetition rate (kHz) | Pulse width (μs) | Maximum pulse energy (nJ) | Ref |
| Ag             | 18.5             | —               | 17.9–58.5        | 11.4–2.4        | 132             | [26] |
| MoS₂           | 9.3              | 15.9            | 7.0 × 10³        | 8.0 × 10⁻⁶      | N/A             | [16] |
| Bi₂Te₃         | 95.3             | 480             | 1.2 × 10³        | 1.21 × 10⁻⁶     | N/A             | [22] |
| MoSe₂          | 4.7              | 3.4             | 26.5–35.4        | 18.9–9.2        | 825             | [17] |
| BP             | 18.6             | 10.74           | 7.0–15.8         | 39.8–10.3       | 94.3            | [24] |
coupler. Both OPMs were calibrated before the beginning of the measurement. Later, the recorded data were fitted using equation (1).

\[
\alpha(I) = \frac{\alpha_s}{1 + \frac{I}{I_s}} + \alpha_{ns}
\]  

(1)

where \(\alpha(I)\) is absorption, \(I\) is intensity, \(I_s\) is saturation intensity, \(\alpha_s\) and \(\alpha_{ns}\) are the modulation depth and non-saturable losses, respectively. As shown in figure 2(a), the saturation intensity and modulation depth were determined to be 0.54 MW cm\(^{-2}\) and 31.6\%, respectively. The modulation depth is 31.6\%, higher than those reported for MoS\(_2\) [17], MoSe\(_2\) [18], BP [24] and SNPs [26]. This proves that the prepared SNP thin-film SA has good stability, as larger modulation depth indicates higher stability of \(Q\)-switching operation [22]. It must be noted that the saturation intensity for the SNP film is rather low, as different SA materials such as Bi\(_2\)Te\(_3\) [6] have a saturable intensity of 58.59 MW cm\(^{-2}\). However, this value is not particularly unusual, as SA materials such as MoS\(_2\) [7] on the other hand, have even lower saturation intensities of only 0.43 MW cm\(^{-2}\). The broadband absorption of the SNP film in the C-band region from 1200–1600nm is shown in figure 2(b), where the insertion loss is measured to be approximately 7 dB.

3. Experimental setup

Figure 3 shows the experimental setup for passively \(Q\)-switched fiber laser based on SNP thin-film SA. The ring cavity laser is pumped by a 974 nm laser diode (LD) with 260 mW maximum pump power through a 980/1550 nm wavelength division multiplexer (WDM). A 3 m long erbium doped fiber (Fibercore M-12(980/125) cut-off wavelength at 911 nm, peak absorption at 18.06 dB m\(^{-1}\), mode field diameter of 6.6 \(\mu\)m) is used as the gain medium. The SNP thin-film SA is incorporated into the ring cavity, which acts as a passive \(Q\)-switcher. An isolator was integrated into the ring cavity to ensure the unidirectional light propagation. The output from the laser cavity is extracted by a 90:10 optical coupler, further split by a 50:50 optical coupler to take two measurements simultaneously. An optical spectrum analyzer (YOKOGAWA AQ6370C) and oscilloscope (YOKOGAWA DLM2054) were used simultaneously to measure for optical spectrum and pulse train. During the experiment, output powers were also
Figure 2. Nonlinear optical absorption properties of Ag-SA: (a) modulation depth and (b) broadband absorption from 1200–1600 nm with the C-band region highlighted.

Figure 3. The schematic diagram of a passive $Q$-switched fiber laser based on SNP thin-film SA.
measured by swapping one of the measuring devices to an OPM.

4. Results and discussion

The lasing threshold of the laser cavity is determined at 8.7 mW while self-starting Q-switched operation was attained at 20 mW pump power. Q-switched operation was observed to increase when pump power was increased from 20–260 mW. Below and beyond this range, no Q-switched operation was detected. Examples of pulse train at 50 mW (31.75 kHz), 80 mW (34.48 kHz), 90 mW (37.735 kHz) and 150 mW (48.7805 kHz) are shown in figure 4. This phenomenon (repetition rate increments alongside pump power increments) is a common characteristic of passive Q-switching operation [1].

Figures 5(a)–(d) display examples of optical spectrum profile, pulse train, single-pulse profile and radio-frequency (RF) spectrum at 100 mW pump power, respectively. The central wavelength of the optical spectrum is 1558.7 nm, which is situated in the C-band region. The distance between pulses is 25.51 µs (corresponds to 39.21 kHz repetition rate). A single pulse profile at this pump power has a full width at half maximum (FWHM) of 4.02 µs. An RF spectrum analyzer with 300 Hz resolution bandwidth (RBW) indicates that the Q-switch has a signal-to-noise ratio (SNR) value of ~35 dB, which indicates good pulse train stability of the Q-switching operation.

The pulse repetition rate, pulse duration, pulse energy, peak power and output power are plotted against pump power as presented in figures 6(a)–(c). Figure 6(a) shows the responses of repetition rate and pulse duration against pump power. When the pump power was increased from 20–260 mW, the repetition rate increased in an almost linear fashion from 19.417–74.074 kHz. In contrast, pulse duration becomes narrower, shortening from 8.88–3.2 µs. This is a typical characteristic of Q-switching operation. As pump power increases, more power circulates inside the laser cavity, thus, saturating the SA faster. From figure 6(a), it can be seen that the SA become almost saturated because of the smaller changes of pulse width from 150–260 mW. This phenomenon can be related to the modulation depth and the cavity length of the laser.

Based on the measurements displayed in figure 6(a) as well as the output power measurement from figure 6(b), peak power and pulse energy as functions of pump power can be calculated, as are shown in figure 6(c). The maximum pulse energy and peak power are 8.17 nJ and 2.55 mW, respectively, attainable at 260 mW pump power. Figure 6(b) illustrates the relationship between the output power and pump power. The output power increases from 0.0349–0.605 mW when the pump power increases from 20–260 mW. From figure 6(c), the peak power increases gradually from 0.202–2.55 mW. On the other hand, the pulse energy also rises from 1.7898–8.17 nJ.

In summary, we have demonstrated a passively Q-switched fiber laser based on SNP thin film. The SA was placed between the two fiber ferrules with the benefits of simplicity, flexibility and easy integration into a laser ring cavity. Self-started and stable Q-switched laser was achieved in the C-band region (central wavelength of 1558.7 nm). As we increase the pump power, the repetition rate increases from 19.417–74.074 kHz.
and the pulse duration decreased from 8.8–3.2 µs. An SNR value of 35 dB was obtained when the pump power was fixed at 100 mW. The SA’s modulation depth and saturation intensity were measured to be 31.6% and 0.54 MW cm$^{-2}$ respectively. Based on our results, our experiment shows that the SNP thin-film SA is suitable for generating passive $Q$-switching in a fiber laser system, which can be employed in many applications.

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