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Zinc-oxide nanoparticle-based saturable absorber deposited by simple evaporation technique for Q-switched fiber laser*

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A Q-switched erbium-doped fiber laser (EDFL) incorporating zinc-oxide (ZnO) nanoparticles-based saturable absorber (SA) is proposed and demonstrated. To form the SA, the ZnO nanoparticles, which are originally in the powder form, are first dissolved in ethanol and subsequently deposited onto the surface of fiber ferrule by using the adhesion effect with the evaporation technique. By integrating the ZnO nanoparticle-based SA into a laser cavity of an EDFL, a self-started and stable Q-switching is achieved at a low threshold power of 20.24 mW. As the pump power is increased, the pulse repetition rate is tunable from 10.34 kHz to 25.59 kHz while pulse duration decreases from 21.39 μs to 3.65 μs. Additionally, this Q-switched laser has a maximum energy per pulse of 19.34 nJ and an average output power of 0.46 mW. These results indicate the feasibility and functionality of the ZnO nanoparticles-based SA for Q-switched generation, which offers the flexibility and easy integration of the SA into a ring laser cavity.

Keywords: zinc oxide, saturable absorber, Q-switched, fiber laser

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1. Introduction

It has been of great interest recently to explore new materials to act as saturable absorbers (SAs) for passively Q-switched fiber lasers, which can find a multitude of applications in the areas that require a high pulse energy source, such as remote sensing, biomedical diagnostics, spectroscopy, communications, material processing and manufacturing.[1–12] Although Q-switching can be undertaken by using active components, the passive scheme is more preferable because additional switching electronics that leads to the bulkiness of the system are not required. In contrast to the active method, passively Q-switching by the SAs provides the significant advantages of low complexity and easy operation due to their simple design, which allows the development of compact and cost-effective pulsed laser sources. The Q-switched fiber lasers based on the SAs are traditionally fulfilled by employing semiconductor saturable absorber mirrors (SESAMs) and carbon nanotubes, which unfortunately have their own several shortcomings.[1,2,13–17]

Over the past few years, extensive research has focused on the two-dimensional (2D) materials for SAs application[18–20] due to their ultrafast carrier dynamics and high third-order optical nonlinear susceptibility.[21–24] Amongst the 2D materials examined are graphene,[25,26] topological insulators (TIs),[27–29] and transition metal dichalcogenides (TMDs),[30] which show a great success in serving as high performing SAs materials. While the performance characteristics of the materials have proven to have tremendous potential applications in SAs, it must be noted that consideration must also be given to other aspects of the SAs, such as easy fabrication and cost. In this regard, significant research has been expanded into the development of a cheaper material used as saturable absorber with less complex fabrication for passive Q-switching, such as copper oxide, magnesium oxide, and nickel oxide nanoparticles.[31–33]

Among these attempts, zinc-oxide (ZnO), which originates from Zn, a semiconductor of the II–VI group, holds the advantage because it is easily available and inexpensive, which could offer a good alternative to the existing SA materials. The ZnO also possesses a direct band gap of 3.4 eV[17,34,35] and high energy value of 60 meV at room temperature,[17,34,36,37] making it highly attractive for many optical applications. Owing to its excellent optical and electrical properties, such as wide band gap, high binding

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energy,[1,17,38] large carrier density excitation,[1,39] and low power threshold for optical pumping,[15,40] the ZnO has recently aroused the great interest in scientific research as a viable material for saturable absorption.[1,15,38,41] In addition, the high third-nonlinear coefficient[1,38,42,43] and ultrafast recovery time of ZnO[1,39] qualifies the desirable properties of an SA, thus further validating the potential of ZnO as a promising SA candidate.

Although there have been a number of reports on ZnO-based SA in Q-switched pulsed fiber laser, the integration of ZnO-based SA into the fiber laser system ever reported requires sophisticated approach such as incorporating ZnO-polyvinyl alcohol (PVA) thin film on sandwiched structure between two fiber pigtails.[41] This ZnO-PVA thin film-based SA can operate well but can be difficult to produce because its fabrication process requires skilful technique and highly precise instrumentation. Therefore, it is still of interest to investigate a simpler method to form a ZnO-based SA.

In this work, we propose a simple approach to the fabrication of ZnO nanoparticles-based SA via evaporation technique to adhere the ZnO nanopowder onto the fiber ferrule. This is made possible by tapping the tip of a fiber ferule in the ZnO nanopowder dissolved in ethanol solution before being connected to another fiber ferrule to form the SA assembly. The ZnO SA assembly is then integrated into an erbium-doped fiber laser (EDFL) to generate a Q-switched pulse, which is self-started at a low threshold power of 20.24 mW. The pulse repetition rate is tunable from 10.34 kHz to 25.59 kHz against the pump power. A minimum pulse width (MPW) of 3.65 μs is obtained at a pump power of ∼ 48.58 mW. The maximum pulse energy (MPE) and average output power (AOP) achieved in this work are 19.34 nJ and 0.46 mW, respectively.

2. Preparation of ZnO nanoparticle-based SA

The ZnO used in this work is originally in the form of powder with a nanoparticle size of $\sim 54.88 \pm 7.87$ nm, which was obtained from Biophysics Laboratory, University Putra Malaysia. To form the SA, the ZnO nanopowder is first dissolved in a few drops of ethanol on a weighing paper. A single mode fiber ferrule (SMFF) with a clean tip is dipped slightly into the suspension, whereby through the adhesion effect, the ZnO nanopowder will stick to the facet of the SMFF with the help of the ethanol. The SMFF is then left to dry for a few seconds to form a layer of ZnO on the SMFF surface through evaporation process to remove the ethanol residue. The SMFF with the deposited ZnO is then connected to another clean SMFF by using a fiber adaptor to form an SA assembly. Figures 1(a)–1(d) illustrate the steps of forming the ZnO SA assembly.

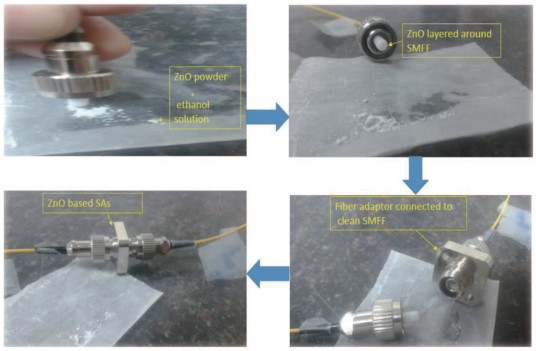


Fig. 1. Steps of forming ZnO nanoparticle-based assembly.

The prepared SA device is then examined with a Witec Alpha 300R Raman spectroscopy. Figure 2 shows the obtained Raman spectrum, which exhibits several intensity peaks at Raman shift ranging from approximately 101 cm^{-1} to 705 cm^{-1}. The vibrational mode of E_2 (low) at 101 cm^{-1} and E_2 (high) at 487 cm^{-1} match the specified peak profile of Raman spectrum for ZnO,[44,45] which confirms the presence of ZnO on the SMFF. It is remarkable that the blue-shift in E_2 (high) from 437 cm^{-1} (theoretical value) to 487 cm^{-1} (experimental value) is created by the impurities or the tensile strain in the sample.[46]

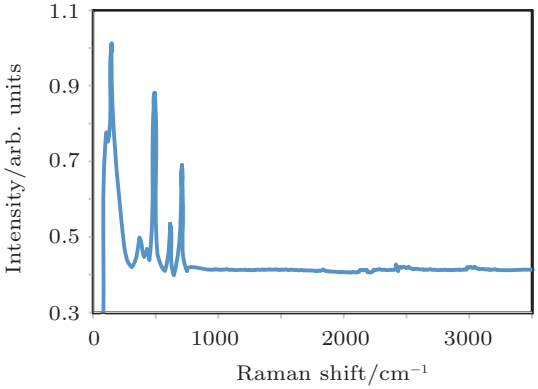


Fig. 2. Raman shift of ZnO on SMFF.

3. Q-switched EDFL experimental setup

Figure 3 illustrates the experimental setup of the ZnO-based Q-switched EDFL. A section of 6.5-m Lucent Technologies HP980 erbium-doped fiber (EDF) is pumped by a 980-nm laser diode (LD) through a 980-nm port of a fused 980-/1550-nm wavelength division multiplexer (WDM). The signal absorption coefficient of the EDF is about 3.5 dB/m at 1530 nm. An optical isolator is spliced at the output port of the EDF, whereby the output signal from the optical isolator will then come into contact with the fabricated ZnO-based SA assembly. The signal is then channeled to an 80:20 coupler for tapping out a 20% portion of the signal oscillating in the cavity for further analysis. Meanwhile, the remaining signal will propagate through the 80% port of the coupler which is

connected to a polarization controller (PC). The signal is finally channeled back to the 1550-nm port of the WDM, thus completing the laser resonator. A Yokogawa AQ6370B Optical Spectrum Analyzer (OSA) with a resolution of 0.02 nm is used to measure the output spectrum of the generated Q-switched laser. The pulse train properties of the Q-switched pulses are analyzed by making use of an oscilloscope (Tektrunin TDS 3012C) together with a Thorlabs SIR51856 Lightwave Detector for optical-to-electrical conversion in place of the OSA.

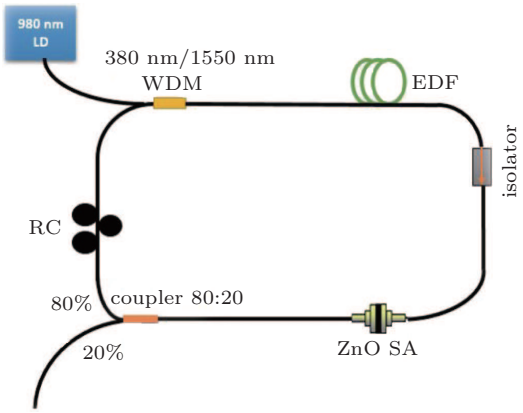


Fig. 3. Experimental setup of ZnO-based Q-switched EDFL.

4. Results and discussion

Figure 4 shows the output spectra of the Q-switched EDFL obtained from the OSA with the pump powers of 15.99 mW, 20.24 mW, and 48.58 mW, respectively. In the initial stage of operation, starting from a pump power of 15.99 mW, the proposed system operates in the continuous wave (CW) mode. The further increase of the pump power to 20.24 mW and above yields a Q-switched operation of the proposed system. The spectrum exhibits a modulation structure as the laser operation transforms from CW to Q-switching mode due to cavity perturbations and multimode oscillations. The peak wavelength of the laser output is fixed at approximately 1558.32 nm against different pump powers.

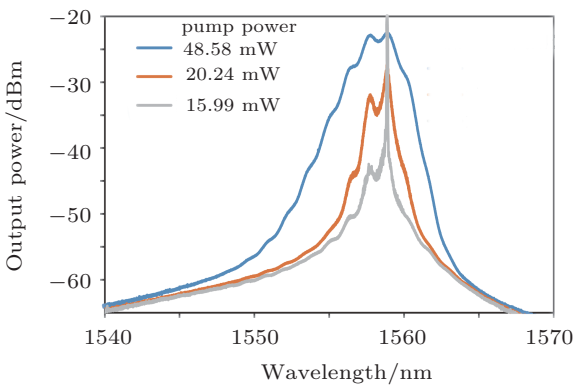


Fig. 4. Optical spectra of Zn-based Q-switched WDFL at different pump powers.

Figure 5 shows the output pulse train of the Q-switched EDFL taken from the oscilloscope, operating at a maximum pump power (MPP) of 48.58 mW, giving a repetition rate value of ∼ 25.59 kHz.

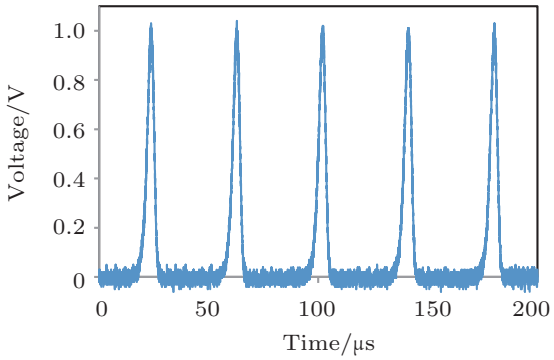


Fig. 5. The Q-switched output pulse train taken at pump power of 48.58 mW.

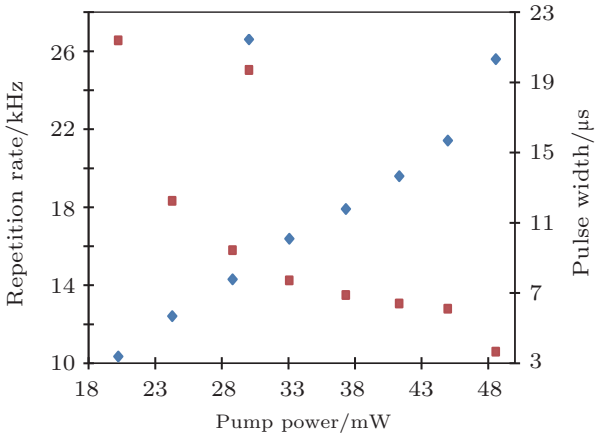


Fig. 6. The evolution of pulse repetition rate and pulse width with pump power.

The evolution of pulse repetition rate and pulse width of the Q-switched EDFL against the pump power is presented in Fig. 6. The figure shows that the pulse repetition rate increases almost linearly with pump power increasing until the maximum value of 25.59 kHz at 48.58 mW. This proposed system also provides a lower Q-switching threshold (QST) than that reported in other work on Q-switched fiber laser using ZnO as the saturable absorber, such as in Refs. [1] and [38]. The moderately low Q-switching threshold of 20.24 mW achieved in this system is probably due to the low non-saturable absorption loss of the ZnO-based SA, with a value of 26.6% as obtained from the nonlinear saturable absorption characterization. In addition, the ZnO also holds a particular characteristic of having low power threshold for optical pumping,[15,40] which is expected to be another contributing factor to the low QST in this system. Meanwhile, the pulse width of the system decreases as the pump power is increased, whereby at the MPP of 48.58 mW, the pulse width is recorded at 3.65 μs. Since the pulse width of a Q-switched laser is also determined by the laser cavity design, it is expected that the pulse width value

in this work could be minimized further by reducing the fiber length in the cavity.

The power development curve of this ZnO-based Q-switched EDFL is plotted in Fig. 7. As can be seen from the figure, the average output power increases linearly with pump power increasing after the CW lasing threshold has reached about 15.99 mW with an increment of about 0.06 mW for every ~ 4 mW rise in pump power. The maximum average output power (MAOP) is approximately 0.46 mW, which is attained at the highest pump power of 48.58 mW. In addition, the laser slope efficiency above the threshold value is estimated at 1.27%.

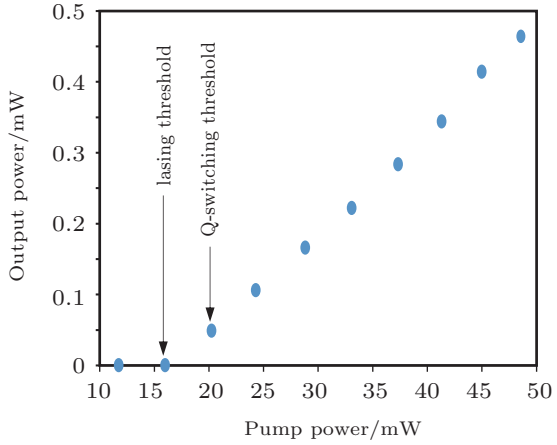


Fig. 7. Power development curve of ZnO-based Q-switched EDFL.

Figure 8 shows the pulse energy against pump power, which evolves from 4.73 nJ to a maximum value of 19.34 nJ in response to the change of pump power from 20.24 mW to 44.98 mW. However, the pulse energy drops slightly to 18.13 nJ as the pump power reaches its maximum value of 48.58 mW. Such a decrease in the pulse energy is possibly due to the system exceeding its optimal operating point, whereby above a certain intracavity power level, other nonlinear effects may take place, which cause more average loss and thus degrading the performance of the system.[47] There is also a possibility that the peak power intensity at this point has surpassed the damage threshold of the fabricated ZnO-based saturable absorber, causing it to experience a slight damage. Based on the peak power of 3.17 mW calculated at 44.98-mW pump power and a fiber core diameter of ~ 9 μm, the damage threshold of the ZnO based saturable absorber is estimated at 49.83 MW/m^2. The low thermal damage threshold of our ZnO-based SA might be attributed to some parameters that are not well optimized during the SA fabrication procedure, such as the dispersion and concentration of ZnO nanopowder in ethanol solution, as well as the thickness of the ZnO layer on the fiber ferrule. It is possible that the careful optimization of these parameters will minimize the excessive scattering loss, thus inducing a higher damage threshold of the SA device.

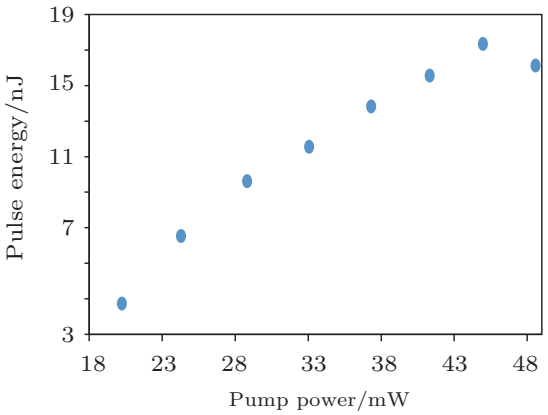


Fig. 8. Pulse energy evolution with pump power.

To further verify the stability of the proposed system, the optical spectrum of the ZnO-based Q-switched EDFL is examined at the MPP of 48.58 mW within an observation period of 30 min at a 5-min time interval as shown in Fig. 9. It is observed that the optical spectrum behavior is well maintained over time with no obvious deviation of the output power or spectral bandwidth, except for negligible shift in the central wavelength, thus validating the good stability of the Q-switched laser operation.

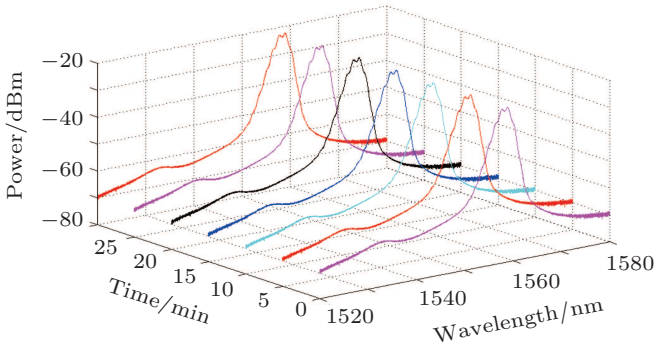


Fig. 9. Stability measurement of output spectrum at 48.58 mW in 30-min observation time.

Table 1 summarizes the performances of Q-switched EDFL utilizing different types of SAs for comparison purpose. All the cited works operate in a 1560-nm wavelength range and use the sandwich technique for the SA integration in the fiber laser cavity. It should be noted that although the overall Q-switched performance in this work is not superior to that of the other work, our proposed system outperforms most of the other work in terms of the Q-switching threshold. It is also worth mentioning that even though the MPW of 3.65 μs generated in this work is quite large, it is still comparable to the values reported in Refs. [33], [47], [50], and [51]. Another criterion for the comparison is the deposition method of the SAs, whereby our work proposes a simple deposition by evaporation technique compared with other work, which mostly involves the fabrication of SA-polymer composite thin film.

Table 1. Summary of Q-switched EDFL performances by various types of saturable absorbers.

Type of SA material	Deposition method	QST/mW	Maximum repetition rate/kHz	MPW/μs	MPE/nJ	References
Nickel oxide	NiO-PEO composite thin film	25	52.2	5.2	31.5	[33]
Copper oxide	CuO-PVA composite thin film	70	83	2.6	66	[31]
Titanium dioxide	TiO_2-polymer composite thin film	140	121	1.84	∼ 2.1	[48]
Tin (IV) oxide	SnO_2-PVA composite thin film	38	65.6	2.9	72.1	[49]
Cobalt oxide	Co_3O_4-PEO composite thin film	55	70.9	5.02	39.3	[50]
Molybdenum disulfide	MoS_2-PVA composite thin film	18.9	43.5	3.3	160	[51]
Tungsten disulfide	mechanical deposition of WS_2 powder	12.7	35.2	2.6	120	[52]
Graphene	graphene-PVA composite thin film	74	103	2	40	[2]
Graphene oxide	optical deposition	18	61	6.4	63.9	[47]
Zinc oxide	evaporation of ZnO-ethanol	20.2	25.6	3.65	19.3	this work

5. Conclusions

In this work, a Q-switched EDFL is successfully demonstrated by using ZnO nanoparticles-based SA with simple deposition method. The SA device is prepared by first dissolving the ZnO nanoparticle powder in ethanol and subsequently deposited onto the SMFF via adhesion effect assisted by evaporation process. The ZnO-deposited SMFF is then connected to another clean SMFF to be integrated into the EDFL cavity. Self-started and stable Q-switching in the EDFL is achieved at a low threshold power of 20.24 mW. At the maximum pump power of 48.58 mW, the Q-switched EDFL generates the central wavelength, pulse repetition rate, pulse width, average output power, and pulse energy of 1558.32 nm, 25.59 kHz, 3.65 μs, 0.46 mW, and 18.13 nJ, respectively.

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