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Dual-Wavelength Passively Q-Switched Ytterbium-Doped Fiber Laser Based on Aluminum Oxide Nanoparticle Saturable Absorbers *

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We report on generation of a dual-wavelength, all-fiber, passively Q-switched ytterbium-doped fiber laser using aluminum oxide nanoparticle (Al_2O_3-NP) thin film. A thin film of Al_2O_3 was prepared by embedding Al_2O_3-NPs into a polyvinyl alcohol (PVA) as a host polymer, and then inserted between two fiber ferrules to act as a saturable absorber (SA). By incorporating the Al_2O_3-PVA SA into the laser cavity, a stable dual-wavelength pulse output centered at 1050 and 1060.7 nm is observed at threshold pump power of 80 mW. As the pump power is gradually increased from 80 to 300 mW, the repetition rate of the generated pulse increases from 16.23 to 59 kHz, while the pulse width decreases from 19 to 6 μs. To the best of our knowledge, this is the first demonstration for this type of SA operating in the 1 μm region.

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Passively Q-switched all-fiber lasers have many advantages compared with other lasers like (solid-state lasers), such as simple structures, cost effectiveness, and insensitivity to electromagnetic interference.[1−3] In spite of the pulse duration with the mode-locked laser being typically shorter than that in Q-switched operation, high pulse energy with Q-switched lasers has found many potential applications in military applications and material processing.[2] Q-switching represents a modulation technique to generate short pulses via active or passive techniques. Active Q-switching techniques employ intracavity electro-optics or acoustic-optics modulators, which adds more complexity to the system.[4,5] However, in passive techniques, only a saturable absorber is incorporated inside the laser cavity. This gives the passively Q-switched laser system significant advantages in terms of compactness, simplicity and ease of implementation compared with the active one.[3−6] Up to now, various kinds of SAs have been implemented to achieve Q-switching operation in various fiber laser cavities, such as semiconductor saturable absorber mirror (SESAM),[7] carbon nanotubes (CNTs),[8] graphene[9] and topological insulator.[10] For a long time, SESAMs were the better choice as SAs due to their stability and flexibility. However, the complexity of the fabrication process as well as their narrowband operating range put limitations on their operation as SAs.[11] CNTs suffer from a few inherent drawbacks concerning complex bandgap control, which prevents saturable absorption at certain wavelengths.[12] The weak absorption coefficient of graphene puts a limitation on its application in modulation and the relevance fields of optics.[13] Recently, the development of dual- or multi-wavelength Q-switched fiber lasers that can generate a Q-switched pulse train at different center wavelengths has attracted much attention due to their potential applications. These applications include wavelength division multiplexing (WDM) in optical fiber communications, optical fiber sensing, terahertz generation and fiber spectroscopy.[14,15] This has spurred further efforts to seek for generating multi- or dual-wavelength pulsed fiber lasers using various materials as SAs, such as selenium bismuth (Bi_2Se_3),[16] and titanium dioxide (TiO_2).[17]

Transition metal oxide, namely aluminum oxide (Al_2O_3), is widely used as the coating material in many commercial solar tint films due to its low absorption in the region near UV to visible. Several works have been reported on the nonlinear optical properties of Al_2O_3 films in the near-infrared region, which confirm that Al_2O_3 as a material is suitable to induce pulse generation.[18] In addition, the film is low cost, easy to prepare, and capable of generating a Q-switched operation that has many fields of applications such as in sensing, spectroscopy and as a laser source for second harmonic generation. In our previous work[19] we demonstrated a successful Q-switched operation in 1.5 μm region. Furthermore, Ahmad *et al.* reported the demonstration of passively Q-switched thulium-doped fiber lasers (2 μm region) with aluminized solar tint film SA.[20]

In this work, we propose and demonstrate a dual-wavelength passively Q-switched ytterbium-doped fiber laser (YDFL) using Al_2O_3 thin film as an SA. By inserting the SA into the laser cavity, the system is capable of generating a pulsed dual-wavelength output, centered at 1050 and 1060.7 nm at a channel spacing of 10.7 nm. To the best of our knowledge, this is the first demonstration of dual-wavelength passively Q-switched fiber laser in the 1 μm region using Al_2O_3-NPs as an SA.

For fabricating the SA, a thin film of Al_2O_3 NP (nanoshell)-based PVA polymer was prepared using the casting method. Figure 1(a) shows the Al_2O_3 nanostructures under scanning electron mi-

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croscopy (SEM) imaging, which are about 20 nm in size (nanoshell). In the preparation process, firstly, the PVA solution was prepared by dissolving 10 mg of PVA powder into 100 ml of deionized water (DI) and stirring at 90℃ for 1 h until it completely dissolved and the solution became homogenous with a viscous appearance at room temperature. The PVA solution was cooled down at room temperature before use. Then, the PVA solution was mixed with 0.25 mg of Al_2O_3 NPs followed by slow stirring for about 30 min. The mixture solution was poured into a well-covered petri dish and left to dry at room temperature for 3 d. In our experiment, the prepared solutions of Al_2O_3-PVA were deposited as thin films onto a thin transparent glass slide. Film thickness was measured accurately using the interference method, using a He-Ne laser as illumination source. The thin-film thickness was measured to be approximately 0.2 μm. To further investigate the absorption band of the prepared Al_2O_3–PVA thin film, the absorption spectrum was measured with an ultraviolet-visible spectrometer (UV-Vis) as shown in Fig. 1(b), indicating that the Al_2O_3-PVA thin film has a strong absorption band at approximately 320 nm, while Fig. 1(c) shows the linear absorption of the SA, where the highlighted region indicates the wavelength range where the Q-switching pulses are obtained. The modulation depth of the Al_2O_3-PVA SA is approximately 3.5% based on minimum pulse duration obtained as reported in our previous work.[19] Typically, the measurement of saturation intensity and the non-saturable loss would be ideal. However, the necessary equipment operating at 1.0 μm is not available at the time of this work. The saturation intensity of our SA would be approximately 0.03 mW/cm^2 based on the quite similar obtained value in the literature.[20]

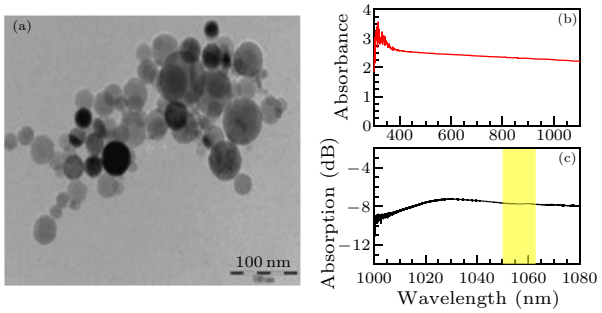

Fig. 1. Material characteristics of the Al_2O_3-based SA: (a) SEM image, (b) UV-vis absorbance spectrum of Al_2O_3-PVA thin film, and (c) linear absorption with operation-band region highlighted.

The schematic setup of the proposed dual-wavelength Q-switched YDFL based on Al_2O_3-PVA-SA is shown in Fig. 2. The fiber laser ring cavity configuration comprises a 1.5 m Yb-doped fiber (YDF) (Nufern SM-YSF-HI) with a peak absorption of 250 dB/m at 975 nm as a gain medium. The YDF pumped by a 975 nm laser diode (LD) has a maximum allowable output power of 330 mW (Thorlabs PL980P330J). The pump power is coupled into gain medium via a 980/1060 fused wavelength division multiplexer (WDM). The measured coupling efficiency for the 980/1060 nm fused WDM is 97.9%. To ensure unidirectional light propagation and to avoid backward reflection in the laser system, a polarization-independent isolator (PI-ISO) is placed after the YDF. A polarization controller (PC) is utilized to optimize the laser output and to adjust the polarization state of light. A 10:90 optical coupler (OC) is used to extract 10% of the laser beam out from the cavity to analyze the characteristics of the output pulse train. The output optical spectrum of the proposed laser was monitored by an optical spectrum analyzer (OSA) (YOKOGAWA AQ6370C) with a minimum resolution of 0.02 nm, and a 5 GHz battery biased InGaAs PIN detector (Thorlabs DET08CFC) combined with a 500 MHz digital phosphor oscilloscope (Tektronix DPO3052). The total cavity length is 6.3 m. The prepared Al_2O_3-PVA thin film was cut into small pieces 1 mm × 1 mm, by attaching one piece onto standard FC/PC fiber ferrule end surface, adhered with index matching gel and after connecting it with another FC/PC fiber ferrule through a standard adapter a compact SA is formed.

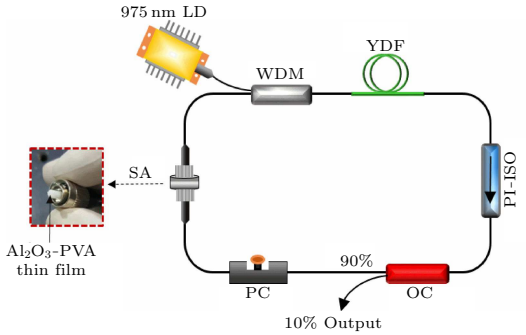

Fig. 2. Schematic diagram of the proposed Q-switched Yb-doped fiber laser with the Al_2O_3 SA.

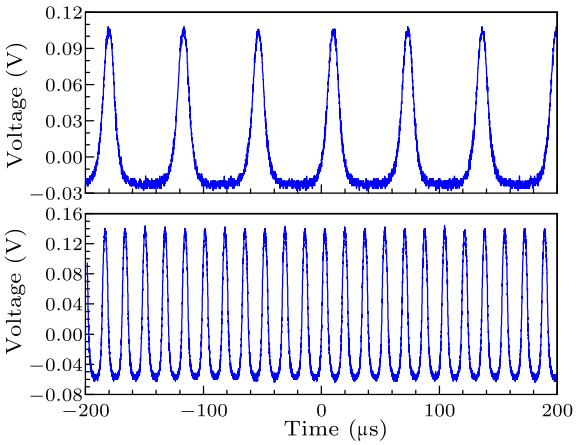

Fig. 3. Oscilloscope traces in the Q-switched pulse train: (a) with a repetition rate of 16.23 kHz at pump power of 80 mW, and (b) with a repetition rate of 59 kHz at pump power of 300 mW.

The YDFL starts to operate in the continuous-wave (CW) mode at the pump power threshold of 70 mW. When the prepared SA is inserted into the cavity and the pump power is enhanced to 80 mW, a stable pulse train is visible on the oscilloscope. To further investigate the behavior of the Q-switching operation, the pump power is increased gradually

from 80 to 300 mW. With the stepwise increase of the pump power, the repetition rate increases from 16.23 to 59 kHz, while the full width at half maximum (FWHM) of the pulse width decreases from 19 to 6 μs as illustrated in Fig. 3, confirming a typical behavior of a Q-switched pulse. The repetition rate and pulse width versus pump power are depicted in Fig. 4(a). The average output power under different pump power levels, and the corresponding calculated pulse energies are illustrated in Fig. 4(b). The pulse energy was calculated by dividing the output power by its corresponding repetition rate. It is observed that the average output power and the pulse energy almost linearly increase with the input pump power. The maximum pulse energy is 16.9 nJ. The calculated energy is the total energy for both the 1050 and 1060.7 nm wavelengths.

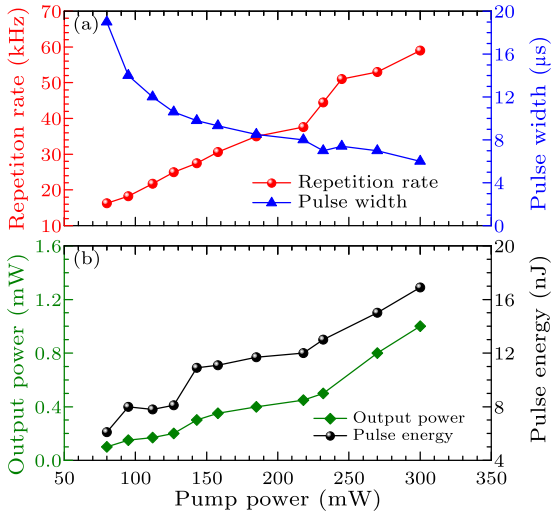

Fig. 4. Q-switched laser characteristics: (a) the repetition rate and pulse width versus pump power, and (b) the average output power and pulse energy versus pump power.

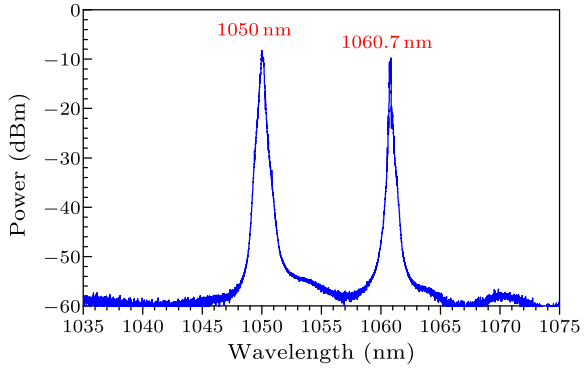

Fig. 5. The dual-wavelength optical spectrum centered at 1050 and 1060.7 nm at pump power of 300 mW.

It is known that the polarization-dependent loss could be generated by squeezing the fiber in the PC inside the ring cavity, which could reduce the mode competition caused by the homogeneous broadening in the YDF gain medium. The combination of the intracavity birefringence effect with polarization-dependent loss can produce a comb filtering effect for achieving multi-wavelength operation.[21] Therefore, a self-starting dual-wavelength Q-switched laser output centered at 1050 and 1060.7 nm is easily observed with proper adjustment of the PC. In our experiments, the PC is employed to adjust the polarization state of light, to change the intracavity losses and the birefringence related filtering. During our experiment, regardless of the existence of the polarization controller, Q-switched pulses are always generated due to the SA. The only noticeable change in the laser performance is that the output power becomes lower when the PC is removed from the cavity. The wavelength spacing between the two peaks is 10.7 nm, which is due to intracavity birefringence. The wavelength spacing ($\Delta\lambda$) between the transmission peaks depends on the cavity birefringence, which is given by $\Delta\lambda = \lambda^2/(LB)$, where λ is the central wavelength, L is the cavity length, and B is the strength of birefringence.[22] Thus the stronger the cavity birefringence is, the smaller the spacing is. Figure 5 shows the obtained output spectrum of the dual wavelength Q-switched operation at the pump power of 300 mW. The wavelengths of these two peaks can be differentiated using a wavelength selective filter, such as a tunable band pass filter and a fiber Bragg grating (FBG). To evaluate the stability of Q-switched operation at pump power of 300 mW, the optical spectrum of the Q-switched fiber laser is recorded for 1 h, as shown in Fig. 6(a). It is noted that the central wavelength locations remain stable without noticeable fluctuation in the output power. Figure 6(b) shows the radio frequency (RF) spectrum at the maximum repetition rate of 59 kHz measured using a radio-frequency spectrum analyzer (Anritsu MS2712E). The spectrum has a signal-to-noise ratio (SNR) of 54 dB, which indicates that the pulses are highly stable.

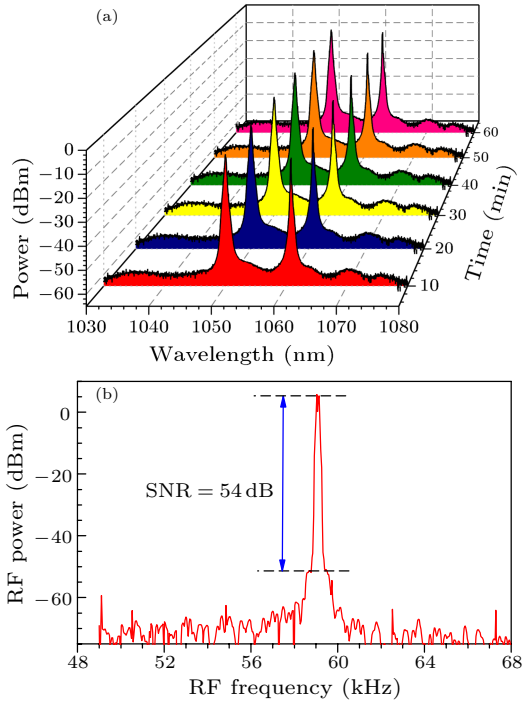

Fig. 6. Laser performance over 1 h at pump power of 300 mW: (a) optical spectrum, and (b) RF spectrum at 59 kHz.

When the Al_2O_3-PVA SA is removed from the fiber connector, the fiber laser returns to its CW mode of operation no matter what the pump power is. This does reflect that the prepared Al_2O_3-PVA film is indispensable to generate Q-switched pulses within the cavity. In our experiment, the measured insertion loss of the Al_2O_3 thin-film-based SA is ∼7.9 dB. This loss includes the absorption of the thin-film-based SA itself and the misalignment between the two ferrules caused by the incorporation of the SA. This high loss can impose some restrictions on the gain of the cavity and limits the pulse width.[23] Thus the Q-switched laser performance and the output power could be enhanced by fabricating thinner and more even film using a spin coating technique.

In conclusion, we have demonstrated a stable dual-wavelength passively Q-switched YDFL based on Al_2O_3-SA without using intracavity spectral filters. The two lasing peaks are located at 1050 nm and 1060.7 nm with a wavelength spacing of 10.7 nm. As the pump power increases from 80 mW to 300 mW, the Q-switched operation can generate pulses with durations from 19 μs to 6 μs and repetition rates from 16.23 kHz to 59 kHz. The pulses have maximum pulse energies of 16.9 nJ. Our results show that Al_2O_3 has a significant potential for generating a Q-switched output in the 1 μm region, and can be used to fabricate a simple, compact, and low-cost pulsed dual-wavelength fiber laser operating under room conditions.

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