Q-switched Ytterbium doped fibre laser using gold nanoparticles saturable absorber fabricated by electron beam deposition

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ABSTRACT

A stable Q-switched Ytterbium doped fibre laser (YDFL) is demonstrated based on ring cavity by incorporating gold nanoparticles (AuNPs) based saturable absorber (SA). The SA is fabricated by depositing AuNPs onto polyvinyl alcohol thin-film surface using electron beam deposition technique. The proposed laser generates Q-switching pulses train as the pump power is increased beyond 61.1 mW. The laser operates at 1063.5 nm with the maximum repetition rate of 61.88 kHz and the thinnest pulse width of 4.23 μs are recorded at the 87.3 mW pump power. The output power increases linearly up to 3.14 mW, while the pulse energy varies from 10.55 nJ to 50.74 nJ as the pump power increased. Meanwhile, the maximum peak power of 12 mW is obtained at the pump power of 87.3 mW.

1. Introduction

Recently, the passively Q-switched pulsed lasers have been widely studied and demonstrated due to their advantages in terms of compactness, simplicity, and easy implementation. In addition, they have potential applications in many areas ranging from medical, material processing, communication to sensing. On the other hand, noble metals, such as gold (Au), copper (Cu), and platinum (Pt) have also drawn great attentions for various photonics applications, due to their fascinating optical features, especially in nanoparticles (NPs) form. The most highlighted features are a large third-order nonlinearity, broad absorption governed by localized surface plasmon resonance (SPR), and fast response times of a few picoseconds.

To date, various materials and methods have been proposed to develop an efficient saturable absorber (SA) for pulsed laser generation. Many works have been reported on Q-switching and mode-locking pulses generations using various SAs based on 2D nanomaterials such as graphene [1–3], transition metal dichalcogenides (TMDs) [4–6], topological insulator (TIs) [7–9], and black phosphorus (BP) [10–14]. Few-layer MXene [15] and Bismuthene [16] were also demonstrated for mode-locking application. These materials exploit bandgap size to indicate operating wavelength regime based on the absorption profile. In contrast, metal-based NPs deploy the advantage of wideband saturable absorption stimulated by SPR at wide wavelength region between visible and infrared [17]. This allow the material to function as SA for pulsed laser generation at wideband wavelength operation. In addition, metal-based NPs such as gold and silver possess a larger third-order nonlinearity compared to other materials such as graphene or carbon nanotubes [17]. Both SPR and nonlinear characteristics determine the absorption profile for light propagation through metal-based...
SA, which is important for pulsed laser generation. The strong third order nonlinearity was expected to suppress mode competition in the gain medium, which in turn can improve the Q-switching performance of the laser.

A few methods were carried out by several researchers in employing gold nanomaterials to generate a pulsed laser. Wu et al. [18] reported a Q-switched pulse generation in visible wavelength region of 635 nm using gold nanoparticles (AuNP). The NPs were prepared by using a hydrochloroauric acid (HAuCl₄) synthetization method and the proposed laser generated pulses train with the highest repetition rate of 546.4 kHz, the lowest pulse width of 235 ns, and the maximum output power of 11.1 mW. The saturable absorption of the NPs was stated at about 11%, signifying the potentiality to serve as SA. Kang et al. [19] reported a passive Q-switched erbium doped fibre laser (EDFL) by using gold nanostars (GNSs) SA. The GNSs SA was reported to have modulation depth of approximately 6.5% and produced laser with repetition rate tunable from 10 to 17 kHz, and the maximum pulse energy of 0.12 μJ. Unfortunately, the GNSs fabrication process is not provided in the article. Both cited articles reveal positive results on Q-switching pulses generation in various regions.

In this paper, a stable Q-switched Ytterbium-doped fibre laser (YDFL) is proposed and demonstrated using AuNP as a passive SA. The laser operates in 1 μm region with the maximum peak power and pulse energy of 12 mW and 50.74 nJ, respectively. Previously, AuNP SA was employed to generate Q-switched EDFL [20], which proves that this SA can work in a wide-band wavelength region.

2. Fabrication and characterization of AuNP thin-film SA

The pure polyvinyl alcohol (PVA) thin-film was used as a host polymer owing to its low optical absorption at the laser operating
wavelength. In addition, it is robust, flexible and can be simply integrated in between fibre ferrules. In preparing PVA film, 1 g of PVA powder was mixed into 120 ml of de-ionized (DI) water. The mixture was stirred at temperature of 145 °C until the powder dissolve completely. Subsequently, 5 ml of PVA solution was poured and left dry in a petri dish under room temperature for 3 days. The PVA thin-film with a thickness of about 30 μm was then coated with AuNPs using electron beam (E-beam) deposition technique as illustrated in Fig. 1.

This AuNPs coating involves two main processes; vacuum and deposition process. Vacuum process works as preliminary process, to generate pressure inside the deposition chamber to form a full vacuum condition. At this condition, electrons can freely propagate in the chamber, allowing it to strike the target material. When the chamber reaches the pressure level of $1 \times 10^{-4}$ mbar or lower, deposition process starts. It begins by supplying the tungsten filament with current flow to generate electrons. These electrons hit the target material and transforms the atoms from the target material into a vapor state. At desired deposition rate (thickness / time), the shutter is open to achieve an approximately 16 nm thickness of AuNP coating.

Fig. 2 shows substance composition of the fabricated AuNP thin-film SA, which was obtained from energy-dispersive x-ray (EDX) analysis. The peak of Au at $\approx 2.2$ KeV indicates that the Au element has the majority weight percentage of about 41.97%. Other
elements such as carbon (C) and oxygen (O) has a weight percentage of 35.38% and 11.64%, respectively. The carbon and oxygen elements on the film most probably originated from the PVA, which was formulated by \((\text{C}_2\text{H}_4\text{O})_n\). Inset of Fig. 2 shows the field-emission scanning electron microscope (FESEM) image, which indicates a homogenous distribution of the AuNP on the film surface.

Fig. 3 illustrates the nonlinear transmission analysis of AuNP in determining the modulation depth of the SA. The nonlinear transmission measurement was performed by launching a mode-locked laser with a pulse width of 3 ps and repetition rate of 1.0 MHz on the SA film. From the data, the modulation depth is measured to be about 13% with non-saturable absorption of 37%, with saturation intensity of 5.7 MW/cm². Due to the surface plasmonic resonance, Au nanospheres also provide a broadband linear absorption band covering the range from visible wavelength band to 2500 nm. Furthermore, AuNPs film has a large third-order nonlinear coefficient of \(\sim 10^{-6}\) esu [21], one order higher than the third-order nonlinear coefficient of graphene \(\sim 10^{-7}\) esu [22]. This makes the AuNPs based SA much easier to start Q-switching operation. Based on the linear absorption range of the AuNPs, the SA is expected to work in other wavelengths such as 1.5- and 2-micron regions.

3. Configuration of the Q-switched YDFL

The fabricated SA was added in the Ytterbium doped fibre laser (YDFL) cavity for realizing a Q-switching pulse train by exploiting the absorption property of the AuNP thin-film SA, as described in Fig. 4. The proposed YDFL ring cavity employs a 2 m long Ytterbium-doped fiber (YDF) as an active gain medium, which was forward pumped by a 980 nm single-mode laser source via a 980/1064 nm wavelength division multiplexer (WDM). The YDF has an ion concentration of 2000 ppm with numerical aperture (NA) of 0.24. A polarization independent optical isolator was included in the cavity to ensure unidirectional light propagation in the cavity. A 10-dB optical coupler taps 10% of the laser output for data collection, while remaining 90% left oscillating inside the cavity. The
AuNP thin-film SA was employed by sandwiching a tiny piece of the SA film between two fibre ferrules to form a fibre compatible device. The insertion loss of the SA device was measured to be around 4.5 dB. An optical spectrum analyser (OSA) with a resolution of 0.07 nm was used to display the optical laser spectrum. A broadband power meter with power detector measures the laser output power. The 350 MHz digital oscilloscope analyses the temporal performance of the pulse, while the radio frequency spectrum analyser (RFSA) measures the pulses train in frequency domain. A 2 GHz photodetector with rise/fall time of 60 ps was pre-integrated with the oscilloscope and RFSA to interpret the output pulses of the laser.

4. Result and discussion

A stable Q-switched pulsed YDFL begins to establish as the pump power reach the laser threshold of 61.1 mW. It can be further observed by increasing the pump power to 87.4 mW. When further increase beyond 87.4 mW, an unstable Q-switched state was observed due to over-saturated SA at high incident intensity. We increased the pump power up to the maximum of 200 mW, but the
Q-switching pulses has been diminished. As we reduced back the pump power below 87.4 mW, the Q-switching pulses are recovered, thus the damage threshold was higher than that value (200 mW). In absence of the SA in the cavity, no pulse is generated, and only a typical CW laser can be observed. The Q-switching occurs when the cavity energy reaches a certain saturable value, determined by

Table 1
Performance comparison of various Q-switched YDFLs.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Pump Power (mW)</th>
<th>Max. Output Power (mW)</th>
<th>Wavelength (nm)</th>
<th>Repetition Rate (kHz)</th>
<th>Pulse Width (μs)</th>
<th>Max. Pulse Energy (nJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>..</td>
<td>61.1–87.4</td>
<td>3.14</td>
<td>1063.5</td>
<td>49.31–61.88</td>
<td>4.23–8.56</td>
<td>50.74</td>
</tr>
<tr>
<td>[23]</td>
<td>109–206</td>
<td>4.8</td>
<td>1069</td>
<td>40–60.2</td>
<td>2.87–4.9</td>
<td>80.7</td>
</tr>
<tr>
<td>[24]</td>
<td>80–330</td>
<td>2.85</td>
<td>1048.9 &amp; 1053.3</td>
<td>25.9–73.4</td>
<td>3.4–11.6</td>
<td>38.8</td>
</tr>
<tr>
<td>[9]</td>
<td>75.4–96.2</td>
<td>10.9</td>
<td>1070.2</td>
<td>24.4–55</td>
<td>6.6–9.8</td>
<td>252.6</td>
</tr>
</tbody>
</table>

Fig. 8. Power and energy performances for the Q-switched YDFL under various pump power.

Fig. 9. Repetition rate and pulse width performances for the Q-switched YDFL under various pump power.

Q-switching pulses has been diminished. As we reduced back the pump power below 87.4 mW, the Q-switching pulses are recovered, thus the damage threshold was higher than that value (200 mW). In absence of the SA in the cavity, no pulse is generated, and only a typical CW laser can be observed. The Q-switching occurs when the cavity energy reaches a certain saturable value, determined by
the recovery time of the material used in SA. The SA will absorb photons to excite electrons up to conduction state. When all the conduction state space is occupied by the electrons excited by those photons, the SA will reach it saturable condition, allowing formation of the pulsed laser.

Fig. 5 illustrate the temporal performances of the Q-switched pulsed laser taken at three different pump powers of 61.1 mW, 74.3 mW, and 87.4 mW for threshold, median, and maximum, respectively. As shown, the pulse train has become narrower in increment of pump power. At maximum accessible pump power, the pulse train has a narrow pulse width of 4.23 μs. The pulse period is measured to be around 16.16 μs, consistent to the repetition rate of 61.88 kHz. As seen, the pulse train has a stable amplitude over 600 μs, indicating the stability of the generated Q-switched pulsed laser. The stability of the pulse can further observe in frequency domain as presented in Fig. 6.

As shown, there are 10 harmonics lining up over the 700 kHz span and the frequency of the fundamental peak is 61.88 kHz, proves with the repetition rate shown before in time domain. The signal to noise ratio (SNR) is measured to be approximately 56.31 dB from the peak to the pedestal, revealing the pulse stability. It is also worth to notice that the proposed laser operated stably in the laboratory condition for at least 48 h without any noticeable degradation of performance.

Fig. 7 illustrates the optical spectra of the Q-switched pulsed laser in comparison with CW laser at threshold pump power of 61.1 mW. As shown, the output laser spectrum of the CW laser originated at 1069.5 nm. Due to cavity loss generated by the incorporated SA in the cavity, the laser shifts to shorter wavelength of 1063.5 nm, where the higher gain is accumulated. The optical SNR of the Q-switched YDFL output spectrum is approximately 19.78 dB, with FWHM of 0.525 nm. It is also observed that the spectral width becomes narrower with the Q-switching operation. This is attributed to the high nonlinear effect inside the cavity.

The Q-switched pulsed YDFL performances are analysed under various pump power and presented in Figs. 8 and 9. As illustrated in Fig. 8, the output power of the proposed YDFL linearly escalates starting from 0.52 mW to 3.14 mW, accommodating a slope efficiency of 9.58%. The efficiency is directly related to intra-cavity loss, which can be further improved through cavity optimization. At the same time, the peak power inclines rapidly compare to output power. This happen from the combination of shorten pulse duration and shrunken pulse width of the Q-switching operation. Thus, the peak power escalates from 1.23 mW to 12 mW as the pulse width shrink from 8.56 μs to 4.23 μs. The pulse energy reading increases from 10.55 nJ to 50.74 nJ and it signified by a total energy contains in a single pulse. Therefore, pulse energy is affected by variation of either one or both the output power and pulse width. As can be observed in Fig. 9, the pulse energy increment with pump power is small at pump power region from 74.3 mW to 78.7 mW. This is attributed to a sudden increase in the repetition rate and a minor drop of the output power.

The experimental results show that the incorporation of AuNP can initiate self-started Q-switching pulses in YDFL cavity. This indicates that the saturable absorption characteristic of the AuNP film has a great potential to be applied in various laser applications. Furthermore, the use of AuNP thin-film SA offers simplicity in integration and fabrication, compactness, and flexibility. This possibly will benefit users in actual laser applications. Table 1 compares the performance of the proposed AuNP based laser with other Q-switched YDFL. As presented, the proposed SA exhibits comparable Q-switched laser performances in various attributes. The performance of Q-switched pulses is expected to be further improved by optimization of both SA parameter and the laser cavity design. The AuNP SA loss can be improved by reducing the thickness of PVA film and AuNP layer. Thinner AuNP layer may reduce the scattering loss.

5. Conclusion

A stable Q-switched pulsed YDFL was successfully demonstrated by integrating AuNP thin-film SA in ring cavity configuration. The CW laser was converted into a self-starting Q-switched laser when the pump power increased beyond 61.1 mW, and the Q-switching performance and laser stability were maintained as the pump power was increased up to the pump power of 87.4 mW. During these pump power variations, the highest repetition rate of 61.88 kHz and the thinnest pulse width of 4.23 μs were obtained. The recorded output power increased linearly up to 3.14 mW, while the pulse energy varied from 10.55 nJ to the maximum value of 50.74 nJ as a pump power increased. Meanwhile, the maximum peak power of 12 mW was obtained at the pump power of 87.3 mW. The AuNP SA shows promising performance in generating Q-switched pulsed in 1 μm region.

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References