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Communication

A Stabilized Single-Longitudinal-Mode and Wide Wavelength Tunability Erbium Laser

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Abstract: An erbium-doped fiber (EDF) laser with quad-ring is designed to reach the broad continuous-wave (CW) tunability and single-longitudinal-mode (SLM) behavior. Here, while a C-band erbium-based gain medium is exploited, the tunable scope can be extended from C- to part of L-bands and narrow the linewidth to several kHz by the presented compound-ring configuration. Additionally, the optical signal to noise ratio (OSNR), output power, and stability behavior of every lasing wavelength are also demonstrated.

Keywords: single-longitudinal-mode (SLM); quad-ring; erbium-doped fiber (EDF); fiber laser

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1. Introduction

As we know, erbium-doped fiber (EDF) lasers have the output behavior of high optical signal to noise ratio (OSNR), broad wavelength tunability, and narrow linewidth, applied in many fields such as bio-photonics, Lidar, optical communication, millimeter-wave (MMW) photonics, optical sensing, and spectroscopy [1–5]. However, due to a longer fiber length of laser cavity and homogeneous broadening of EDF [6], the EDF laser could cause an unstable multi-longitudinal-mode (MLM) fluctuation. To solve the MLM concern in EDF lasers, the compound-ring design [7,8], saturable absorber (SA) based filter [9], optical injection technique [10], Rayleigh backscattering (RB) effect [11], and Mach–Zehnder interferometer (MZI) scheme [12] have been studied to realize constant single-longitudinal-mode (SLM) action. Furthermore, due to the bandwidth restriction of C-band erbium gain, the mostly wavelength-tuning scopes could be obtained from 1528 to 1560 nm [13,14]. Therefore, to achieve a broad tunability in EDF lasers, use of the high concentration EDFs [9,15] and hybrid optical amplifiers [16,17] has also been demonstrated.

In this work, an EDF laser with a simple quad-ring scheme applying a gain-medium of C-band erbium fiber is investigated experimentally. To attain the SLM action in the proposed fiber laser, the quad-ring can lead to a mode-filter operation to suppress the MLM noises according to the Vernier effect [8]. In addition, the caused mode-filter can also suppress the available gain and increase the tunability scale from 1519.0 to 1584.0 nm involving both the C- and part of the L-bands. The optical signal to noise ratio (OSNR) of 50.4 and 64.8 dB and output power of −3.1 to 5.8 dBm are measured over the available tuning range, respectively. The detected stabilities of each wavelength and power are within the fluctuations of 0.10 nm and 0.1 dB through 40 min measurement over the effective tuning bandwidth. Furthermore, the 3 dB Lorentzian linewidths of the presented laser are measured between 2 and 5 kHz. Therefore, the designed EDF laser not only achieves a board and stable wavelength-tuning range, but also reaches the laser linewidth of <5 kHz.

2. Experiment and Results

The demonstrated EDF laser with the quad-fiber-ring design is schemed in Figure 1. In the measurement, two 2 × 2 and 50:50 optical couplers (CPR_1), an erbium-doped fiber amplifier (EDFA), a tunable bandpass filter (TBF), a polarization controller (PC), and a 1 × 2 and 50:50 optical coupler (CPR_2) are exploited to build the fiber ring laser. Here, the commercial EDFA module (GIP, Taiwan), having the saturable output power of 13 dBm in the obtainable C-band gain range of 1528 to 1562 nm, is applied in the ring cavity as the gain medium. The input power range of EDFA is −30 to −10 dBm with the corresponding gain and noise figure of 30 and 5.5 dB over the operation bandwidth, respectively. The PC is used to manage the polarization direction and reach the greatest output power. To tune the continuous-wave (CW) output, a TBF is placed in the fiber ring structure for wavelength selection arbitrarily, as exhibited in Figure 1. Moreover, the CPR_1 and CPR_2 can build a simple quad-ring architecture in the presented EDF laser. In order to observe the wavelength spectrum and measure the output power from the output port of CPR_1, the optical spectrum analyzer (OSA) with 0.06 nm resolution and the power meter (PM) are utilized for measurement.

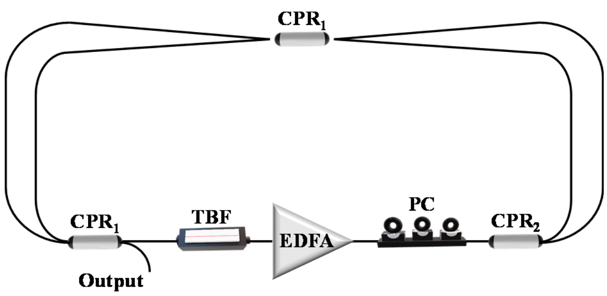

Figure 1. Experimental setup of demonstrated EDF laser architecture.

To attain the SLM operation, the compound-ring configuration can be employed to lead to the mode-filter operation consistent with the Vernier effect [8]. The plotted quad-ring structure composes of the Ring 1, Ring 2, Ring 3, and Ring 4, respectively, as expressed in Figure 2. Hence, each fiber ring will have its corresponding free spectrum range (FSR). The FSR can be expressed by the formula,

$$FSR = c/(n \cdot L) \tag{1}$$

where L, c, and n are the ring length, speed of light in vacuum, and index of single-mode fiber, respectively. When the four FSRs (FSR 1 to FSR 4) of Ring 1 to Ring 4 comply with the least common multiple owing to the Vernier effect, a wider scale of effective FSR can be caused to lead to a mode-filter effect to suppress the MLM noises [17]. Therefore, we need to choose different fiber length for each ring based on the plotted structure. Here, in order to cause different FSRs for the mode-filter effect, the lengths of Ring 1 to Ring 4 of 26, 25, 23, and 27 m, respectively, are used. The corresponding four FSRs of 7.86 (FSR 1), 8.17 (FSR 2), 8.88 (FSR 3), and 7.57 MHz (FSR 4) can be attained in the demonstrated EDF laser. As displayed in Figure 3, the multiple longitudinal modes could be reduced excellently due to the use of the quad-ring structure, which is used in the EDF laser to serve as the mode filter and to facilitate the SLM output when the TBF is randomly applied for wavelength selection. Therefore, the proposed quad-ring scheme can suppress the dense MLM and make it easier for SLM selection.

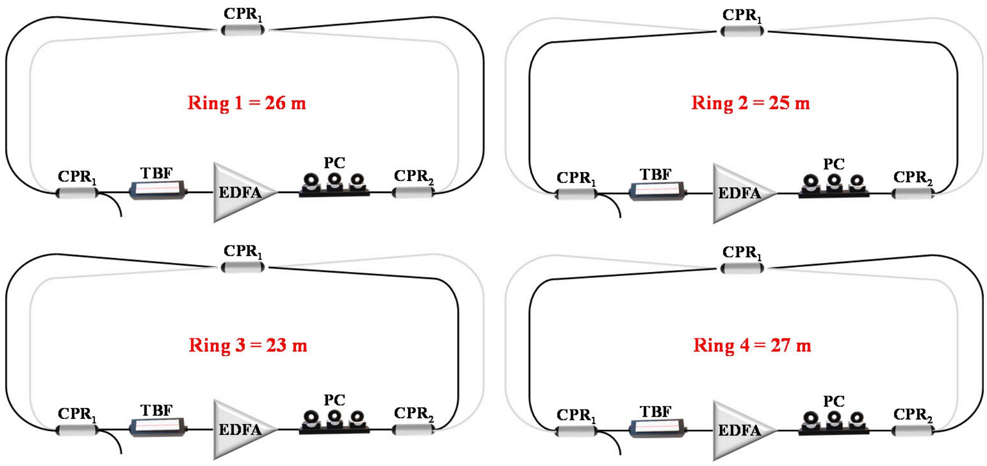

Figure 2. Schematic of Ring 1, Ring 2, Ring 3, and Ring 4 in the EDF quad-ring laser, respectively.

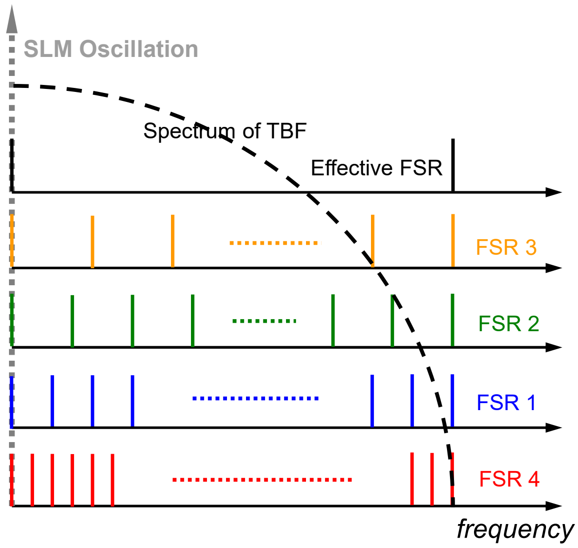

Figure 3. The schematic of SLM oscillation based on the Vernier effect under the proposed fiber structure of Ring 1 to Ring 4.

Once the TBF is adjusted continuously in the presented laser cavity, the generated wavelength can be tuned from 1519.0 to 1584.0 nm. Here, the 3 dB bandwidth and insertion loss of the TBF used are 0.4 nm and 6 dB in the achievable bandwidth of 1520 to 1610 nm. Therefore, Figure 4 exhibits the five selected wavelength spectra of 1519.0, 1533.0, 1548.0, 1562.0, and 1576.0 nm in the EDF quad-ring laser, when the pumping power of C-band EDFA is fixed. In addition, Figure 4 also presents the discovered output power in a spectral scale of 1519.0 to 1584.0 nm with 2 nm wavelength interval. The obtained power output range is from −3.1 to 5.8 dBm. The observed output powers drop gradually on the right side, as shown in Figure 4, due to the insufficient gain on the right range in the proposed EDF laser. The largest power of 5.8 dBm is measured at the 1533.0 nm wavelength. As mentioned above, the original reachable gain of EDFA is between 1528 and 1562 nm. However, the achieved tunability of the presented quad-ring based EDF laser can be extended from 1519.0 to 1584.0 nm. This means that the quad-ring scheme can also suppress and increase the gain-medium range. Therefore, the proposed EDF laser results in a smaller output power over the obtainable tuning bandwidth, as seen in Figure 4.

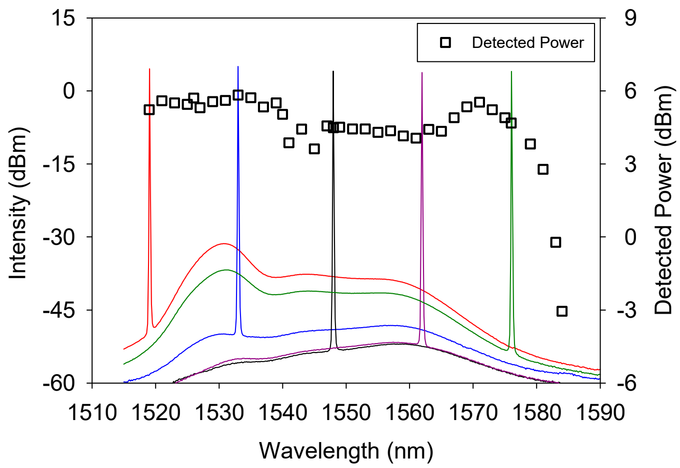

Figure 4. Measured output spectrum of proposed fiber laser and corresponding output power in a tuning range of 1519.0 to 1584.0 nm.

Figure 5 exhibits the observed optical signal to noise ratio (OSNR) versus the output wavelengths of 1519.0 to 1584.0 nm when the pumping power is fixed. The entire obtained OSNRs are between 50.4 and 64.8 dB. Moreover, as shown in Figure 5, the observed OSNR can be larger than 60.2 dB and cause the adjustable wavelength range of 52 nm from 1523.0 to 1575.0 nm.

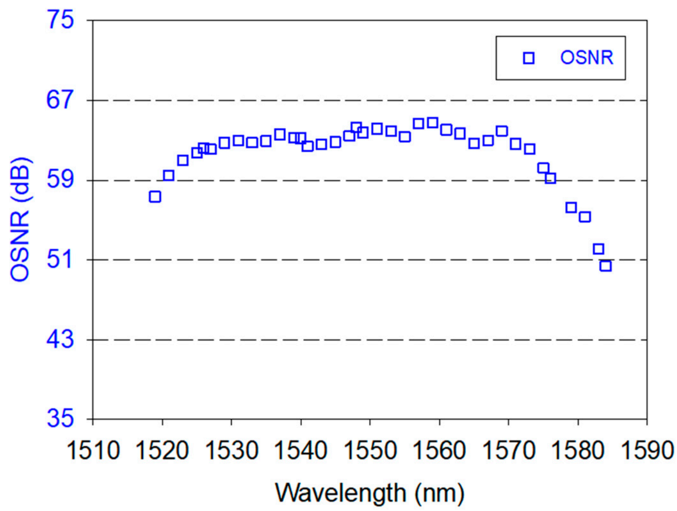

Figure 5. Measured OSNR of each wavelength in the tuning range of 1519.0 to1584.0 nm.

The output stability is also an important topic for the EDF laser. We initially chose the wavelength of 1519.0 nm for this experiment. Through a measuring time of 40 min, the detected output variations of power and wavelength can be lower than 0.6 dB and 0.09 nm, respectively, as illustrated in Figure 6a. Then, we applied ten lasing wavelengths over a spectral range of 1519.0 nm to 1584.0 nm for the demonstration of output stabilization through the same measurement time. Thus, Figure 6b displays the observed largest oscillations of power and wavelength versus an achievable scale of 1519.0 nm to 1584.0 nm. The observed output power and wavelength changes are in the ranges of 0.2 to 1 dB and 0.04 to 0.10 nm, respectively, as illustrated in Figure 6b. In addition, the maximum 1 dB power fluctuation and 0.10 nm wavelength variation are both caused at the wavelength of 1584.0 nm.

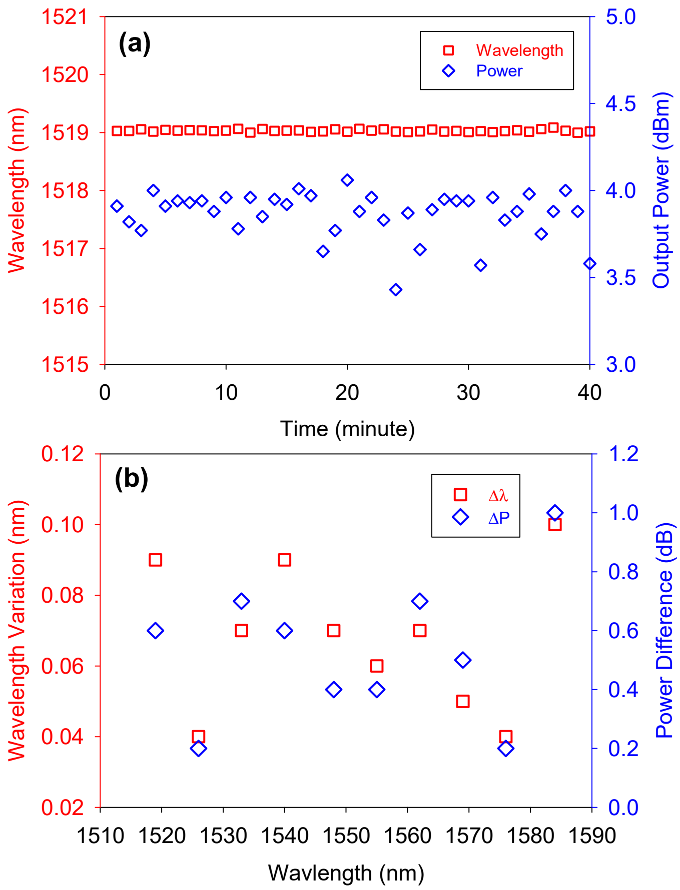

Figure 6. (**a**) Measured output power and wavelength variations of 1519.0 nm wavelength through 40 min observation. (**b**) Measured power and wavelength differences over a bandwidth from 1519.0 to 1584.0 nm.

Next, we will confirm the SLM behavior of the demonstrated quad-ring EDF laser design. A self-homodyne technique is applied for measurement. The optical setup comprises two CPR_2, a PC, and a length of 50 km fiber by the MZI architecture [9,10]. Hence, each lasing wavelength can be verified by the beat signal from the MZI for SLM observation. Here, a generated wavelength of 1519.0 nm is also originally chosen for the experiment. Figure 7 plots the measured RF electrical spectrum of 1519.0 nm wavelength in the frequency scale of 0 to 1 GHz by applying an electrical spectrum analyzer (ESA). We observe that no spike noise oscillation over the frequency range. That means that the dense MLM noises are suppressed significantly. Moreover, while we reduce the measured frequency scale to 500 MHz for observation, there is still no spike oscillation, as seen in the inset of Figure 7. Thus, the SLM operation of the quad-ring erbium laser can be certificated.

To measure the output linewidth of the proposed quad-ring EDF laser, a self-heterodyne method is exploited [10]. First, we also employ the selected wavelength of 1519.0 nm and apply RF signal of 125 MHz to cause the beat signal for linewidth detection. Figure 8a displays the detected electrical spectrum from 124.99 to 125.01 MHz by using the ESA with a resolution bandwidth of 1 kHz, as plotted in the green circle. Essentially, to attain the actual output linewidth, the Lorentzian fitting is applied for observation based on the measured result. Figure 8a presents the observed 3 dB Lorentzian linewidth of 2 kHz, as illustrated in the red dash line. Then, ten selected wavelengths are used over the obtainable bandwidth of 1519.0 to 1584.0 nm for linewidth measurement. The 3 dB Lorentzian linewidth of 2 and 5 kHz is achieved in the whole tuning scale. Thus, the maximum difference of laser linewidth is 3 kHz.

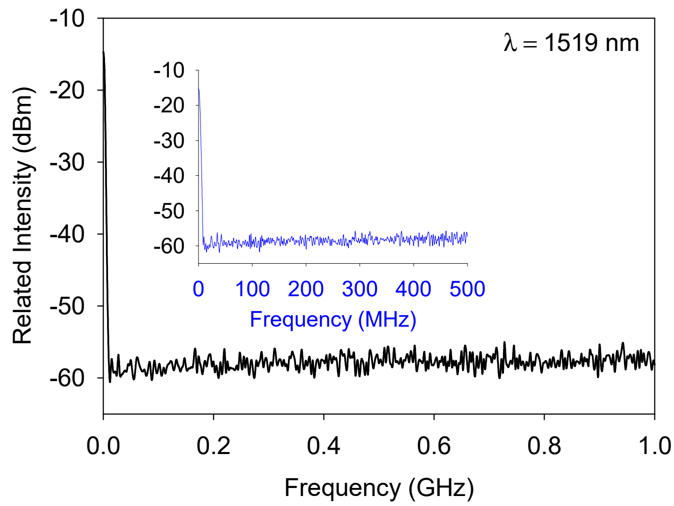

Figure 7. Measured electrical spectrum at the wavelength of 1519.0 nm within the frequency scope of 1 GHz for SLM exhibition. Inset is the measured spectrum from 0 to 500 MHz.

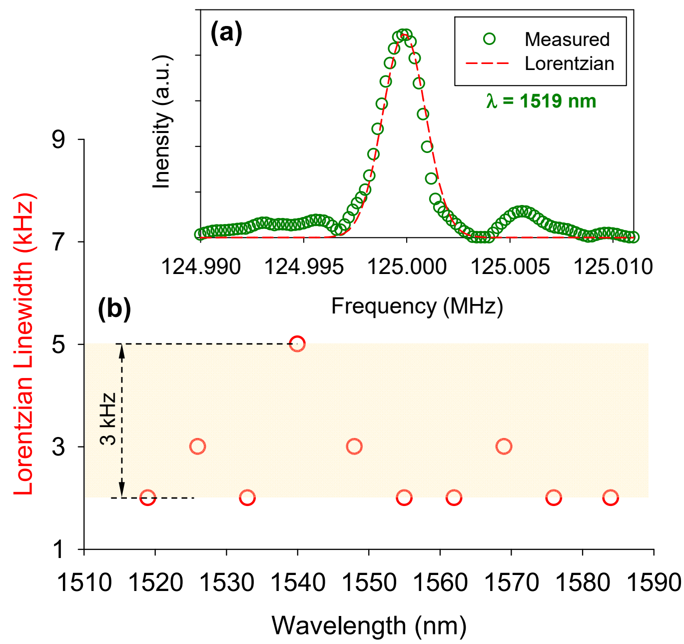

Figure 8. (**a**) The frequency spectra of measured data and Lorentzian fitting at 1519.0 nm wavelength. (**b**) Obtained Lorentzian linewidth over the tuning scope of 1519.0 to 1584.0 nm.

3. Conclusions

In summary, we exhibited a quad-ring EDF laser with selectable CW output and stabilized SLM oscillation. The simple quad-ring architecture was designed to generate the mode-filter influence based on the Vernier effect for MLM suppression. The output power and detected OSNR of the presented EDF laser were in the spans of −3.1 to 5.8 dBm and 50.4 and 64.8 dB over the entire tuning scope of 1519.0 to 1584.0 nm, respectively, when a C-band erbium-based gain medium was applied. That means that the quad-ring could also suppress and extend the gain distribution including the C- and part of the L-bands. Therefore, the presented fiber laser concluded a broader tuning scale and achieved the better OSNR performance.

The measured fluctuations of output power and wavelength were in the scales of 0.2 to 1 dB and 0.04 to 0.10 nm over an available tuning bandwidth, respectively, after 40 min detection. Moreover, the 3 dB Lorentzian linewidths of 2 to 5 kHz were also reached in the achievable wavelength scale. As a result, the presented quad-ring architecture could complete the stabilized SLM action and narrow laser linewidth to several kHz.

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