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PASSIVE Q-SWITCHING OPERATION OF ERBIUM-DOPED FIBER LASER WITH GOLD NANOPARTICLES EMBEDDED INTO PVA FILM AS SATURABLE ABSORBER

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We demonstrate a Q-switched Erbium-doped fiber laser (EDFL) using a newly developed gold nanoparticles (GNPs) based saturable absorber (SA) for the first time. The GNPs were embedded in polyvinyl alcohol (PVA) for film-forming and inserted into an Erbium-doped fiber laser (EDFL) cavity to achieve passive Q-switching. The Q-switched EDFL operates at 1560 nm with a pump power threshold of 35 mW, a pulse repetition rate tunable from 19.7 to 89.9 kHz, and the smallest pulse-width of 2.64 μs. The Q-switching pulse shows no spectral modulation with a peak-to-pedestal ratio of 69 dB indicating the high stability of the laser. The highest pulse energy of 103 nJ was obtained at 118 mW pump power. These results show that the GNPs based SA is available for pulsed operation in the 1550 nm spectral range.

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1. Introduction

Q-switched fiber lasers are widely employed in applications which require high pulse energy such as range finding, remote sensing, optical communication, laser processing, and etc. [1, 2]. They are typically obtained based on the modulation of the quality factor, Q of a cavity, which can be realized by either active or passive technique. Compared with the active technique, passive Q-switching based on intensity saturable absorbers (SAs) possesses the advantages of compactness, low cost, and simple cavity configuration. It has been reported that various kinds of functional materials are used as SAs to achieve passive Q-switching, such as graphene [3], gold nanorods[4], carbon nanotubes [5], Bi_2Se_3[6], MoS_2[7], WS_2[8], and so on. However, there are still interest on exploring other new SA materials and designing new schemes for realizing passive Q-switched EDFLs.

Despite many methods and new materials are explored in developing the SA for Q-switching pulse generation, metal nanoparticles-based SA especially transition metal elements are rarely being investigated. These elements pick up a great interest amongst scientific researchers as they hold a unique optical property such as ultrafast response time, broad saturable absorption band and large third-order nonlinearity [6]. Very recently, Wu et. al. reported a Q-switching pulse generation by using Copper Nanowires (CuNW) as saturable absorber at visible range laser region (635 nm) with repetition rate ranging from 239.8 – 312.4 kHz, pulse width of 0.685 - 0.394 µs and

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maximum output power up to 9.6 mW[9]. The visible 635 nm Q-switched fiber laser was also reported using Gold nanoparticle (GNP) in Peodymium (Pr^{3+})-doped fiber laser cavity [10].

In this paper, we propose and demonstrate a passively Q-switched fiber laser using GNP, which is embedded in polymer film as a SA. The laser generates Q-switching pulse train with pulse width of 2.64 μs, repetition rate of 89.9 kHz and output power of 8.56 mW at the maximum input power of 142.5 mW. Our results indicate that GNP has potential for pulse generation in the 1550 nm region.

2. Preparation of Sa film and experimental set up

In this work, poly(sodium 4-styrenesulfonate) (PSSS), gold (III) chloride trihydrate (~50% Au basis) ($HAuCl_4$), tri–sodium citrate ($Na_3C_6H_5O_7$, TSC) and sodium borohydrate ($NaBH_4$) are used in GNPs synthesis. Deionized water (resistivity 18 MΩ) was used for the preparation of all solutions. All chemicals and solvent were used as received without further purification. Reactions were carried out in the fume hood. GNPs used for this demonstration were prepared using a $NaBH_4$ reduction method. The Au NPs was prepared initially with an addition of 50 mL TSC, 3 mL PSSS and 3 mL of $NaBH_4$ into a beaker containing 1000 mL deionized water while stirring at 450 rpm. 50 mL $HAuCl_4$ (5 mM, in water) was added dropwise (~2 mL/min) to the mixture with continuous stirring followed by the addition of excess amount of TSC (20 mL). The reaction was let for 5 minutes before continued with centrifugation as cleaning purpose. The resulting GNPs solution (Fig. 1(a)) was mixed with PVA solution for the practical usage. Fig. 1(b) shows the SEM image of the PVA solution, which confirms visually the existence of GNPs. The PVA solution was prepared by dissolving PVA powder (40000 MW, Sigma Aldrich) into 80 ml of DI water and then it is stirred at 145^o C until the powder completely dissolves. The GNP and PVA mixture solution was slowly stirred for about 2 hrs. The resulting suspension was then poured into the petri dish and left dry at room temperature. After 2 days, the thin film was slowly peeled from the petri dish. The GNPs film was then cut into a small piece to attach into an FC/PC fiber ferrule as shown in Fig. 1(c). The ferrule was then matched with another fresh ferrule via a fiber adaptor after depositing a small amount of index matching gel onto the fiber end to construct an all-fiber SA device.

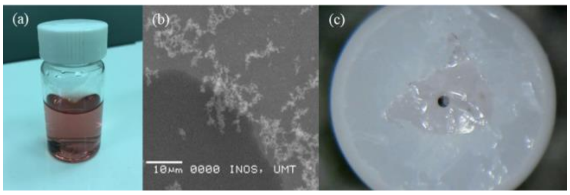


Fig. 1. GNPs characteristics. (a) Solution. (b) SEM image. (c) Film position on fiber ferrule.

The SA device was integrated into an EDFL cavity for the Q-switching experiment as illustrated in Fig. 2. The laser cavity consists of a 3m long erbium doped fibre (EDF) as an active medium, a wavelength division multiplexer (WDM), an isolator, the fabricated GNP PVA SA and an 80/20 output coupler. The 980 nm pump was launched into the EDF via WDM. The EDF with an Erbium ion absorption of 23 dB/m at 980 nm was used. A polarization independent isolator was used to ensure unidirectional propagation of the oscillating laser in the ring laser cavity. The laser output was tapped out using 80:20 coupler which keeps 80% of the light to oscillate in the ring cavity. The spectral characteristic was measured using an optical spectrum analyzer (OSA). The temporal characteristics were measured using a 500 MHz oscilloscope and a 7.8 GHz radio-frequency (RF) spectrum analyzer via a 1.2 GHz photodetector.

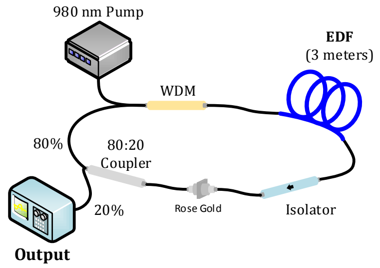
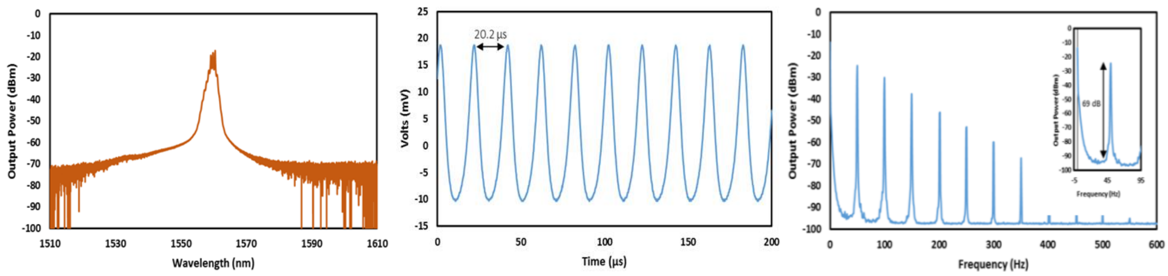


Fig. 2. Schematic illustration of the proposed GNPs based passive Q-switched EDFL.

3. Results and discussion

In this experiment, 980 nm pump power was slowly increased until we obtained a stable Q-switched pulse train. Stable, robust and self-starting Q-switching oscillation was obtained as soon as the incident pump power exceeded the threshold of 35 mW. There is no lasing below the threshold pump power. Such a low threshold power for Q-switching operation resulted from the small intra-cavity loss performed by the GNPs PVA SA. The spectral and temporal characteristics of the Q-switched laser is presented in Fig. 3. Fig. 3(a) shows the spectrum of the laser at a pump power of 35 mW, which centered at a wavelength of 1560 nm. It shows an obvious spectral broadening due to self-phase modulation effect in the ring cavity. Fig. 3(b) illustrates the typical oscilloscope trace of the Q-switched fiber laser at a pump power of 35 mW.It shows the peak to peak duration of 20.2 μs, which can be translated to the repetition rate of 49.7 kHz.The Q-switching pulses output was stable and no amplitude modulation was observed in the pulses train. This shows that there was no self-mode locking (SML) effect during the Q-switching operation.

Fig. 3(c) shows the RF spectrum of the Q-switching pulses at a pump power of 35 mW. The spectrum indicates the fundamental frequency at 49.71 kHz with a signal to noise ratio (SNR) of 69 dB. The high SNR indicates an excellent pulse train stability, comparable to other Q-switched fiber lasers based on CNT and graphene [6-8]. To verify that the passive Q-switching was attributed to the GNPs film, the SA device was removed from the ring cavity. In this case, no Q-switched pulses were observed on the oscilloscope even when the pump power was adjusted over a wide range. This finding confirmed that the GNPs PVA SA was responsible for the passively Q-switched operation of the laser.GNPs possess saturable absorption band in the 1550 nm region induced by surface plasmon resonance (SPR).

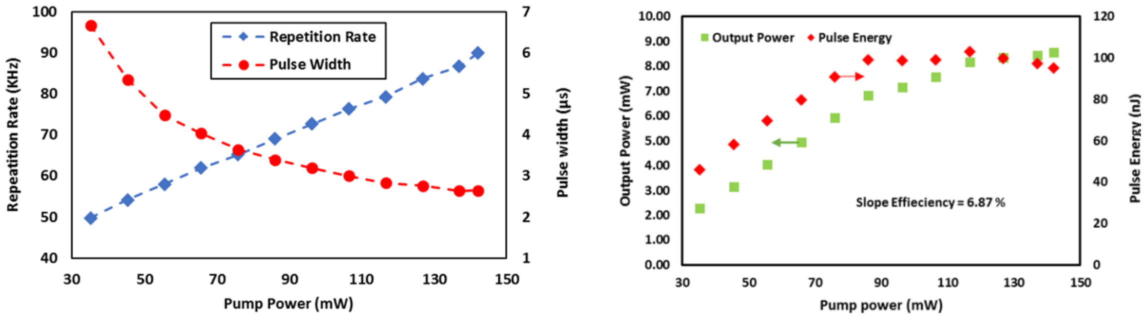


(a) (b) (c)

Fig. 3. Spectral and temporal characteristics of the Q-switched EDFL at a pump power of 35 mW (a) Output spectrum (b) Typical pulses train (c) RF spectrum. Insert figure of 2(c) shows an enlarged RF spectrum at the fundamental frequency.

Fig. 4(a) draws the variation tendency curves of pulse repetition rate and pulse width with the incident pump power. When the pump power is varied from 35 mW to 142.5 mW, the repetition rate increases almost linearly from 49.71 to 89.89 kHz. This is a typical characteristic of the Q-switched laser, which is mainly due to the higher pump power provides more gain to saturate the SA. On the other hand, pulse duration reduces from 6.67 to 2.64 μs μs as the pump power increases within the same range. We observe a smaller reduction of pulse width as the pump power increases. This is due to the fact that the SA is becoming saturated when more photons circulate inside the laser cavity as the pump power increased. The minimum attainable pulse duration is 2.61 μs, which is believed to be related to the modulation depth of the SA. The pulse duration can be further decreased by shortening the cavity length and improving the modulation depth of the SA.

Fig. 4(b) shows the output power and pulse energy as a function of the incident pump power. The output power increases linearly at first and then becomes saturated. Likewise, the pulse energy increases linearly before it saturates and even slightly decreases at higher pump power. These are most probably due to the bleaching and thermal accumulation effects of the GNPs SA under high pump intensity. It is observed that the output power can recover again as we decreased the incident pump power, indicating no damaged of the GNPs SA. At the pump power of 142.5 mW, the maximum output power was measured to be 8.56 mW. The maximum pulse energy of 103 nJ was obtained with the pump power of 118 mW. It is expected that the higher pulse energy could be achieved by further improving the quality of GNPs SA, or optimizing the cavity designs.



(a) (b)

Fig. 4.Laser performance within 35 mW to 142.5 mW. (a) Repetition rate and pulse width. (b) Output power and pulse energy.

4. Conclusions

We have successfully demonstrated a Q-switched EDFL using a GNPs, which is embedded into a PVA film as a passive SA. The film was sandwiched between two ferrules via a fiber connector to form a fiber-compatible SA. Stable Q-switched pulses train operating at 1560 nm was successfully achieved within the incident pump power range from 35 mW to 142.5 mW. The repetition rate ranges from 19.7 to 89.9 kHz and the pulse width can be as narrow as 2.64 μs. The highest pulse energy of 103 nJ was obtained at 118 mW pump power. These results exhibit that the GNPs PVA film has good saturable absorption ability in the 1550 nm spectral region.output.

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