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Single-/dual-wavelength switchable and tunable compound-cavity erbium-doped fiber laser with super-narrow linewidth*

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A single-/dual-wavelength switchable and tunable erbium-doped fiber laser (EDFL) with super-narrow linewidth has been proposed and experimentally demonstrated at room temperature. The fiber laser is based on a compound cavity simply composed of a ring main cavity and a two-ring subring cavity (TR-SC). Regardless of single- or dual-wavelength operation, the EDFL could always work well in single-longitudinal-mode (SLM) state at every oscillating wavelength. In dual-wavelength operation, the spacing could be tuned from 0 nm to 4.83 nm. In single-wavelength operation, the EDFL could lase at a fixed wavelength of 1 543.65 nm or another wavelength with a tunable range of 4.83 nm. The super-narrow linewidths of 550 Hz and 600 Hz for two wavelengths are obtained. The proposed EDFL has potential applications in microwave/terahertz-wave generation and high-precision distributed fiber optical sensing.

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Dual-wavelength single-longitudinal-mode (SLM) erbium-doped fiber lasers (EDFLs) are considered to be excellent sources for applications such as wavelength division multiplexing transmission system, fiber sensing, optical signal processing, LIDAR, and microwave photonic generation[1-5]. The single-/dual-wavelength switchable operation is another crucial target for research of EDFLs[6].

In order to achieve SLM operation for EDFLs, many configurations have been proposed in the past few decades, such as distributed feedback[7,8], short-cavity distributed Bragg reflector[9], conventional linear and ring cavities incorporating complicated ultra-narrow-band filters[10-13], and compound cavity[14-17]. Due to the drastic mode competition induced by homogenous gain broadening effect in EDF, stable dual-wavelength SLM oscillation is not easy to achieve. In recent years, many researchers have reported different techniques to demonstrate stable dual-wavelength SLM EDFLs, such as a novel symmetrical fiber Bragg grating (FBG) structure as compact dual-wavelength laser cavity[2], a reconfigurable dual-pass Mach-Zehnder interferometer (MZI) filter[18], an unpumped polarization-maintaining EDF saturable absorber filter[19], two superimposed FBGs and an in-line two-taper MZI filter[20], a 70 cm long EDF loop attached to a microfiber coupler as wavelength filter[21], a polarization-maintaining chirped Moiré FBG as ultra-narrow filter[22], and a special U-bending apparatus based filter[23]. However, all of the techniques cannot achieve continuously tunable wavelength-spacing, switchable single-/dual-wavelength operation and narrow linewidth lasing simultaneously.

In this paper, we propose and demonstrate a single-/dual-wavelength switchable and tunable SLM EDFL with super-narrow linewidth based on a compound cavity which consists of a ring main cavity and a two-ring subring cavity (TR-SC). The performance of this EDFL is investigated in detail.

The configuration of the proposed EDFL is shown in Fig.1. The fiber laser is based on a compound cavity consisting of a main cavity and a TR-SC. In the main cavity, a 7 m long commercial EDF is utilized as the gain medium pumped by a 980 nm laser diode (LD) with maximum power of 500 mW through a 980/1 550 nm wavelength division multiplexer (WDM). Two narrow-band FBGs (NB-FBGs), NB-FBG-1 and NB-FBG-2, are chosen as the original wavelength-selecting components for two wavelengths of λ_1 and λ_2, respectively. An optical

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circulator is employed to ensure the unidirectional oscillation in the ring cavity and to make two NB-FBGs work as reflectors. A variable optical attenuator (VOA) is introduced to adjust the reflection spectrum of NB-FBG-2 to enable the lasing at λ_1, λ_2, or both. A broad-band in-line polarizer, with the help of a polarization controller (PC), is used to introduce polarization dependent loss to suppress the mode-hopping significantly[24]. Also, the PC can balance the losses of λ_1 and λ_2 by adjusting their polarization states to achieve stable dual-wavelength oscillation. A 50:50 coupler is adopted to extract the laser for measurement. Due to the insertion of the VOA, the lengths of the main cavity for λ_1 and λ_2 lasing are about 23.5 m and 24.5 m, corresponding to the free spectrum ranges (*FSRs*) of ~8.7 MHz and ~8.4 MHz, respectively.

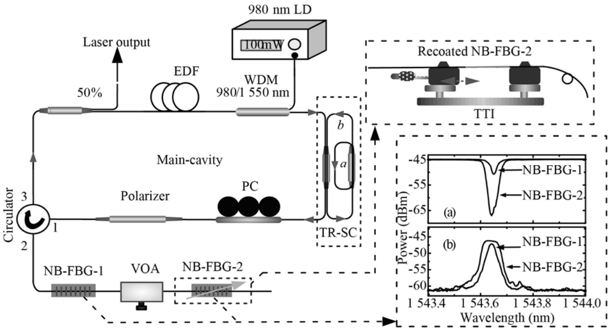


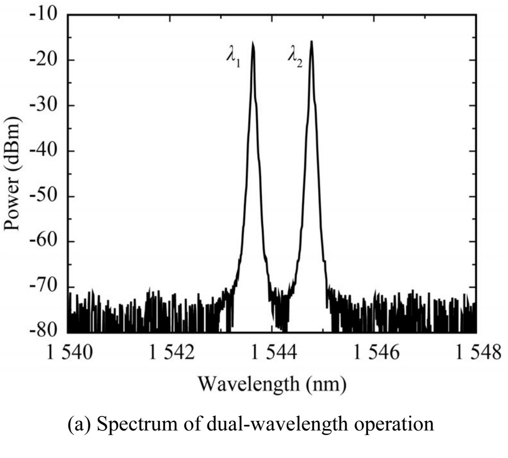
Fig.1 Experimental configuration of the proposed EDFL with (a) reflection and (b) transmission spectra of NB-FBG-1 and NB-FBG-2, respectively

The transmission and reflection spectra of the unperturbed NB-FBG-1 and NB-FBG-2 are also given in Fig.1, measured by an ANDO AQ6317C optical spectrum analyzer (OSA) with a resolution of 0.01 nm and an amplified spontaneous emission (ASE) source. The two FBGs were written in two sections of hydrogen-loaded Corning SMF-28 fibers using phase mask method. The center wavelengths of NB-FBG-1 and NB-FBG-2 are 1 543.650 nm and 1 543.642 nm, respectively. Their lengths are 5 cm and 10 cm, respectively, with different center wavelength reflectivities of 5.5 dB (71.82%) and 22 dB (99.37%) and 3-dB bandwidths of 0.035 nm and 0.071 nm. The reflectivity of NB-FBG-2 is higher than that of NB-FBG-1, which enables stable dual-wavelength operation by appropriately adjusting the VOA and PC. The NB-FBG-2 was recoated by a type of electronic silica glue to increase the strength of the fiber, while the optical characteristics were not influenced. As shown in Fig.1, fixed on a tension-tunable instrument (TTI), the period of NB-FBG-2 could be tuned continuously by shifting the left fiber chuck in the horizontal direction, and subsequently the center wavelength could be tuned.

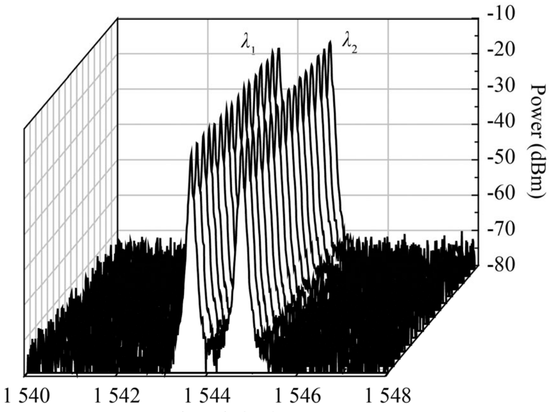
The TR-SC is based on two 3 dB couplers (50:50) as shown in Fig.1, and the lengths of rings *a* and *b* are 13 cm and 50 cm, respectively. Compared with the conventional single coupler subring cavity[25], the TR-SC possesses better mode selection capability. The *FSRs* of rings *a* and *b* are 1 600 MHz and 410 MHz, respectively, calculated by the equation of $FSR=c/nL_i$ (L_i denotes the ring length, and i denotes *a* or *b*), so the TR-SC has an *FSR* of 65.6 GHz according to the Vernier effect[26]. 65.6 GHz *FSR* is approximately corresponding to a wavelength range of 0.525 nm which is far beyond the 3-dB bandwidths of NB-FBG-1 and NB-FBG-2, indicating that there is only one longitudinal mode in the reflection bandwidth of NB-FBG-1 or NB-FBG-2. That means the SLM operation of the fiber laser is verified theoretically.

All measurements were carried out at room temperature, and we did not employ any vibration isolation method for the fiber laser system. The measured pump threshold is about 32 mW, which is a little high due to 50% coupling ratio used to extract the laser from the cavity.

The pump power is fixed at 120 mW. By shifting the left fiber chuck of the TTI to a random position and adjusting the VOA and PC appropriately to control the light loss and laser polarization state to weaken the mode competition, the fiber laser could be in stable dual-wavelength operation. Fig.2 shows the spectra of dual-wavelength oscillation measured by a YOKOGAWA AQ6375 OSA with the maximum resolution of 0.05 nm. As seen in Fig.2(a), the wavelength-spacing is 1.11 nm, the 3-dB bandwidths of two wavelengths are both 0.04 nm, and the side-mode suppression ratios (*SMSRs*) are both higher than 55 dB. The stability of the laser output is investigated by repeatedly scanning the OSA. The spectra of 16 times of repeated scans at 10 min intervals are shown in Fig.2(b). In 150 min experimental period, there is no wavelength hopping or switching, indicating that the dual-wavelength operation is stable. The maximum center wavelength shift and power fluctuation are less than 0.03 nm and 1 dB, respectively, for λ_1 and λ_2 both, which are relatively large and might mainly come from the jitter of the peak searching algorithm induced by the detector noise and finite step size of the YOKOGAWA AQ6375 OSA. More accurate results might be given by utilizing another OSA with higher resolution. Additionally, the stability of dual-wavelength operation can be improved further by employing a section of high nonlinear fiber[5,27].



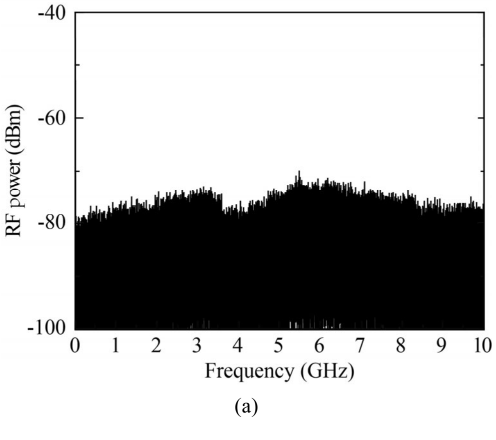
(a) Spectrum of dual-wavelength operation



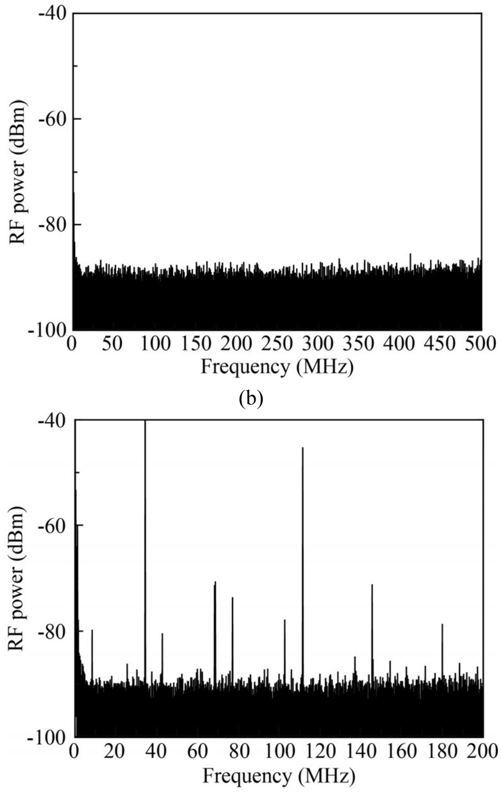
(b) Stability of dual-wavelength operation

Fig.2 Dual-wavelength operation with spacing of 1.11 nm

SLM operation of the proposed EDFL was confirmed through the self-homodyne measurement system composed of a photodetector (PD) (Tektronix CSA803A SD-48 PD Sub-unit, 33 GHz) and a radio frequency electrical spectrum analyzer (RF-ESA) (Agilent N9010A, 9 kHz—26.5 GHz). Fig.3(a) shows the measured RF beating spectrum of the laser output in 0—10 GHz scanning span corresponding to a wavelength range of ~0.08 nm which is wider than the 3-dB bandwidths of the used two NB-FBGs. Considering that the calculated *FSR* of the main cavity is approximately 8—9 MHz, the RF beating spectrum in 0—500 MHz range was also measured using higher resolution RF-ESA as shown in Fig.3(b). Since there is no significant beating signal observed in either Fig.3(a) or (b), the EDFL is in stable SLM operation for each wavelength. In order to investigate the SLM selection capability of the compound cavity, the RF beating spectrum was measured again in 0—200 MHz range, as shown in Fig.3(c), without the TR-SC connected. Many strong beating signals with the frequency separation of about 8—9 MHz induced by the multimode oscillation can be observed, indicating that the fiber laser is not in SLM operation, and the utilization of the TR-SC could suppress the number of longitudinal modes significantly.



(a)



(b)

(c)

Fig.3 Measured RF beating spectra of the laser output in (a) 10 GHz span, (b) 500 MHz span, and (c) 200 MHz span without the TR-SC connected

Due to the original reflection center wavelength of NB-FBG-2 is a little less than that of NB-FBG-1, the wavelength-spacing in dual-wavelength operation could be tuned starting from 0 nm by tuning the recoated NB-FBG-2. Keeping VOA and PC still, the wavelength-spacing can be continuously tuned as wide as 4.83 nm by moving the left fiber chuck of the TTI in the horizontal direction, as shown in Fig.4. During the tuning, there is no obvious power fluctuation or single-/dual-wavelength switchable operation, which results from the excellent resonant cavity structure of the EDFL. The spacing tuning range from 0 nm to 4.83 nm enables the EDFL to be used for tunable microwave/THz-wave generator with frequency tuning range from 0 Hz to 606 GHz.

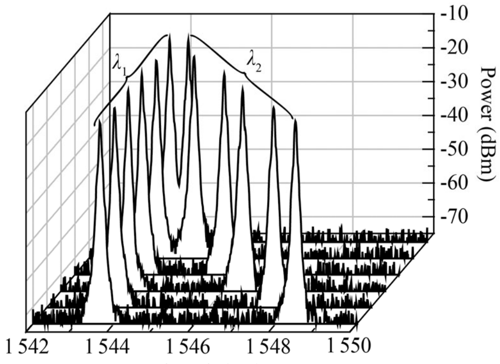
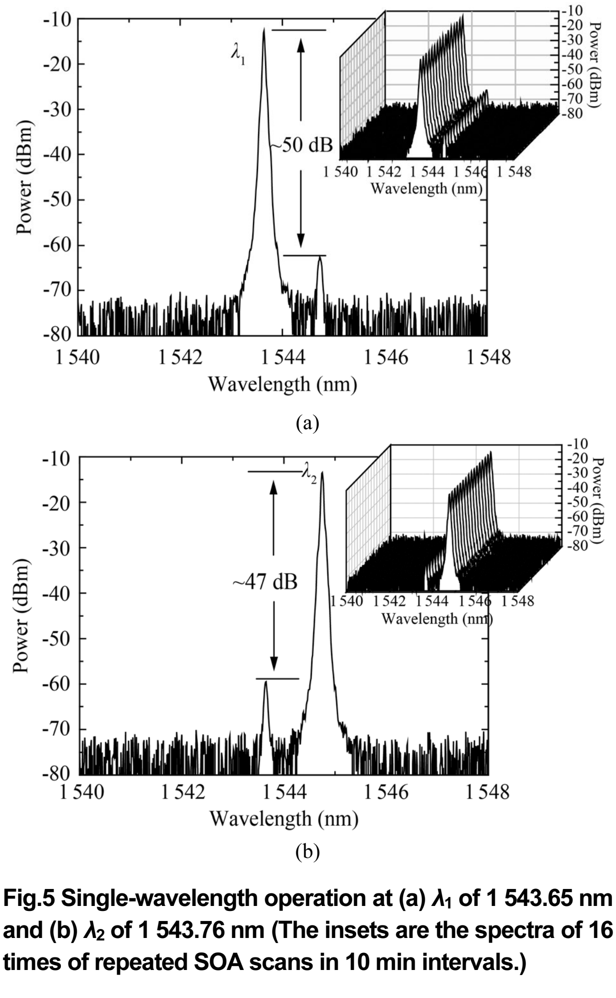


Fig.4 Wavelength-spacing tuning of dual-wavelength operation in the range of 0—4.83 nm

Fixing the pump power at 120 mW and keeping the wavelength-spacing at 1.11 nm, λ_1 or λ_2 single lasing could be achieved by easily adjusting the VOA as described above. Fig.5(a) and (b) show the spectra of λ_1 and λ_2 lasing at 1 543.65 nm and 1 544.76 nm, respectively measured by the AQ6375 OSA. In Fig.5(a), the 3-dB bandwidth is 0.03 nm and the *SMSR* is higher than 50 dB. In Fig.5(b), the 3-dB bandwidth is 0.04 nm and the *SMSR* is higher than 47 dB. The spectra of 16 times of repeated OSA scans in 10 min intervals are given correspondingly in the insets, indicating the EDFL is stable in a long operating time. To further investigate the operating stability, the fluctuations of wavelength and output power were measured in 1 h by an Exfo/Burleigh WA-1600 wavemeter (WM) with the resolutions of 0.1 pm and 0.01 dBm, respectively for single-wavelength lasing. As shown in Fig.6(a) and (b), the wavelength and power fluctuation are less than 0.4 pm and 0.38 dB respectively for λ_1, and less than 0.6 pm and 0.27 dB respectively for λ_2. The relatively high power fluctuation might result from the instability of the 980 nm pump LD. Due to the weaker mode competition, a higher stability is exhibited for single-wavelength operation than dual-wavelength operation. As indicated in Fig.4, in λ_2 single lasing, the EDFL has a continuous wavelength-tuning range of 4.83 nm from 1 543.65 nm to 1 548.48 nm. With better FBG recoating materials and techniques, the tunable range will be enlarged further.

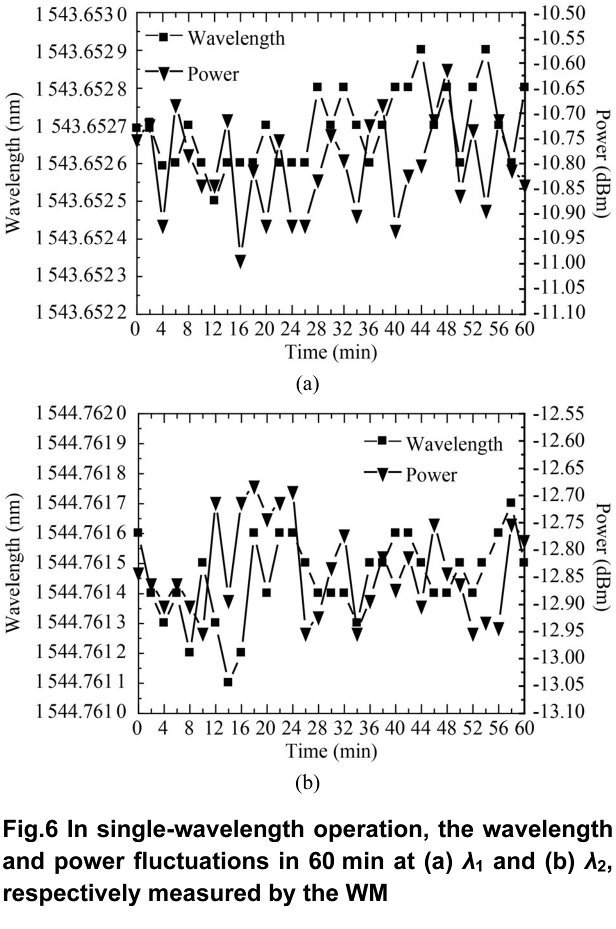
The linewidth properties of λ_1 and λ_2 lasing were studied by using the delayed self-heterodyne linewidth measurement system (DSHLMS). In the DSHLMS, a 40 km long Corning SMF-28 fiber was utilized as the delayed line, corresponding to a nominal linewidth measurement resolution of ~5 kHz, and a 100 MHz acoustic optical modulator was employed as the frequency shifter. Before entering the DSHLMS, the laser outputs are amplified by an erbium-doped fiber amplifier firstly. The linewidths at λ_1 and λ_2 are obtained by the RF-ESA as shown in Fig.7. Fig.7(a) gives the measured data in 0—150 MHz frequency range for λ_1 lasing. There is only one strong beating signal produced by the delayed laser and frequency shifted laser, indicating that the fiber laser is operating well in SLM state. Fig.7(b) shows the detailed linewidth characteristic obtained by the RF-ESA using higher resolution in the scanning range of 99.750—100.250 MHz. As marked, the −20 dB bandwidth from the peak of the fitting curve is 11 kHz. Due to the laser linewidth is predicted to be 1/20 of the −20 dB bandwidth of the fitting curve, the linewidth of the fiber laser operating at λ_1 is 550 Hz. The similar investigations are given for λ_2 lasing as shown in Fig.7(c) and (d). Fig.7(c) also verifies that the EDFL is in good SLM operation and Fig.7(d) reveals that the measured linewidth is 600 Hz.



(a)

(b)

Fig.5 Single-wavelength operation at (a) λ_1 of 1 543.65 nm and (b) λ_2 of 1 543.76 nm (The insets are the spectra of 16 times of repeated SOA scans in 10 min intervals.)



(a)

(b)

Fig.6 In single-wavelength operation, the wavelength and power fluctuations in 60 min at (a) λ_1 and (b) λ_2, respectively measured by the WM

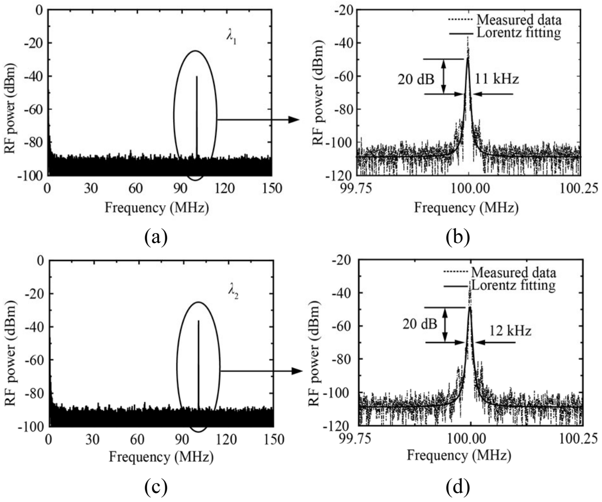


Fig.7 Measured linewidths of the fiber laser operating at (a, b) λ_1 and (c, d) λ_2, respectively using the DSHLMS (In (a) and (c), the ESA resolution is 10 kHz; in (b) and (d), the ESA resolution is 1 kHz.)

We demonstrate a single-/dual-wavelength switchable and tunable EDFL based on a compound cavity structure simply composed of an active ring main cavity and a passive TR-SC at room temperature. The TR-SC could suppress the multimode oscillation significantly. There is no complicated or expensive ultra-narrow-band filter in the cavity. The EDFL is always in good SLM operation and has high stability. Better performance for the narrow-linewidth EDFL can be obtained by using better FBG packaging materials and techniques, stable vibration isolation platforms and effective temperature compensation technologies. The proposed fiber laser will find applications in the areas of microwave/ THz-wave generation and distributed fiber sensing with high precision.

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