Use of Simple Octa-Ring Configuration for Tunable Erbium Laser With Single-Mode Output

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ABSTRACT In this paper, an erbium-doped fiber (EDF) octa-ring laser system with continuous-wave (CW) tunability and stable single-longitudinal-mode (SLM) output is presented and investigated. The octa-ring configuration can cause a mode-filter operation based on the Vernier effect for dense side-mode suppression and gain extension. Therefore, the available wavelength-tuning bandwidth of the laser can be achieved from 1519.0 to 1575.0 nm by utilizing conventional C-band EDF based gain-medium. Moreover, the output power, output stability, optical signal to noise ratio (OSNR) and laser linewidth of the demonstrated EDF laser are also executed and discussed.

INDEX TERMS Erbium-doped fiber (EDF), fiber laser, tunability, single-longitudinal-mode (SLM), octa-ring.

I. INTRODUCTION

Lately, tunable and switchable single-longitudinal-mode (SLM) erbium-doped fiber (EDF) based laser has been considered to be a desired candidate owing to its features of narrow linewidth, high power, wide tuning range, high optical signal to noise ratio (OSNR) and low intensity noise [1]–[4]. And the EDF based laser also can be exploited for potential applications of wavelength division multiplexing (WDM) communications data storage, optical sensing, spectroscopy, bio-photonics, millimeter-wave (MMW) photonic and coherent signal generation [5]–[8]. However, the strong homogeneous line broadening of EDF gain could produce wavelength competition and longer fiber cavity of fiber laser would cause the unstable multi-longitudinal-mode (MLM) oscillation [9]. To achieve stable and wide SLM wavelength output, some related methods have been demonstrated, such as using the compound-fiber-ring structure [10], [11], Mach-Zehnder interferometer (MZI) method [12], [13], Sagnac interferometer (SI) loop [4], [14], saturable absorber (SA) based filter [15], [16], optical injection [17] and ultranarrow bandpass filter [18], [19]. Besides, to obtain a wider wavelength-selection range of EDF laser scheme, the parallel erbium-doped fiber amplifier (EDFA), hybrid optical amplifiers and high concentration EDFs were applied inside laser cavity as gain-medium [20]–[22].

In the paper, we present and demonstrate an EDF laser with octa-ring structure for wide wavelength tunability and stable SLM operation. Here, the designed octa-ring can generate a mode-filter behavior according to the Vernier effect to suppress the dense MLM spikes for SLM output. And the gain operation range of the EDF laser also can be extended from 1519.0 to 1575.0 nm by applying conventional C-band EDF based gain-medium. The detected OSNRs and output powers of the laser are in the ranges of 71.1 to 75.3 dB and −0.7 to −0.1 dBm in the obtainable wavelength scale of 1519.0 to 1575.0 nm, respectively. The obtained largest fluctuations of output power and wavelength are smaller than 0.54 dB and 0.09 nm over the whole tuning range through 30-minute measuring time. In addition, the presented octa-ring scheme also can narrow the linewidth to 2 kHz for all lasing wavelengths. As a result, the proposed fiber laser not only can result in SLM action and kHz level linewidth, but also can increase the useful wavelength-tuning bandwidth both including C- and L-bands based on a C-band EDF based gain-medium. Compared to previous triple-ring fiber lasers, which need three CPRs for construction [10], [11], our simple designed EDF laser can result in octa-ring scheme to cause mode-filter by using three CPRs for mode suppression and achieve high OSNR. Moreover, in our prior work [17], the proposed C-band EDF-based octa-ring fiber laser...
laser scheme can not only achieve wide wavelength tunability including C and L bands, but also can obtain high OSNR of > 71.1 dB.

II. DESIGNED RING-BASED LASER STRUCTURE

To obtain the SLM action in EDF based laser system, a compound fiber ring configuration is presented and shown in Fig. 1. A C-band erbium-doped fiber amplifier (EDFA), three 50:50 and 2 × 2 optical couplers (CPR₁), a polarization controller (PC), a tunable bandpass filter (TBF), and a 50:50 and 1 × 2 optical coupler (CPR₂) are exploited in the presented EDF ring laser, respectively. The EDFA, which is acted as gain-medium inside fiber laser loop, has 13 dBm saturated output power over the available gain bandwidth of 1528.0 to 1562.0 nm. The PC is applied to vary the polarization state in fiber and achieve the optimal power output. We can adjust continuously the passband of TBF in the fiber cavity to generate the different lasing wavelength.

In the investigation, to achieve compound fiber ring architecture for causing the Vernier effect-based mode-filter [23], three CPR₁ are applied to construct multiple-ring configuration, as demonstrated in Fig. 1. Based on the designed fiber scheme, the eight fiber rings, which means the Ring 1, Ring 2, … and Ring 8, respectively, can be obtained, as shown in Fig. 2. Each ring has its own corresponding free spectrum range (FSR). Here, the FSR can be expressed by the formula of c/(nلام), where the c, n and L represents the velocity of light, average index of fiber and fiber ring length, respectively. Hence, the Ring 1 to Ring 8 will have the corresponding FSR 1 to FSR 8, respectively. To achieve the mode-filter effect for mitigating MLM generation based on octa-ring scheme, a broader effective FSR (FSReff) can be induced, when the eight FSRs meet with the least common multiple based on the Vernier operation. And the simplified diagram of each FSR is schemed in Fig. 3. In the demonstration, the fiber lengths of Ring 1 to Ring 8 are 26, 25, 23, 22, 12, 11, 9 and 8 m, respectively. Therefore, the homologous FSR1 to FSR 8 will be 7.86, 8.17, 8.89, 9.29, 17.03, 18.58, 22.71 and 25.54 MHz, respectively.

Furthermore, the proposed fiber laser also can result in a Mach-Zehnder interferometer (MZI) by applying two bottom CPR₁, as also shown in Fig. 1. The MZI scheme also can cause a wavelength selection filter effect to perfect the SLM performance and output linewidth. The EDFA already contain two optical isolators (ISOs) for unidirectional signal transmission. Thus, the designed EDF laser configuration only causes light propagation in counterclockwise. And there will be no signal interference existing in the presented ring cavity.

III. EXPERIMENT AND RESULT

To realize the available tuning range, the output band of TBF can be tuned in the exhibited octa-ring EDF laser.
In the measurement, Fig. 4 show the four selected wavelength spectra in the wavelength scale from 1519.0 to 1575.0 nm. Owing to the octa-ring based mode-filter behavior, the original C-band erbium gain can be suppressed and extended for wide tunability, as seen in Fig. 4. During tuning of each wavelength output, we appropriately adjust the PC to control its polarization state. Besides, the black dash line of Fig. 4 is the original amplified spontaneous emission (ASE) spectrum of C-band EDFA. Here, the larger ASE peak is around in the wavelength of 1530 nm. So, the demonstrated octa-ring scheme can reduce the ASE background noise of 1530 nm completely, as plotted in Fig. 4.

Then, Fig. 5 indicates the observed output power and optical signal to noise ratio (OSNR) of every generated wavelength in the designed EDF octa-ring laser over the achievable tunability range of 1519.0 to 1575.0 nm. The detected output powers and OSNRs of the laser are in the scopes of −10.7 to −0.1 dBm and 71.1 to 75.3 dB in the whole wavelength bandwidth, respectively. Two low powers of −8.2 and −10.7 dBm are observed at the wavelengths of 1519.0 and 1567.0 nm due to the small gain of original C-band EDF, respectively, as plotted in Fig. 5. The two wavelengths also have higher OSNRs. The results show that the octa-ring based mode-filter effect can filter the background noise fully and achieve high OSNR performance. Therefore, the octa-ring laser not only increases the wavelength-tuning scale, but also achieves the OSNR of >71.1 dB.

To understand the performance of output stability of the designed EDF octa-ring laser, the 1555.0 nm wavelength with −1.86 dBm power output is exploited for measurement first. Through 30-minute observation, the greatest power change and wavelength oscillation of 1555.0 nm wavelength are less than 0.1 dB and 0.05 nm, respectively, as displayed in Fig. 6(a). Then, we utilize the seven selected wavelengths of 1519.0, 1525.0, 1535.0, 1545.0, 1555.0, 1565.0 and 1575.0 nm for examining the stabilization measurement after a short-term time. As displayed in Fig. 6(b), the detected greatest fluctuations of output power and lasing wavelength are in the scopes of 0.1 to 0.54 dB and 0.04 to 0.09 nm through 30-minute observing period in the entire tuning range, respectively. The larger wavelength variations occur on the both sides of available tuning range, due to the gain competition, as seen in Fig. 6(b). Furthermore, the wavelength tunability of the laser can be tuned continuously over 56 nm tuning range by adjusting the TBF without mode hopping oscillation. According the obtained results, the proposed octa-ring fiber laser can reach the better output stability performance.
Next, a delayed self-homodyne setup is constructed to proof the SLM performance of the EDF octa-ring laser, for investigation. The measurement is composed of two 50:50 and 1 × 2 CPRs, a 60 km single-mode fiber (SMF) and a PC to generate the Mach-Zehnder interferometer (MZI) setup. Thus, we exploit the same seven selected wavelengths as for the SLM observation. Every wavelength will pass through the MZI configuration and be received by a PIN photodiode (PD) for converting to electrical signal. Seven lasing wavelengths from 1519.0 to 1575.0 nm as the same as above are applied for testing. The related RF electrical spectra are measured by an electrical spectrum analyzer in the frequency range of 0 to 1 GHz, as expressed in Fig. 7. According to the measured RF curve of every wavelength, no dense MLM spikes can be observed over the whole frequency bandwidth. When we decrease the measured bandwidth to 10 MHz, also no fluctuation noise will be observed, as seen in the inset of Fig. 7. Moreover, after a 30-minute measurement period, the entire obtained RF spectra of the seven wavelengths are kept without any oscillation noises.

Finally, we apply the delayed self-heterodyne configuration based on the same MZI setup for determining the laser linewidth of designed EDF octa-ring laser. Here, a phase modulator is located in the one of arm to apply a carrier frequency of 210 MHz for generating beat signal. Initially, Fig. 8(a) indicates the measured linewidth of the 1575.0 nm wavelength in the red triangle symbol. Then, we can apply the Lorentzian curve to fit the real laser linewidth. So, the 3 dB Lorentzian linewidth of 2 kHz of 1575.0 nm is attained in the black line of Fig. 8(a). Next, the other six linewidths of selected wavelengths are also measured over the whole tuning bandwidth of 1519.0 to 1575.0 nm. Therefore, all the obtained 3 dB Lorentzian linewidths are 2 kHz, as also shown in Fig. 8(b). Hence, the results show that the designed octa-ring can enhance the OSNR of >71.1 dB and compress the linewidth to 2 kHz.

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