Switchable Q-switched and mode-locked erbium-doped fiber laser operating in the L-band region

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We demonstrate a switchable Q-switched and mode-locked erbium-doped fiber laser (EDFL) operating in the L-band region using the nonlinear polarization rotation effect. The switching operation is achieved by controlling intensity-dependent loss using a polarization controller. In Q-switching mode, the EDFL produces a pulse train with a repetition rate of 21.1 kHz, pulse width of 7.7 μs, and pulse energy of 13.6 nJ. The EDFL also generates a multi-wavelength comb with a very narrow and constant wavelength spacing of 0.045 nm and optical signal-to-noise ratio of at least 10 dB. During mode locking, the EDFL produces stretched pulses with 3-dB bandwidth of 26.2 nm, pulse width of 350 fs, repetition rate of 2.38 MHz, and pulse energy of 48.56 pJ.

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Pulsed fiber lasers elicit considerable attention because of their reliability, compactness, and low cost. These lasers have numerous potential applications in optical signal processing, optical communications, and optical sensing and measurement[1,2]. These lasers can be generated using Q-switching and mode-locking techniques. Mode-locked fiber lasers have high repetition rate (GHz) and narrow pulse width, whereas Q-switching lasers have lower repetition rate (kHz) but higher pulse energy and broader pulse width[3]. Interest in erbium-doped fiber lasers (EDFLs) operating in the L-band region is mainly ascribed to the prospect in exploiting the optical spectrum of the optical fiber. Furthermore, fiber loss is slightly lower in the L-band region compared with that in the conventional C-band region[4,5]. Passive mode-locked and Q-switched EDFLs have been extensively applied and tested in the C- and L-band regions[6,7]. The lasers normally consist of saturable absorbers, which are mainly semiconductor-saturable absorber mirrors[8−10], graphene[11,12], and carbon nanotubes[13], to achieve passive mode locking or Q switching.

Nonlinear phenomena in optical fibers such as nonlinear polarization rotation (NPR) can also be used for sub-100-fs pulse generation by dispersion management in the cavity[14]. A previous study reported the generation of a 50-fs pulse train using a NPR technique in a normal dispersion erbium fiber oscillator[15]. Given the rapid development in technology, different kinds of lasers are needed for different applications. A versatile system is thus important, in which different lasers can be generated from a single system. However, only a few reports on such multi-function laser systems have been published. Tian *et al.*[16] demonstrated the switchable function of mode locking and continuous wave (CW) single-wavelength and multi-wavelength lasing using nonlinear optical loop mirror configuration. Gao *et al.*[17] reported on switchable functions between passive single-pulse and multiple-pulse mode locking, coherent pulse pattern, and passive Q switching. In this letter, a switchable Q-switched and mode-locked EDFL operating in the L-band region is demonstrated based on a switchable NPR effect using a Mach–Zehnder interferometer (MZI) as a comb filter. Depending on the intensity-dependent loss in the ring cavity, the laser can operate in either one of two working regimes, namely, Q switching or mode locking. The operation of this laser can be switched by merely adjusting the polarization state of light with a polarization controller (PC).

The configuration of the dual function switchable EDFL is shown in Fig. 1; it consists of an erbium-doped fiber (EDF), a PC, polarization-dependent isolator (PDI), a MZI, a 10-dB output coupler, and a wavelength division multiplexing (WDM) coupler. The EDF is forward pumped by a 1480-nm pump through a WDM coupler for an amplified spontaneous emission in the L-band region, which oscillates in the ring cavity to generate laser. A MZI, which is constructed by connecting two 3-dB couplers, functions as a comb filter in the ring cavity. The MZI has upper and lower path lengths of approximately 374.2 and 378.8 cm, respectively. Thus, the optical path length difference is approximately 3.6 cm. The phase difference between the two recombined light at the output end of the MZI produces a comb filter in the ring cavity. The operating wavelength of the oscillating laser is determined by the comb characteristics, as well as the cavity loss and erbium gain characteristics.

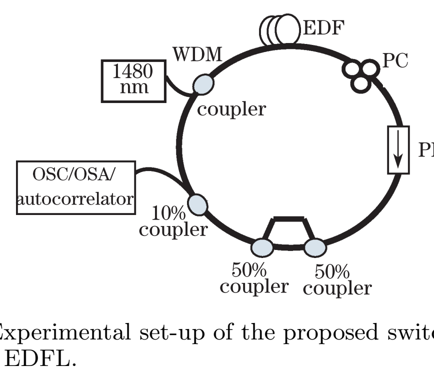

Fig. 1. Experimental set-up of the proposed switchable dual-function EDFL.

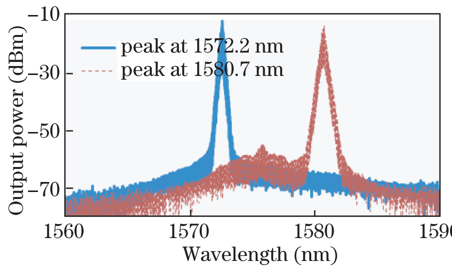

Fig. 2. Output spectrum of the EDFL at two different PC settings when the 1480-nm pump is fixed at 130 mW.

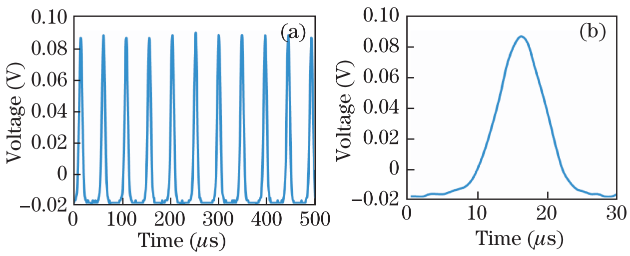

Fig. 3. Pulsing behavior of the proposed Q-switched EDFL: (a) pulse train showing a repetition rate of 21.2 kH and (b) single-pulse envelope showing a pulse width of 7.7 μs.

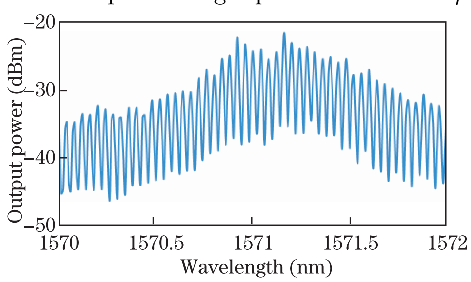

Fig. 4. Enlarged figure of the output spectrum of the Q-switched EDFL showing a comb spectrum.

The PC is used to adjust the polarization state of the oscillating light, and the PDI is used to enforce unidirectional operation. Aside from ensuring unidirectional operation, the PDI also acts as a polarizer. Mode locking and Q switching are achieved through the NPR effect from the PC and PDI, which induces intensity-dependent loss. A 10-dB coupler is placed after the MZI to tap and channel some portions of the light to the optical spectrum analyzer (OSA), oscilloscope (OSC), and autocorrelator for the analysis of the characteristics of the output pulses. The estimated cavity length is approximately 62.6 m, which includes a piece of 50-m EDF and 12.6-m standard single mode fiber (SMF-28). The EDF has an erbium concentration of 440 ppm, a cutoff wavelength of 953 nm, a pump absorption rate of 5.5 dB/m at 979 nm, and a dispersion coefficient of –21.64 ps/(nm·km) at $\lambda = 1\,550$ nm. SMF-28 has a dispersion coefficient of 17 ps/(nm·km). This laser operates at the normal dispersion region.

The ring EDFL starts to generate a multi-wavelength comb as the 1 480-nm pump power is increased above 62 mW. Figure 2 shows the output spectrum of the laser at the 1 572.2-nm region with a peak power of –12.5 dBm at the maximum pump power of 130 mW. The comb laser can be tuned to a longer wavelength of up to 1 580.7 nm by adjusting the polarization state in the cavity. At 1 580.7 nm, the laser produces a maximum peak power of –14.1 dBm. When the pump power of the laser system is increased above 116 mW, a stable Q-switched operation commences from the modulation of population inversion induced by the phase modulation of our laser cavity, which consists of a MZI filter. This condition is achieved when the PC is adjusted so that the cavity loss is high, thereby preventing the light from oscillating. Meanwhile, population inversion increases, resulting in a high stored energy in the gain medium. After some time, the gain medium becomes saturated, and amplification occurs where the Q-switched pulse is formed. The pulses formed by the Q-switching process in the resonator are detected using a 6-GHz photodetector and a 500-MHz digital phosphor oscilloscope.

Figures 3(a) and (b) show a typical oscilloscope trace of the pulse train and single pulse envelop of the laser at the pump power of 130 mW. The Q-switched laser produces a pulse train with a repetition rate of 21.2 kHz and an average output power of 0.29 mW, which translates to a pulse energy of 13.6 nJ. The measured pulse width of the Q-switched output laser is approximately 7.7 μs. The repetition rate and output power of the generated Q-switched laser exhibit a monotonically increasing trend with pump power. Figure 4 shows an enlarged output spectrum of the laser measured by the OSA with a resolution of 0.1 nm. The laser produces a multi-wavelength comb with a very narrow constant spacing of 0.045 nm and optical signal to noise ratio (OSNR) of ~10 dB within the 1 570–1 572-nm wavelength region. The spacing of the comb is expressed by

$$\Delta\lambda = \lambda^2/(n\Delta L),$$

where λ is the operating wavelength, n is the fiber refractive index, and ΔL is the difference in path length between the MZI arms. The spacing can be tuned by changing the filtering characteristic of the MZI.

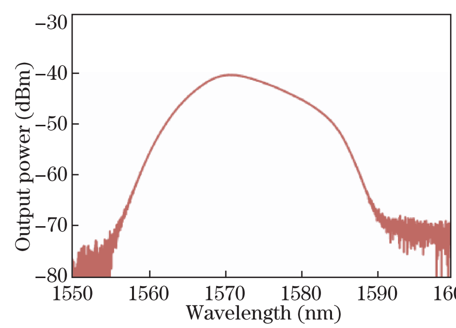

Fig. 5. Optical spectrum of the mode-locked fiber laser at pump power of 130 mW.

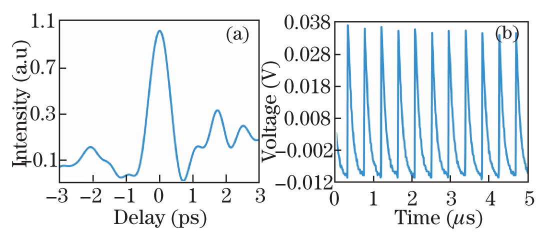

Fig. 6. Temporal characteristics of the mode-locked laser: (a) autocorrelation trace of the stretched pulse mode-locked laser and (b) pulse train with repetition rate of 2.38 MHz.

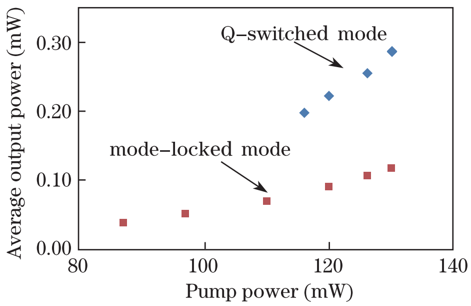

Fig. 7. Average output power against pump power for Q-switched and mode-locked EDFL.

The PC is re-adjusted to reduce the cavity loss. Consequently, stable mode-locked pulses are generated when the pump power is set above the threshold power of 72 mW. Mode locking is achieved through the NPR effect of the PC and PDI, which induces intensity-dependent loss. Light leaving the PDI has a linear polarization state. The linearly polarized light is then changed to elliptically polarized light by adjusting the PC. When elliptically polarized light propagates through a Kerr media, its two orthogonal components undergo different nonlinear phase shifts depending on the intensity of the light. The center of the pulse with higher intensity rotates at a different degree compared with the edge of the pulse. The state of light polarization in the PC is optimized so that only the center of pulse passes through the PDI, whereas the edges of the pulse with lower intensity are blocked. This process of passing through and amplifying the center of the pulse is repeated. After many cycles, a train of mode-locked pulses is generated. Figure 5 displays the output spectrum of the mode-locked laser showing a stretched pulse characteristic. The laser operates at a wavelength centered at 1 570.5 nm with a maximum output power of –39.9 dBm and a 3-dB bandwidth of 26.2 nm. The temporal characteristics of the pulse are shown in Fig. 6. Figure 6(a) shows the autocorrelation trace of the pulse with full-width at half-maximum (FWHM) of 350 fs using a sech fitting function. Figure 6(b) shows the pulse train with a repetition rate of 2.38 MHz. The corresponding pulse energy is 48.56 pJ. The mode-locked pulse is generated because of the NPR effect, which induces the intensity modulation in the ring cavity. The stretched pulse is generated because the total group velocity dispersion is positive in the ring cavity. Figure 7 shows the relation between average output power and 1 480-nm pump power. The output power linearly increases with pump power for both Q-switched and mode-locked lasers. The Q-switched laser produces a higher average output power compared with the mode-locked laser. Therefore, pulse energy is relatively higher in the Q-switch laser compared with that in the mode-locked laser.

In conclusion, a switchable Q-switched and mode-locked EDFL operating in the L-band region is demonstrated based on the NPR effect and on the polarization state of light in the ring cavity. Depending on the intensity-dependent loss in the cavity, the laser can operate in either the Q-switching or mode-locking regime. Q-switched EDFL is generated by adjusting the PC to obtain a higher cavity loss; it produces a pulse train with a repetition rate of 21.1 kHz, pulse width of 7.7 μs, and pulse energy of 13.6 nJ at the maximum pump power of 130 mW. The EDFL also produces a multi-wavelength comb with very narrow spacing of 0.045 nm and OSNR of at least 10 dB. By re-adjusting the PC to reduce the cavity loss, mode-locking stretched pulses with 3-dB bandwidth of 26.2 nm can be generated; it has a pulse width of 350 fs, repetition rate of 2.38 MHz, and pulse energy of 48.56 pJ.

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