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Zinc Oxide-Based Q-Switched Erbium-Doped Fiber Laser *

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We demonstrate a Q-switched erbium-doped fiber laser (EDFL) using a newly developed zinc oxide- (ZnO) based saturable absorber (SA). The SA is fabricated by embedding a prepared ZnO powder into a poly(vinyl alcohol) film. A small piece of the film is then sandwiched between two fiber ferrules and is incorporated in an EDFL cavity for generating a stable Q-switching pulse train. The EDFL operates at 1560.4 nm with a pump power threshold of 11.8 mW, a pulse repetition rate tunable from 22.79 to 61.43 kHz, and the smallest pulse width of 7.00 μs. The Q-switching pulse shows no spectral modulation with a peak-to-pedestal ratio of 62 dB indicating the high stability of the laser. These results show that the ZnO powder has a great potential to be used for pulsed laser applications.

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Passively Q-switched fiber lasers have attracted much attention in recent years due to their potential applications in many areas such as micromachining, metrology, medicine, telecommunications and fiber optical sensing.[1,2] Compared with the active technique, the passive technique is better in terms of simplicity, compactness, and flexibility of implementation.[3] The passive Q-switching can be realized by using either a nonlinear polarization rotation (NPR)[4] or saturable absorber (SA) techniques. To date, various SAs have been implemented such as semiconductor saturable absorber mirrors (SESAMs),[5] carbon nanotubes[6] and graphene[7] for Q-switching generation in various fiber lasers and cavities. However, the applications of these SAs are restricted due to certain intrinsic drawbacks such as complex optical alignments, environmental sensitivity, complicated fabrication and limited operating bandwidth. Therefore, there have been many new attempts in recent years to develop new high-performance SAs for Q-switching laser operation.[8,9]

Despite many methods and new materials being explored in developing the SA for Q-switching pulse generation, metal nanoparticles-based SA, especially transition metal elements, are rarely being investigated. Transition metal oxides such as zinc oxide (ZnO), titanium dioxide (TiO_2) and cobalt oxide (Co_3O_4) are another class of nonlinear optical materials that have been intensively investigated over the past few decades due to their large optical nonlinearity and the advantages of good thermal and chemical stability in addition to mechanical strength. For instance, ZnO has been seen as a potential SA candidate due to its optical and electrical properties. Derived from Zn, a semiconductor of the II–VI group, ZnO has a direct band-gap of 3.4 eV[10] and a high energy of 60 meV[10,11] at room temperature, thus making it a strong potential candidate for developing pulsed output. Furthermore, ZnO has additional favorable properties which make it highly suited towards optical applications, including biocompatibility, radiation hardness, low power threshold for optical pumping and wet chemical etching.[12] These characteristics make ZnO a highly valuable candidate for emerging electro-optical applications such as thin-film transistors, light-emitting diodes, ultra violet laser diodes, nanotechnology-based devices and transparent electrodes in liquid crystal displays.[12] Most importantly, however, these characteristics also make ZnO a highly viable candidate as a material for saturable absorption.

In this Letter, a Q-switched erbium-doped fiber laser (EDFL) uses a ZnO-based SA as a Q-switcher. The SA is fabricated by embedding a prepared ZnO powder into a poly(vinyl alcohol) (PVA) film. By incorporating a small piece of the film in a laser cavity, the proposed laser generates a stable Q-switched pulse train at 1560.4 nm with repetition rate increases from 22.79 to 61.43 kHz while the pulse width decreases from 20.36 to 7.00 μs as the pump power is increased from 11.8 mW up to 77.9 mW.

First, the ZnO-based SA was fabricated. In the process, 10 mM of zinc nitrate hexahydrate ($Zn(NO_3)_2{\cdot}6H_2O$, Ajax Finechem Pty Ltd) and hexamethylenetetramine ($(CH_2)N_4$, Sigma-Aldrich) was dissolved in 600 ml of DI water under stirring for 15 min. Then, the 100 ml of the solution was poured into a separate beaker and placed in the oven for 5 h. After 5 h, white precipitates were formed, showing the existence of ZnO powder. The precipitates were collected and left to dry in ambient conditions for 2 d. The PVA solution was prepared by dissolving PVA powder (40000 MW, Sigma Aldrich) into 80 ml of DI water and stirred at 145 C until it completely dissolves. To fabricate the thin film, the ZnO powder was dissolved in 10 ml of DI water and centrifuged for 10 min to form ZnO solution. Then, the solution was mixed with the PVA solution and followed by slow stirring for 2 h. The mixture solution was poured into the petri dish and left to dry at room temperature. After 2 d,

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the thin film was slowly peeled from the petri dish.

We verify the quality of the ZnO PVA film by using the field emission scanning electron microscopy (FESEM) as shown in Fig. 1. The FESEM image shows the existence of the uniform layers and confirms the absence of >1 μm aggregates or voids in the composite SA, which otherwise results in non-saturable scattering losses. The inset in Fig. 1 shows the physical thin film as viewed normally. The thin-film thickness was measured to be approximately 50 μm. We cut a small piece of the ZnO film and attached it onto a standard FC/PC fiber ferrule end surface with index matching gel. After connecting it with another FC/PC fiber ferrule with a standard flange adapter, the all-fiber ZnO-based SA was finally ready.

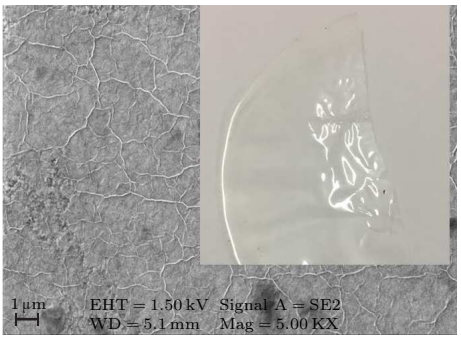

Fig. 1. FESEM image capture of the ZnO PVA film. The inset shows the actual film, as viewed without any magnification.

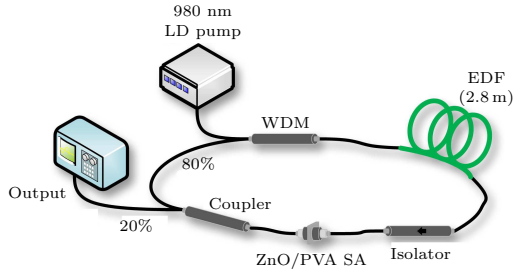

Fig. 2. Configuration of the Q-switched EDFL setup employing a ZnO PVA film as a Q-switcher.

The fabricated SA device is incorporated in an EDFL cavity for Q-switching generation as shown in Fig. 2. The cavity uses a 2.8-m-long erbium-doped fiber (EDF), which was pumped by a 980-nm laser diode (LD) via a 980/1550 nm wavelength division multiplexer (WDM). The EDF used has a numerical aperture (NA) of 0.16 and erbium ion absorption of 23 dB/m at 980 nm with core and cladding diameters of 4 μm and 125 μm, respectively. To ensure unidirectional propagation of the oscillating laser in the ring laser cavity, a polarization-independent isolator was used. The fabricated ZnO PVA film was integrated into the ring cavity to act as a passive Q-switcher. The laser signal was coupled out using 80:20 output coupler which keeps 80% of the light oscillating in the ring cavity for both spectral and temporal diagnostics. The output laser was tapped from a 20% port of the coupler. The spectral characteristic was measured using an optical spectrum analyzer (OSA) with a spectral resolution of 0.02 nm while 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.

In this experiment, the pump power was slowly increased until we obtained a stable Q-switched pulse train when the pump power exceeds lasing threshold. Stable, robust and self-starting Q-switching operation is obtained at pump power threshold of 11.8 mW. There is no lasing below the threshold pump power. Such a low threshold power for Q-switching operation results from the small intra-cavity loss performed by the ZnO PVA SA. The spectrum of the Q-switched pulse train is shown in Fig. 3(a). It operates at 1560.4 nm with an obvious spectral broadening due to the self-phase modulation effect in the ring cavity. A stable pulse train with an increasing repetition rate was observed within the pump power from 11.8 to 77.9 mW, which is a typical characteristic for the Q-switched laser. Figure 3(b) shows the typical oscilloscope trace of the Q-switched pulse train at the pump power of 77.9 mW. It shows the peak-to-peak duration of 16.28 μs, which is equal to the repetition rate of 61.43 kHz. It is also observed that the Q-switched pulse output is stable and no amplitude modulations in the pulse train can be observed, which indicates that there is no self-mode locking (SML) effect during the Q-switching operation. A single Q-switched pulse is shown in Fig. 3(c), which has an almost symmetric shape with a pulse width of approximately 7.0 μs. To verify that the passive Q-switching was attributed to the ZnO PVA SA, the film 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 confirms that the ZnO PVA SA is responsible for the passively Q-switched operation of the laser.

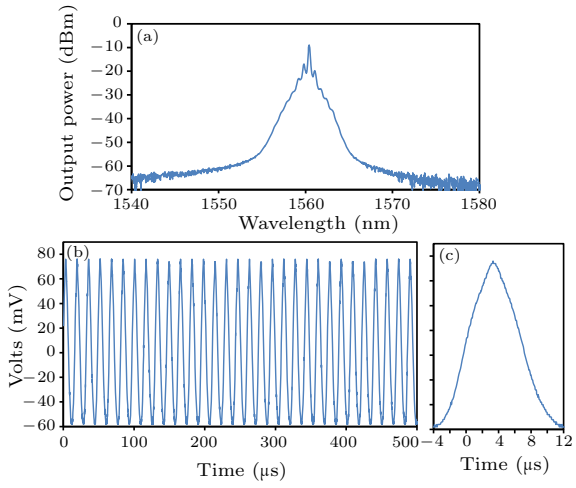

Fig. 3. Pulse characteristic at a pump power of 77.9 mW, showing the pulse wavelength spectrum (a), the typical pulse train (b) and a single envelope of the pulse (c).

Figure 4 illustrates the pulse repetition rate and the pulse duration versus the pump power. It is clear that with the pump power increasing from 11.8 mW to 77.9 mW, the repetition rate grows monotonously from 22.79 to 61.43 kHz. The pulse repetition rate increases almost linearly with the pump power at the

rate of ∼0.56 kHz/mW. On the other hand, the pulse duration decreases from 20.36 µs to 7.00 µs with the increase of the pump power from the threshold of 11 mW to 77 mW. At a lower pump power (<30 mW), the pulse duration drops exponentially. At a higher pump power (>30 mW) the pulse duration linearly reduces while the repetition rate increases. As the pump power increases, more power circulates inside the laser cavity, thus hastening the saturation of SA. From Fig. 4, it can be seen that smaller changes of pulse width from 30–77 mW indicates that the SA were becoming saturated with continually increasing the light intensity (pump power). It is also worth noting that the pulse operation is switched into the cw mode as the pump increases to be larger than 77 mW. The pulse duration can be further decreased by shortening the length of the laser cavity (including the length of the gain material), but this would compromise the optical output.

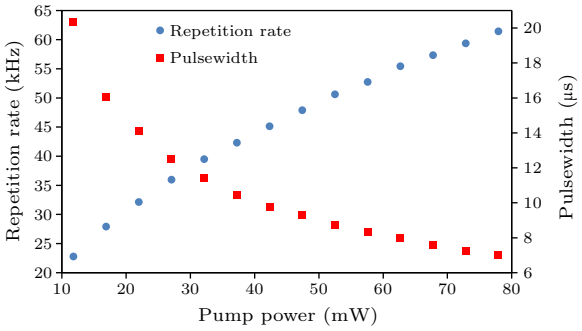

Fig. 4. The pulse repetition rate and the pulse duration as a function of the pump power.

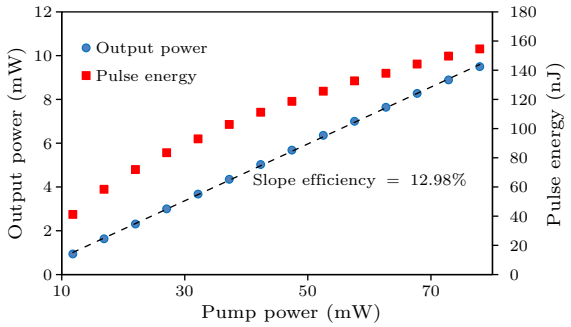

Fig. 5. The pulse average output power and energy as a function of the pump power.

Figure 5 shows the dependence of the pulse energy and the average output power of the laser against the pump power. The average output power increases linearly with the pump power with a slope efficiency of 13%. The pulse energy also increases monotonously with the pump power where the maximum pulse energy of 154.6 nJ is obtained at the pump power of 77 mW. The increase of the pump power leads to a rise of average output power and shortening of the pulse width and hence a higher pulse energy is extracted in the Q-switching process.

To investigate the stability of our Q-switched pulse, the RF spectrum is obtained at the pump power of 77.9 mW as shown in Fig. 6. The RF spectrum shows the fundamental frequency of 64.43 kHz with a high signal-to-noise ratio (SNR) of ∼62 dB. The SNR indicates good pulse train stability, comparable with Q-switched fiber lasers based on TiO.[13] The proposed laser was observed to be highly stable, with no significant changes observed in any of the output parameters after two hours of operation, and has repeated cycles of operation in the two days following. It is expected that a better Q-switched pulse can be obtained by optimizing the design of the cavity, including reducing the cavity length and cavity losses as well as optimizing its cavity structure and using higher-quality ZnO-based SAs.

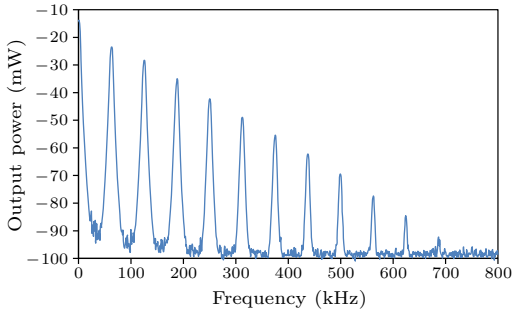

Fig. 6. The output pulse spectrum in the frequency domain at the pump power of 77.9 mW.

In conclusion, we have successfully demonstrated a Q-switched ring EDFL using a ZnO powder, which is embedded into a PVA film as a passive SA. The film with 50 µm thickness is sandwiched between two ferrules via a fiber connector to form a fiber-compatible SA. A stable Q-switched pulse train at 1560.4 nm is successfully obtained within the 980 nm pump power range from 11.8 mW to 77.9 mW. At the pump power 77.9 mW, the laser shows the repetition rate 61.43 kHz, pulse energy 154.6 nJ, and pulse duration 7.00 µs. These results show that ZnO is a new potential SA material for pulsed laser applications.

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