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Wavelength-tunable, dual-wavelength Q-switched Ho^{3+}-doped ZBLAN fiber laser at 1.2 µm

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Abstract

Wavelength-flexible Q-switched Ho^{3+}-doped ZBLAN fiber laser at 1.2 µm is experimentally investigated for the first time. The gain medium is Ho^{3+}-doped ZBLAN fiber, which is pumped by a 1137-nm Raman fiber laser. Nonlinear polarization rotation technique works as the saturable absorber in the ring cavity to provide the intensity modulation. An artificial Lyot filter is inserted into the cavity and its periodic transmission spectrum varied with the polarization allows for the tunability and multi-wavelength operation of the laser. As a result, the laser spectrum tunable from 1190 to 1196 nm and dual-wavelength Q-switched pulses are observed. At a pump power of 2.01 W, stable Q-switched pulse train with the pulse duration of 0.76 µs and pulse energy of 0.62 µJ is achieved.

1 Introduction

Wavelength-flexible fiber lasers are of great interest for such applications as in fiber-optic systems, nonlinear optics, and wavelength division multiplexing networks. However, wavelength-tunable or multi-wavelength fiber lasers operating around 1.2 µm are seldom reported because of lack of efficient gain medium. Coherent radiation at these wavelengths can generally be obtained by ytterbium (Yb^{3+}) [1] and bismuth (Bi) [2] ions-doped silicon fiber, as well as nonlinear frequency conversion technique like stimulated Raman scattering [3, 4]. Nevertheless, due to the relatively weak gain of Yb^{3+}, Bi ions at this region and the lengthy gain fiber in Raman lasers, more efficient and compact laser with new type of gain medium are demanded. ZrF_4–BaF_2–LaF_3–AlF_3–NaF (ZBLAN) is a highly stable heavy metal fluoride glass and an ideal host for rare-earth ions. Holmium (Ho^{3+})-doped ZBLAN fibers have been demonstrated as high-efficiency gain media for 1.2-µm lasers [5, 6].

In many application areas, such as industrial marking, trimming, and machining, pulsed laser performs pretty better than continuous laser owing to the high peak power and less thermal effect. Up to now, there are only few reports on pulsed lasers at 1.2 µm based on Ho^{3+}-doped ZBLAN fiber. Yang et al. [7] and Wang et al. [8] successively investigated mode-locked Ho^{3+}-doped ZBLAN fiber lasers at 1.2 µm with nonlinear polarization rotation (NPR) technique and carbon nanotube, respectively. However, their reported mode-locked lasers can only provide pulses with pulse energy on the order of few nJ. Compared to mode-locked lasers, Q-switched lasers usually can produce pulses with much higher pulse energy. In 2015, Liu et al. reported a Q-switched Ho^{3+}-doped ZBLAN fiber laser at 1190 nm using graphene as saturable absorber (SA) [9]. Wang et al. demonstrated a semiconductor-saturable absorber mirror (SESAM) Q-switched Ho^{3+}-doped ZBLAN fiber laser operating at ~1190 nm in a linear cavity [10]. Nevertheless, the process of making and using graphene and SESAM are fairly complex and inconvenient. Moreover, they are easy to be damaged by high energy pulse. From the viewpoint of easy operation, nonlinear polarization rotation is a simpler Q-switching technique.

In this letter, we report a wavelength-tunable, dual-wavelength Q-switched Ho^{3+}-doped ZBLAN ring-cavity fiber

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laser at 1.2 μm employing NPR technique as an artificial SA. A Lyot filter based on the combination of birefringence of 50 cm polarization maintaining (PM) fiber and a polarizer was inserted into the all-fiber cavity to generate wavelength-tunable and dual-wavelength Q-switching operation. Stable Q-switched pulse train with the pulse duration of 0.76 μs and pulse energy of 0.62 μJ are obtained at a pump power of 2010 mW. By appropriately adjusting the polarization controller (PC), wavelength-tunable Q-switching laser with various wavelengths from 1190 nm to 1196 nm is achieved. Dual-wavelength emission at 1192 and 1196 nm are obtained by rotating the PC in the cavity. As far as we know, it is the first reported wavelength-tunable and dual-wavelength Q-switched Ho^{3+}-doped ZBLAN fiber laser at 1.2 μm.

2 Experimental setup

The configuration of the Q-switched ring fiber laser is illustrated in Fig. 1. According to the absorption and emission cross sections of Ho^{3+} ions, Ho^{3+}-doped ZBLAN fiber has an absorption band around 1150 nm and the emission around 1.2 μm is generated when the population transition from $^5I_6$ level to the ground state $^5I_8$ occurs [5]. In our experiment, a 1137-nm linearly polarized Raman fiber laser is used as the pump source and it can pump Ho^{3+} ions directly into the upper laser level with low quantum defect. The gain fiber is a 12.5 cm 3 mol% Ho^{3+}-doped ZBLAN fiber, which has a core diameter of 5.3 μm and a cladding diameter of 125 μm. Two pieces of HI1060 silica fiber are spliced with the Ho^{3+}-doped ZBLAN fiber at both ends applying NP photonics proprietary splicing technique [11], which can highly reduce the splice losses (single point < 0.5 dB). A polarization-dependent isolator (ISO) with the fast axis blocked is used to force the unidirectional operation of the ring laser and still employed as an in-line polarizer. A fused-type wavelength division multiplexer (WDM) is utilized to couple the 1137-nm laser into the ring cavity. The propagation directions of the pump and the signal light are opposite. An output coupler, which is designed as a PM 1120/1180 nm WDM, is employed to deliver 20% of the Q-switched laser out at 1.2 μm and extract the residual 1137 nm pump laser as well. An artificial Lyot filter working as a waveplate is formed by the PM fiber coupler spliced with a 50 cm long PM980 fiber at an angle of 45° [12]. In addition, a PC is implemented to adjust the polarization state inside the ring cavity to control the tunable-wavelength and dual-wavelength Q-switching operation. The total length of this ring-cavity fiber laser is about 15 m. In the experiment, the pulse train and single pulse width is recorded with a photoelectric detector (THORLABS, DET01CFC) and analyzed with a 1-GHz digital phosphor oscilloscope. The output power is measured with a power meter (THORLABS, S145C). The optical spectrum of the laser is measured with an optical spectrum analyzer (YOKOGAWA, AQ6370B) with a resolution of 0.02 nm

3 Results and discussion

Wavelength-tunable fiber lasers are usually achieved based on optical filters such as fiber Bragg gratings, fiber Fabry Perot and reflective diffraction grating, which can be used to select the lasing wavelength and introduce large loss to other wavelengths. Compared to the filters mentioned above, an intra-cavity Lyot filter induced by cavity birefringence can simplify the laser structure and save costs. An artificial Lyot fiber filter is ordinarily constructed by placing a high birefringence PM fiber between two polarizers with the PM fiber slow axis at an angle of 45° relative to the polarizer

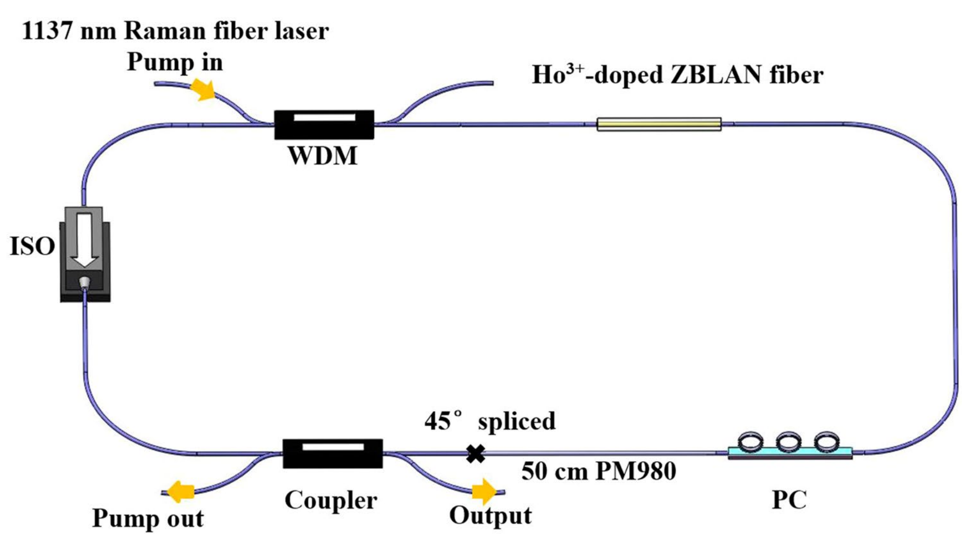

Fig. 1 Experimental configuration of the Q-switched Ho^{3+}-doped ZBLAN fiber laser

axis. Fortunately, it is not necessary to insert two polarizers for a ring fiber cavity, since one polarizer can be qualified the function of the second polarizer at the end of one round trip. In our experiment, a 0.5-m-long PM980 fiber served as the birefringence waveplate and the fast axis blocked isolator is utilized as the polarizer. The wavelength-dependent different phase accumulation between the two axes of the PM fiber can generate a quasi-periodic filter transmission function given by $T = \cos^2(\pi L\Delta n/\lambda)$ [13], where Δn is the birefringence of the PM fiber, L is the length of the PM fiber, and λ is the wavelength. The transmission spectra of our composite Lyot filter are theoretically calculated and shown in Fig. 2a. The peak transmission positions of the intra-cavity Lyot filter can be shifted from the black curve to red or blue one by rotating the PC, resulting that the cavity loss varies with wavelength.

In the experiment, NPR technique is employed as the SA to start Q-switching operation by transforming intensity-dependent polarization into intensity modulation.

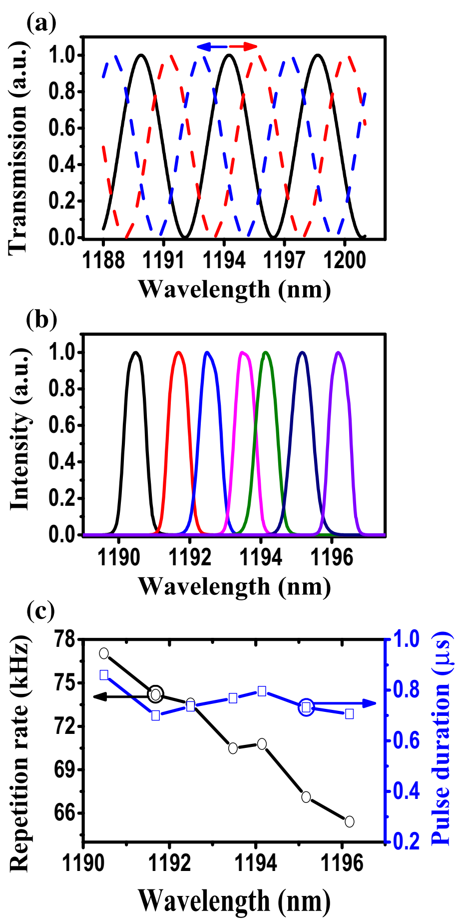

Fig. 2 **a** The simulated transmission spectra of the artificial Lyot filter. **b** The intensity-normalized tunable wavelength spectrums at a pump power of 1840 mW. **c** The repetition frequency and pulse duration versus the lasing wavelength at a pump power of 1840 mW

Q-switched operation starts when the pump power exceeds the threshold of about 780 mW. At a pump power of 1840 mW, the wavelength-tunable Q-switched operation is obtained by properly adjusting the angle of the PC. Figure 2b shows the intensity-normalized optical spectrum for seven wavelengths from 1190.5 to 1196.2 nm at the pump power of 1840 mW. The pulse train repetition frequency and single pulse duration as a function of pump power are shown in Fig. 2c. With the laser wavelength shifting from 1190 to 1196 nm, the repetition rate of the Q-switched pulses decreases gradually from 77 to 65.5 kHz. In Q-switching lasers, the repetition frequency relies on the SA's saturation rate which is related to the in-cavity power. In the region from 1190 to 1196 nm, the longer wavelength is, the smaller emission cross section of Ho^{3+} ions is Zhu et al. [6], and the weaker laser power is. Thus, the small emission cross section for long wavelength lasing should be responsible for the low repetition rate. However, compared with the generated laser power, the pump power plays a dominant role in the cavity. When the pump power is fixed at 1840 mW, the gain provided to saturate the SA is fairly stable and the pulse duration is related to the recovery time of SA. Therefore, the pulse duration keeps relatively stable about 0.75 µs as the lasing wavelength shifting.

Stable Q-switched operation starts at a pump power of 930 mW by adjusting the PC and maintains until the pump power reaches 2010 mW. Figure 3a shows the pulse repetition rate and pulse energy as a function of pump power, respectively. As the pump power increases from 930 to 2010 mW, the pulse energy increases from 0.29 to 0.62 µJ, and the repetition rate increases from 34.5 to 71.1 kHz. It is the reason that higher intensity exerted to saturate the SA as the pump power rising causes faster saturation that the pulses repetition rate relies on. The maximum output average power is measured to be 44 mW at 2010 mW pump power, corresponding to a slope efficiency of 3.6%. Besides, with the pump power increasing, the pulse duration has a significant narrowing from 2.1 to 0.76 µs and the pulse peak power increases from 0.14 to 0.82 W, which are shown in Fig. 3b. When the pump power is fixed at 2010 mW, the output spectrum is illustrated in Fig. 3c. The central wavelength is 1192.7 nm with 3 dB bandwidth of about 0.4 nm and the spectral signal-to-noise ratio is about 42.5 dB that means high spectral purity. The stable Q-switched pulses train and single pulse are recorded by an oscilloscope using an InGaAs photodiode with 1.5 GHz bandwidth at this pump power, as shown in Fig. 3d. The repetition rate is 71.1 kHz and the single pulse duration is about 0.76 µs.

A Lyot filter has a quasi-periodic wavelength transmission feature, as mentioned above. Therefore, it is possible to oscillate multi-wavelengths simultaneously when the active gain medium has a broad emission spectrum. The free spectral range (FSR) of a Lyot filter is given by $\Delta\lambda = \lambda^2/L\Delta n$

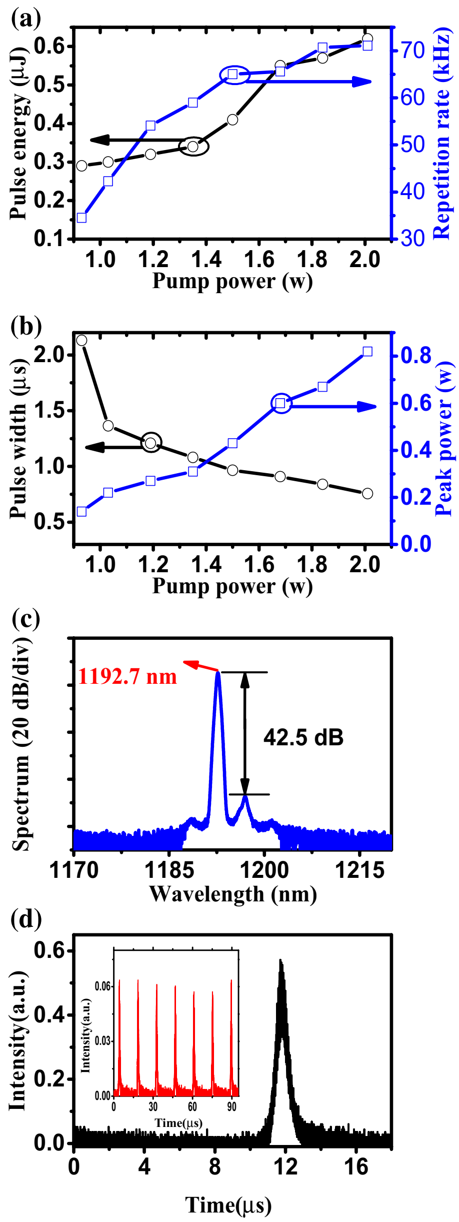

Fig. 3 Laser output characteristics: **a** the repetition frequency and pulse energy, respectively, and **b** pulse duration and pulse peak power versus the pump power. **c** Output spectrum, **d** pulse profile and pulse train (inset) at a pump power of 2010 mW

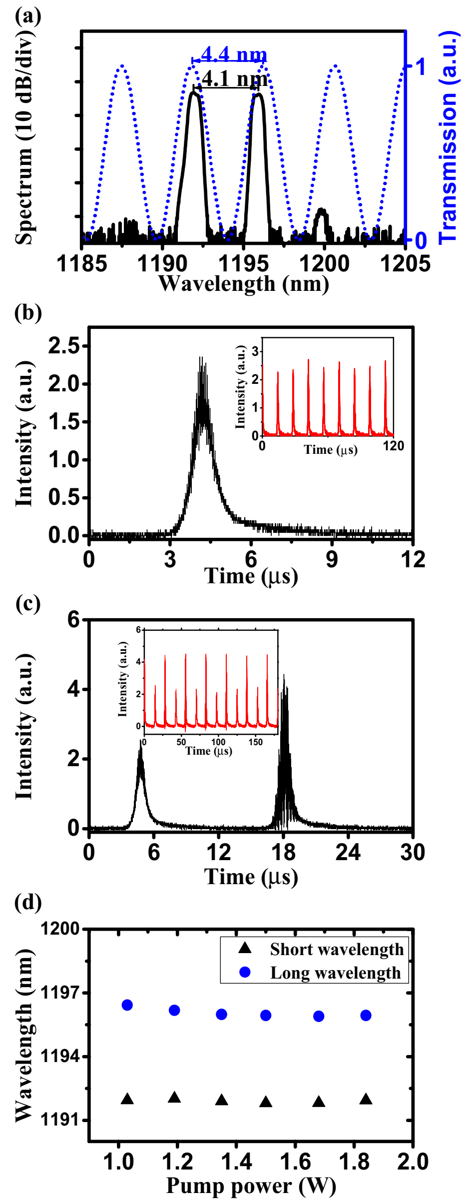

Fig. 4 Dual-wavelength laser characteristics: **a** typical optical spectrum (solid black curve) of dual-wavelength Q-switched operation of the fiber ring laser at the pump power of 1840 mW and the simulated transmission of the Lyot filter (dotted blue curve). **b** Typical pulse profile and pulse train (inset). **c** Pulse profile and pulse train (inset) of an intermediate process from the Q-switching establishment to stabilization. **d** The short and long wavelength distribution as a function of pump power in dual-wavelength Q-switched operation

[13], where λ is the wavelength, L is the length of the PM fiber, and Δn is the birefringence. The FSR can be arbitrarily chosen by changing the length of PM fiber. In our experiment, a 50-cm PM980 fiber is used in the Lyot fiber and the wavelength space is calculated about 4.4 nm which is shown in the dotted blue curve in Fig. 4a.

At the pump power of 1840 mW, dual-wavelength passively Q-switched operation is observed by appropriately rotating the PC and the spectrum is recorded and illustrated in Fig. 4a, the solid black curve. The two simultaneous lasing wavelengths are at 1191.94 nm and 1195.94 nm with a wavelength separation of 4 nm, which is very close to the theoretical value of 4.4 nm. The reason for the slight deviation may be that the length of the PM fiber after fuse splicing and the birefringence ($\sim 6.5 \times 10^{-4}$) are inaccurate. The output power is about 25.6 mW and the stable dual-wavelength Q-switched pulses are recorded and shown in

Fig. 4b. The repetition rate is 71.9 kHz and the single pulse duration is about 0.73 µs. An intermediate process from the Q-switching establishment to stabilization is captured by the oscilloscope, which is illustrated in Fig. 4c. The pulse train recorded has a distinct periodic amplitude fluctuation where the pulse repetition is about 72.7 kHz and the intensity proportion of the taller pulse and the lower pulse is 55% and 45%, respectively. This instantaneous pulse intensity floating may be related to the spectral ratio of two oscillating wavelengths at that time. When the pump power is decreased from 1840 to 1030 mW, stable dual-wavelength Q-switched lasing is maintained. As illustrated in Fig. 4d, the large dropping of pump power has little influence on the lasing wavelengths. The shorter wavelength is around 1192 nm, the longer is around 1196 nm, and the space between them is about 4 nm.

4 Summary

We have firstly demonstrated a wavelength-flexible Q-switched Ho^{3+}-doped ZBLAN fiber laser at 1.2 µm using NPR technique. The gain medium is Ho^{3+}-doped ZBLAN fiber that is pumped by a 1137-nm Raman fiber laser. Stable Q-switched pulse trains with the pulse duration 0.76 µs and pulse energy 0.62 µJ are achieved. An all-fiber intra-cavity Lyot filter, combined with a PC, wavelength tunable from 1190 to 1196 nm and dual-wavelength Q-switching operation is obtained.

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