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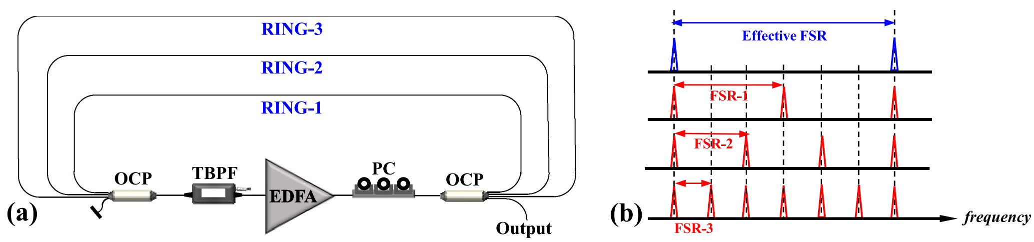

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A Single-Mode Erbium Fiber Laser With Flat Power Output and Wide Wavelength Tunability

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Abstract: In this research, we present and study an erbium fiber laser with triple-fiber-ring (TFR) scheme for continuous-wave (CW) wavelength-selection. The designed TFR not only can achieve single-longitudinal-mode (SLM) oscillation, but also can spread the tuning range from 1519.0 to 1583.0 nm covering C- and part of L-bands. Moreover, 0 dB power fluctuation can be obtained from 1523.0 nm to 1559.0 nm for flattened operation based on the compound-ring configuration. The Lorentzian laser linewidths of 22 to 29 kHz are also attained in the entire wavelength-tunable range.

Index Terms: Single-longitudinal-mode (SLM), fiber laser, erbium-doped fiber (EDF), compound-ring.

1. Introduction

In recent years, continuous-wave (CW) erbium-doped fiber (EDF) laser sources with broad tunability, constant single-longitudinal-mode (SLM) action and flat output spectrum have appealed to great interests, because of the promising applications of optical fiber communication, optical fiber sensor, microwave-photonic, and biophotonics [1]–[4]. To reach the wavelength selection in the EDF lasers, using the linear- and ring-based fiber cavities have been studied [5]. The ring-based EDF laser could prevent the spatial hole burning, which is induced by the standing-wave influence in linear cavity EDF laser [6]. However, the longer fiber cavity and homogenous broadening of erbium properties would produce unstable and changeable multi-longitudinal-mode (MLM) oscillation in the erbium fiber lasers [7]. Thus, the dense MLM output would produce unstable power and wavelength output.

To suppress MLM oscillation, the related approaches have been designed for improvement, such as using Rayleigh backscattering (RB) effect [8], employing unpumped saturable absorber [9], utilizing optical injection loop scheme [10], exploiting ultra-narrow optical filter [11], developing

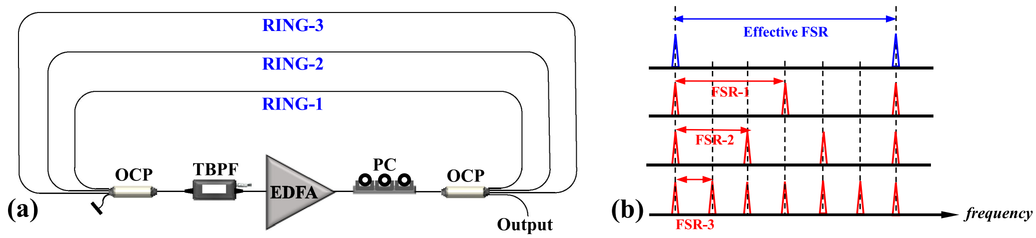

Fig. 1. (a) Proposed EDF TFR laser architecture. (b) Schematic of each FSR based on Vernier effect for suppressing MLM.

Mach-Zehnder interferometer (MZI) structure [12], applying fiber Bragg grating (FBG) based filter [13] and proposing compound-ring architecture [14], [15]. However, the obtainable wavelength tunability would be limited according to the effective gain range of EDF. To reach wide tuning range, an EDF-based gain medium must be in wider operation range [16].

In the paper, an EDF triple-fiber-ring (TFR) laser with flat power spectrum output and stable SLM behavior is presented and demonstrated. Here, we utilize two 1×4 optical couplers (OCPs) to build a TFR structure with various fiber lengths serving as the mode-restriction-filter. Therefore, the dense MLM fluctuations of the presented EDF laser can be suppressed wholly. The presented TFR also can broaden the available gain range from 1519.0 to 1583.0 nm covering C- and part of L-bands for broad tunability. The received output power and optical signal to noise ratio (OSNR) are between 3.9 and 7.7 dBm and 31.3 and 34.6 dB, respectively. Furthermore, a flattened power output range with 0 dB fluctuation is also accomplished in the bandwidth of 1523.0 and 1559.0 nm. The measured Lorentzian linewidth of the fiber laser is obtained from 22 to 29 kHz over the whole tuning range.

2. Experimental Setup

In the investigation, the presented EDF triple-fiber-ring (TFR) laser is composed of two 1×4 optical couplers (OCPs), a polarization controller (PC), a tunable bandpass filter (TBPF), and an erbium-doped fiber amplifier (EDFA), respectively, as plotted in Fig. 1(a). The commercial C-band EDFA, having saturated output power of 13 dBm over an obtainable gain bandwidth of 1528 to 1562 nm, is utilized to regard as a gain medium in laser cavity. To accomplish the CW wavelength tunability, a TBPF is applied in fiber loop for adjustment. Besides, a PC is employed in the presented EDF laser to adjust the birefringence of fiber for controlling the properly polarization direction and maintaining the optimal output power after passing through the EDFA based gain medium. In the demonstration, the optical spectrum analyzer (OSA) and optical power meter (OPM) are applied to detect and record the output spectrum and intensity power, respectively.

Two 1×4 OCPs are applied to construct a simple TFR architecture to generate the SLM oscillation of each output lightwave, as shown in Fig. 1(a). The coupling ratio and insertion loss of the two OCPs are around 25% and 6 dB. Here, three fiber rings (Ring-1, Ring-2 and Ring-3) can be produced. Compared with the previous works [14], [15], the presented TFR scheme is simple and the number of OCPs is less. In the laser scheme, the fiber lengths of Ring-1, Ring-2 and Ring-3 are 28, 27, and 26 m long, respectively. The three ring lengths would lead to various free spectrum ranges (FSRs), which represent FSR-1, FSR-2 and FSR-3, respectively. As we know, the $\mathrm{FSR} = c\,/\,(n_{\mathrm{eff}} \cdot L)$ is expressed for use, where the c, n_{eff} and L are the light speed in vacuum ($= 3\times10^8$ m/s), average index of fiber ($n_{\mathrm{eff}} = 1.4682$) and ring length, respectively. In addition, when the obtained FSR-1, FSR-2 and FSR-3 meet with the least common multiple, respectively, it could cause an effective FSR with broad bandwidth in line with the Vernier effect, as illustrated in Fig. 1(b). Hence, the produced effective FSR could cause a mode-restriction-filter effect [15].

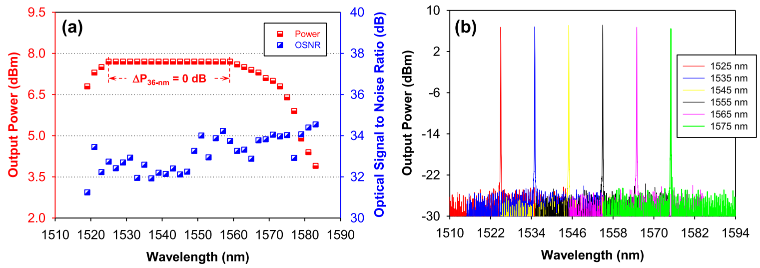

Fig. 2. (a) The measured output power and OSNR of the designed EDF TFR laser, respectively. (b) Observed output spectra of six selected wavelengths.

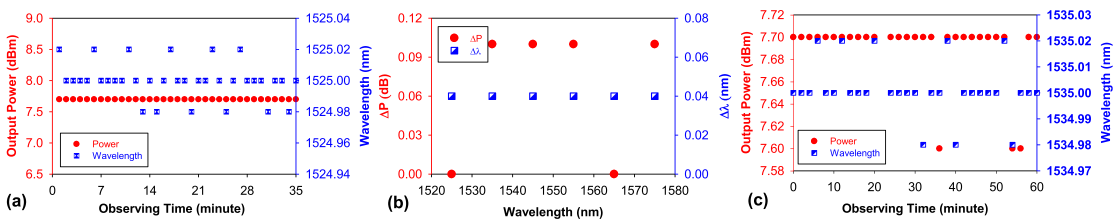

Fig. 3. (a) Detected output fluctuations of power and wavelength during 35 minutes observation, when 1525.0 nm wavelength is exploited. (b) Detected largest differences of output power and wavelength over the measuring bandwidth of 1525 to 1575 nm. (c) Measured output fluctuations of power and wavelength through 60 minutes observation, when 1535.0 nm wavelength is used.

Then, the presented TFR structure could repress the densely MLM noises to guarantee the SLM oscillation, as illustrated in Fig. 1(b).

To perform the widest tunability of the designed EDF TFR laser, the lasing wavelength can start from 1519.0 nm, when a TBPF is applied for tuning different wavelengths. In the experiment, the full width at half maximum (FWHM) and insertion loss of TBPF are 0.4 nm and 6 dB over a tuning range from C to L bands. Fig. 2(a) represents the measured output power and OSNR of the designed fiber laser in the wavelength scale of 1519.0 to 1583.0 nm. The received output power (P_{out}) range is from 3.9 to 7.7 dBm. In accordance with the proposed TFR-based laser diagram, the reachable tunability of 64 nm covering C- and part of L-bands can be achieved, while the C-band EDF based gain-medium is used. Hence, the designed TFR scheme also can expand the gain range and broaden the wavelength-tuning bandwidth. Furthermore, a flatter output range of 1521.0 to 1571.0 nm with 0.7 dB power deviation (7.0 dBm $\leq P_{out} \leq$ 7.7 dBm) is also obtained, as displayed in Fig. 2(a). Besides, the flatness of the laser output power can achieve 0 dB over 36 nm bandwidth from 1523.0 to 1559.0 nm, as also seen in Fig. 2(a). And the optical signal to noise ratios (OSNR) of output wavelengths are between 31.3 and 34.6 dB in the measurement. Moreover, due to the larger saturation output power of EDFA, the optical background noise of each lasing may be not easy to suppress fully for achieving higher OSNR.

Fig. 2(b) exhibit the six selected wavelengths with 10 nm channel interval from 1525.0 to 1575.0 nm. Similarly, the attained optical signal to noise ratios (OSNRs) and peak powers of the six lasing wavelengths are greater than 6.2 dBm and 32.1 dB, as viewed in Fig. 2(a). As a result, the designed fiber laser not only can complete the largely tunability, but also can achieve a flattened output power in C-band range.

Furthermore, the output stability is a crucial issue of the EDF laser. Thus, a wavelength of 1525.0 nm with 7.7 dBm output power is selected for measuring output stabilization originally. The observed greater wavelength variation and power fluctuation are 0.04 nm and 0 dB, respectively, through 35 minutes observation time, as exhibited in Fig. 3(a). Then, to verify the stabilization of other outputs in the available operation range, 1535.0, 1545.0, 1555.0, 1565.0 and 1575.0 nm are

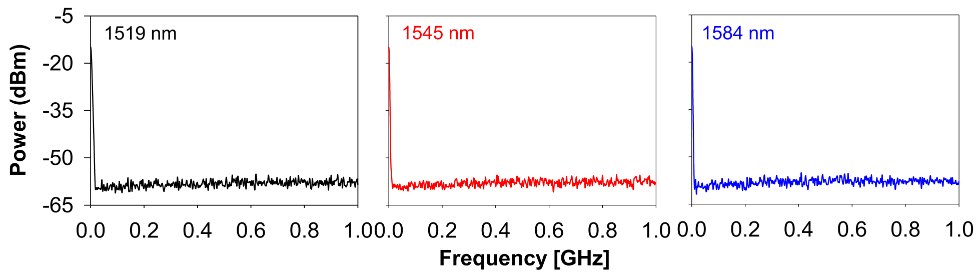

Fig. 4. Received RF spectrum of 1519.0, 1545.0 and 1584.0 nm, respectively, by using the delayed self-homodyne measurement.

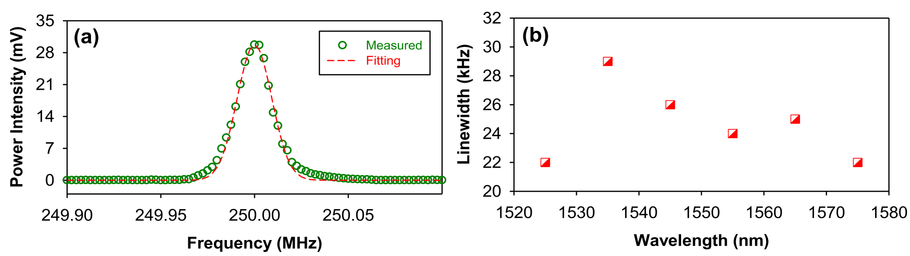

Fig. 5. (a) The detected and fitted electrical spectra of1525.0 nm through the delayed self-heterodyne measurement. (b) Obtained Lorentzian linewidth of each lasing wavelength.

chosen for measurement. Fig. 3(b) plot the largest output power and wavelength differences of the six wavelengths from 1525.0 to 1575.0 nm during the same observing period. The discovered power variations and wavelength fluctuations are 0, 0.1, 0.1, 0.1, 0 and 0.1 dB; and 0.04, 0.04, 0.04, 0.04, 0.04 and 0.04 nm, respectively, at the six selected wavelengths, as seen in Fig. 3(b). The discovered oscillations of power and wavelength are small than 0.1 dB and 0.04 nm in the entire wavelength bandwidth. Moreover, we also use a lasing wavelength of 1535.0 nm for stability measurement after an observation of 60 minutes. The measured output power and wavelength fluctuations are less than 0.1 dB and 0.04 nm, as seen in Fig. 3(c). Therefore, through one-hour measurement, the whole realized stabilities of power and wavelength are still held within these obtained oscillations.

Then, to confirm the SLM quality of the EDF TFR laser, a delayed self-homodyne measurement is developed. The experimental setup contains a delay line of 25 km single-mode fiber (SMF), a 10 GHz photodiode (PD), and a PC to generate a Mach-Zehnder interferometer (MZI) diagram, respectively [14]. Here, the output wavelength will enter the MZI configuration and launch into the 10 GHz PD for converting to electrical signal for observation. Here, three output wavelengths of 1519.0, 1545.0 and 1584.0 nm are applied for the SLM measurement, respectively. Fig. 4 indicates the measured RF electrical spectrum over the frequency bandwidth of 0 to 1 GHz at the wavelengths of 1519.0, 1545.0 and 1584.0 nm, respectively. There is no dense MLM oscillation in the presented EDF laser, respectively, as shown in Fig. 4. Therefore, the presented TFR scheme can bring the mode-restriction-filter effect for filtering the dense MLM spikes. Moreover, through one-hour observation, the detected SLM operation without mode-hopping oscillation is also achieved.

Next, we will evaluate the laser linewidth of proposed EDF TFR laser by exploiting a delayed self-heterodyne structure [17]. In the experiment, we apply a 10 GHz phase modulator (PM) to generate 250 MHz RF beating signal for measuring. Initially, 1525.0 nm wavelength is selected for linewidth examination. Fig. 5(a) shows the observed RF beating signal of 1525.0 nm wavelength at the frequency of 250 MHz. The obtained linewidth spectrum is shown in the green circle of

Fig. 5(a). Theoretically, the actual linewidth of proposed laser can be fitted through the Lorentzian curve. Thus, the 3-dB Lorentzian linewidth of 22 kHz is reached, as demonstrated in the red line of Fig. 5(a). Subsequently, we also perform the measurement of the Lorentzian linewidth when the wavelengths of 1535.0, 1545.0, 1555.0, 1565.0 and 1575.0 nm are applied, respectively. The related 3-dB linewidth of 29, 26, 24, 25 and 22 kHz are achieved by using the Lorentzian fitting, respectively, as exhibited in Fig. 5(b). Hence, over the operated bandwidth of 1525.0 to 1575.0 nm, the achievable Lorentzian linewidths are evaluated between 22 to 29 kHz. The same linewidth obtained by the two wavelengths of 1525.0 and 1575.0 nm may be due to the measurement results.

3. Conclusion

We investigated an SLM EDF TFR laser to achieve broad and selectable wavelength output. The designed TFR was embedded in EDF laser regarding as a high-quality mode-restriction-filter to restrain the dense MLM fluctuation and extend the operation range by using C-band EDF based gain medium. To generate different wavelength output, a TBPF was used inside the laser cavity for selecting. The obtainable output powers and OSNRs were in the scales of 3.9 to 7.7 dBm and 31.3 to 34.6 dB over the wavelength bandwidth of 1519.0 to 1583.0 nm covering C- and part of L-bands, respectively. The presented EDF laser also could complete a flatted output spectrum with 0 dB power fluctuation in the wavelength scale of 1523.0 to 1559.0 nm. Here, the observed stabilities of output power and wavelength were kept within the variations of 0.1 dB and 0.04 nm over the available bandwidth, respectively. Moreover, the achievable 3-dB Lorentzian linewidth was also accomplished in the range of 22 to 29 kHz.

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