A Selectable Single-Mode Erbium Fiber Laser With Mach-Zehnder Interferometer and Rayleigh Injection Scheme

Chien-Hung Yeh, Li-Hung Liu, Han-Shin Ko, Yi-Ting Lai, and Chi-Wai Chow

***Abstract*—In the paper, a hybrid Mach-Zehnder interferometer (MZI) and Rayleigh backscattering (RB) injection is designed and applied in the erbium-doped fiber (EDF) ring laser configuration. The MZI scheme and RB-induced signal can accomplish the single-longitudinal-mode (SLM) oscillation and narrow the linewidth to kHz target for each generated wavelength over the available wavelength-tuning bandwidth. In the measurement, the output power, optical signal to noise ratio (OSNR) and wavelength linewidth of the designed fiber laser are also executed and discussed.**

***Index Terms*—Fiber laser, erbium-doped fiber (EDF), Mach-Zehnder interferometer (MZI), single-longitudinal-mode (SLM), tunability.**

I. Introduction

Recently, with the growth and maturity of laser demand gradually, erbium-doped fiber (EDF) baser lasers have been assumed and expected in several optics-related applications, such as the optical communication, mm-wave photonics, spectroscopy, bio-photonics, optical Lidar, fiber sensing system or other fields [1]–[5]. The EDF laser can achieve the output characteristics of the high optical signal to noise ratio (OSNR), narrow laser linewidth, and broad wavelength tunability. However, the EDF ring lasers with stable single-longitudinal-mode (SLM) operation will be hard to accomplish principally because of the long fiber cavity and the dense multi-longitudinal-mode (MLM) oscillation induced by the homogenous broadening effect of EDF [6], [7]. To ensure and reach the SLM action in the EDF ring fiber laser with advantageous output performance, numerous methods have been operated in the fiber ring cavity, such as using the Mach-Zehnder interferometer (MZI) scheme [8], saturable absorber (SA) based filter [9], [10], Rayleigh backscattering (RB) injection [11], compound fiber ring configuration [12], [13], and narrower optical filter [14], [15].

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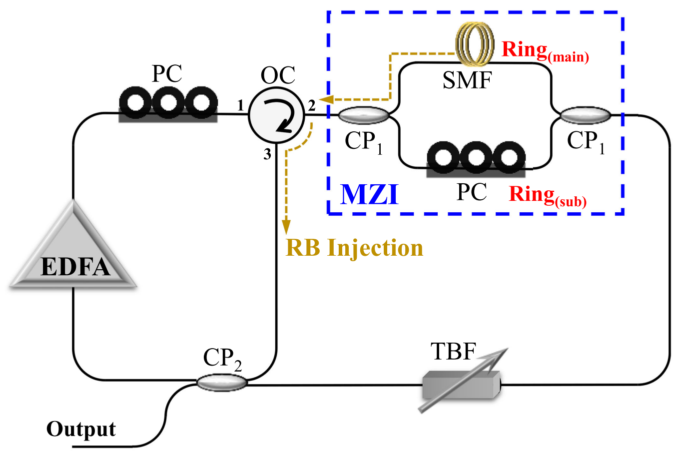

Fig. 1. Experimental setup of designed EDF based ring laser.

To reach the SLM operation, the MZI structure and RB signal injection loop are applied in the presented EDF ring laser in the demonstration. Here, a C-band erbium-doped fiber amplifier (EDFA) is operated acting as gain-medium inside the ring cavity. We can achieve the wavelength-selectable tunability from 1526.0 to 1564.0 nm together with the output power and optical signal to noise ratio (OSNR) between –16.2 and –10.6 dBm and 48.4 and 56.7 dB, respectively. In the measurement, the SLM oscillation of the EDF laser can be proved by using delayed self-homodyne setup. Moreover, the achievable 3 dB Lorentzian linewidth of 1 to 2 kHz also can be obtained in the whole tuning span of 1526.0 to 1564.0 nm.

II. Experiment and Discussions

Fig. 1 presents the architecture of demonstrated selectable-wavelength EDF laser with SLM action. To achieve the tunable SLM and narrow linewidth output, the combined Mach-Zehnder Interferometer (MZI) and Rayleigh backscattering (RB) injection configuration is designed and investigated. The presented fiber laser constructs by two 1×2 optical couplers (CP_1) with same coupling ratio, a 2×2 and 50:50 optical coupler (CP_2), a C-band tunable bandpass filter (TBF), a length of 102 m single-mode fiber (SMF), two polarization controllers (PCs), a 3-port optical circulator (OC) and a commercial erbium-doped fiber amplifier (EDFA) acting as gain-medium, respectively. The saturated power of EDFA is 13 dBm in an available gain range of 1526.0 to 1562.0 nm. The C-band TBF with 6 dB insertion loss and 0.4 nm bandwidth is put inside ring cavity to adjust the corresponding passband for wavelength selection. Two PCs are applied to operate the optimal output power and polarization state. The MZI is composed of two CP_1, as shown in Fig. 1. The upper arm is connected to the 102 m SMF, the other is connected to a PC having 3 m long length. Hence, the MZI structure can cause the comb filter effect for dense side-mode suppression [16]. The 102 m SMF can generate the RB-induced wavelength injection via the OC (port 2 to port 3) entering the gain-medium by the proposed laser configuration. Then, the RB-caused lightwave can be amplified and excited through the EDFA for creating long coherence length and high gain. Once the Rayleigh bandwidth become narrow reasonably, the pump wavelength obtained in the laser cavity will become narrower and narrower to cause the SLM operation through millions of resonances. Actually, when the SMF length is increasingly increased, the attained linewidth in the RB-based EDF laser would also become narrower [17]. The related principle and explanation of RB effect have been detailed in Refs. [8], [16], [17]. However, too long SMF length will result in less stable output of EDF laser. If too short, it will not be able to achieve RB effect. Hence, the selection of the appropriate SMF length is also an important consideration. In the demonstration, the RB signal also could narrow the laser linewidth, while a SMF with 102 m is applied in the presented EDF laser scheme. To observe the output spectrum and power of the EDF laser, an optical spectrum analyzer (OSA) and a power meter are used to connect to the output port of CP_2.

First, we can control the passband of TBF in the presented EDF laser to realize the achievable wavelength-tuning scope. Then, the lasing wavelength can be tuned continuously from 1526.0 to 1564.0 nm. The lasing wavelengths of 1526.0, 1535.0, 1545.0, 1555.0 and 1564.0 nm are presented for demonstration as seen in Fig. 2, respectively. Besides, the amplified spontaneous emission (ASE) curve of C-band EDFA is also shown in the inset of Fig. 2. And the larger ASE power is around 1530 nm. As exhibited in Fig. 2, the ASE background noise can be suppressed effectively according to the proposed laser structure.

Then, the measured optical signal to noise ratio (OSNR) of each generated wavelength versus the different output power over a tuning scope of 1526.0 to 1564.0 nm is shown in Fig. 3. The output powers of –16.2 to –10.6 dBm and corresponding OSNRs of 48.4 and 56.7 dB are exhibited in the available tuning bandwidth of 1526.0 to 1564.0 nm. Moreover, the largest and smallest output powers of –10.6 and –16.2 dBm are measured at the wavelengths of 1526.0 and 1560.0 nm together with the OSNRs of 48.4 and 56.7, respectively. In the measurement, the proposed EDF laser configuration also can result in two fiber rings, which mean the main- and sub-rings ($\text{Ring}_{(\text{main})} = 124$ m and $\text{Ring}_{(\text{sub})} = 28$ m) as illustrated in Fig. 1, to cause a mode-filter behavior based on the Vernier effect [5], [6]. The MZI and Vernier based mode-filters could suppress and shift

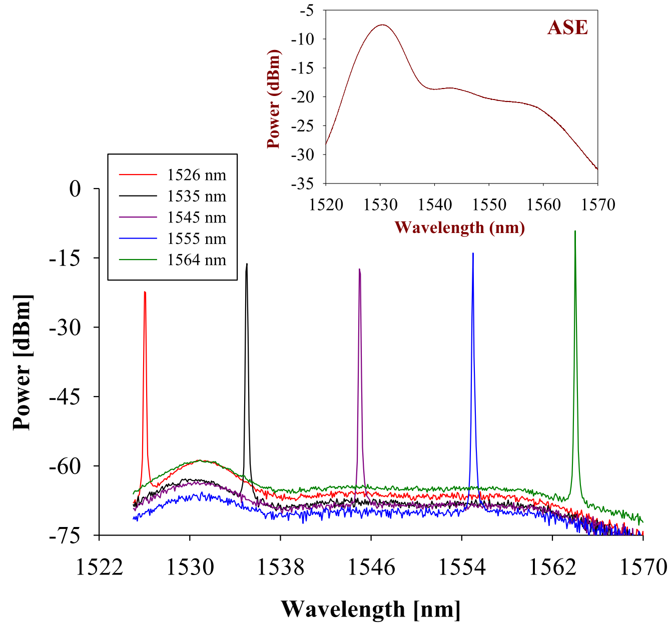

Fig. 2. Measured output spectra of the presented EDF ring laser from 1526.0 to 1564.0 nm. Insert is the obtained ASE spectrum of original C-band EDFA.

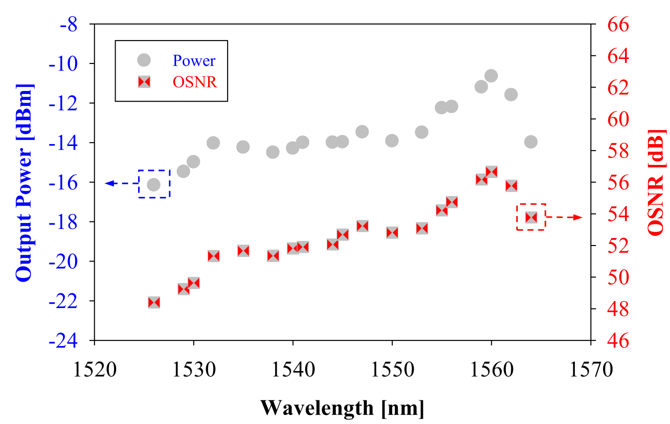

Fig. 3. Measured OSNR and output power versus the various lasing wavelength in a range of 1526.0 to 1564.0 nm.

the erbium gain to long wavelength range probably. Hence, the lasing wavelength in the long wavelength range will have larger output power and higher OSNR. As exhibited in Fig. 3, when the output wavelength moves slowly to the longer wavelength, the obtained output power and OSNR will also gradually rise until the end of 1560.0 nm, due to the effective gain competition of the laser cavity.

To proof the SLM behavior of the presented EDF laser, a delayed self-homodyne setup is built for investigation. The setup is illustrated in Fig. 4, when this square block does not exist. The setup composes of two CP_1, a 60 km single-mode fiber (SMF) and a PC to produce the MZI configuration. Here, nine generated wavelengths of 1526.0, 1530.0, 1535.0. 1540.0, 1545.0, 1550.0, 1555.0, 1560.0 and 1564.0 nm are employed into the MZI for SLM observation. Then, each lasing wavelength can be received by a photodiode (PD) to convert to electrical signal. The converted self-homodyne RF beat spectra can be observed by an

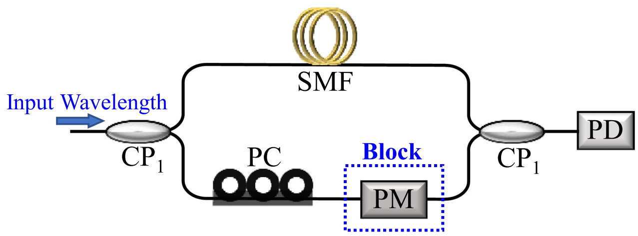

Fig. 4. The setups of delayed self-homodyne (without square block) and delayed self-heterodyne (with square block).

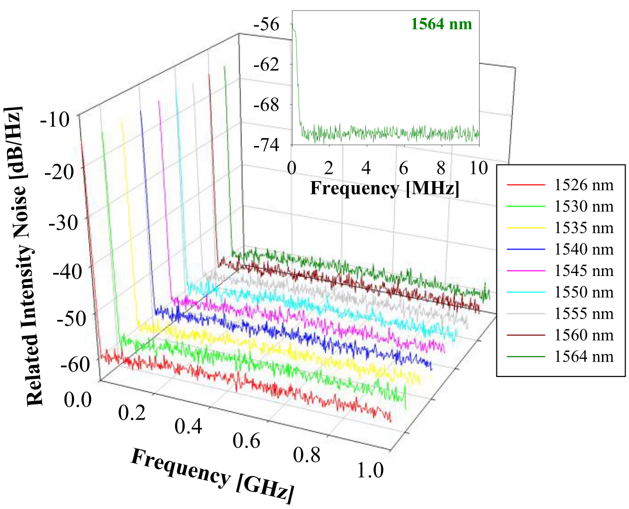

Fig. 5. Measured RF beating spectral of nine selected wavelengths from 1526.0 to 1564.0 nm over the frequencies of 0 to 1 GHz, respectively. Inset is the observed spectrum of 1564.0 nm within 10 MHz bandwidth.

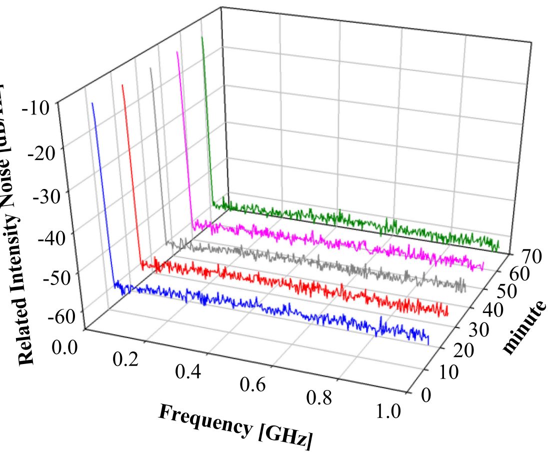

Fig. 6. Measured RF beating spectrum of 1564.0 nm within 1 GHz frequency during 60-minute observation.

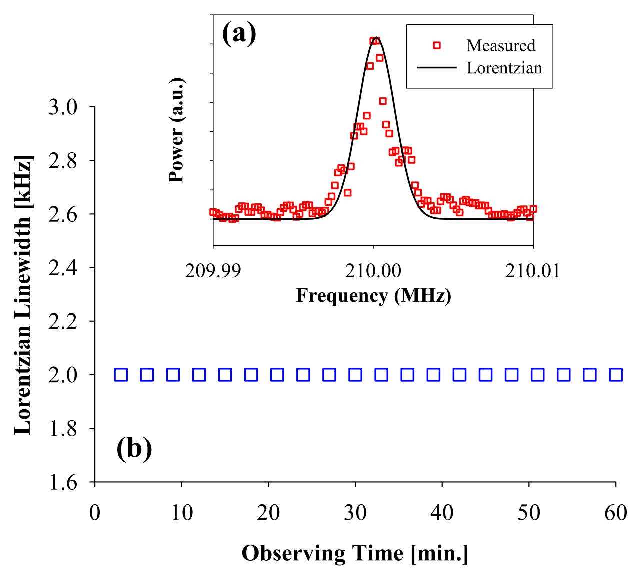

Fig. 7. (a) Measured and Lorentzian fitting frequency spectrum at the wavelength of 1564.0 nm, respectively. (b) Measured Lorentzian linewidth of 1564.0 nm through 60-minute observation.

electrical spectrum analyzer (ESA). Fig. 5 present the obtained self-homodyne spectra of the nine selected wavelengths over the frequency scope of 0 to 1 GHz, respectively. Fig. 5 also shows the related signal intensity to noise over the measured frequency range. There are no any apparent beating longitudinal-mode can be captured over the whole tuning bandwidth of 1526.0 to 1564.0 nm, as seen in Fig. 5. We also perform this experiment within the frequency range of 10 MHz at the wavelength of 1564.0 nm for demonstration, as illustrated in the inset of Fig. 5. And no beating noise is also observed in the measured RF spectrum. Therefore, the measured results indicate that the proposed laser can maintain the stable SLM operation. Moreover, through an observation of 60 minute, the SLM oscillation also can be accomplished, when the wavelength of 1564.0 nm is selected for observation, as illustrated in Fig. 6.

Next, a delayed self-heterodyne system is applied to measure the output linewidth of each lasing wavelength, as shown in Fig. 4. Here, the MZI configuration is composed of a 10 GHz phase modulator (PM) in one arm and a 60 km long SMF in the other one. To generate beat frequency in the measurement, a 210 MHz RF signal is applied on the PM. To execute the laser linewidth first, we also select the wavelength of 1564.0 nm for observation. The measured wavelength linewidth of 1564.0 nm is plotted in the red square in inset of Fig. 7(a), when the beat frequency is generated at 210 MHz. To attain the practical linewidth, the Lorentzian curve is exploited for fitting, as also shown in the black line in the inset of Fig. 7(a). The 3 dB Lorentzian linewidth of 1564.0 nm is 2 kHz. In addition, to verify the obtained linewidth of 1564.0 nm within one hour, we measure the line width every 3 minutes. The reachable Lorentzian linewidth is also maintained at 2 kHz, as shown in Fig. 7(b). Finally, we also use the same selected wavelengths as above for measuring the 3 dB Lorentzian linewidth. In the observation, the obtainable Lorentzian linewidth of the presented EDF laser is measured between 1 and 2 kHz in the achievable tuning scope of 1526.0 to 1564.0 nm, as shown in Fig. 8. The obtained linewidth of the laser is 1 kHz at the three wavelengths of 1550, 1560 and 1570 nm, respectively. The possible reason may be caused by the temperature and disturbance differences in the laboratory. As a result, the demonstrated MZI and Vernier based filter effect and RB injection method can not only suppress the dense MLM noises, but also can narrow the linewidth to kHz level.

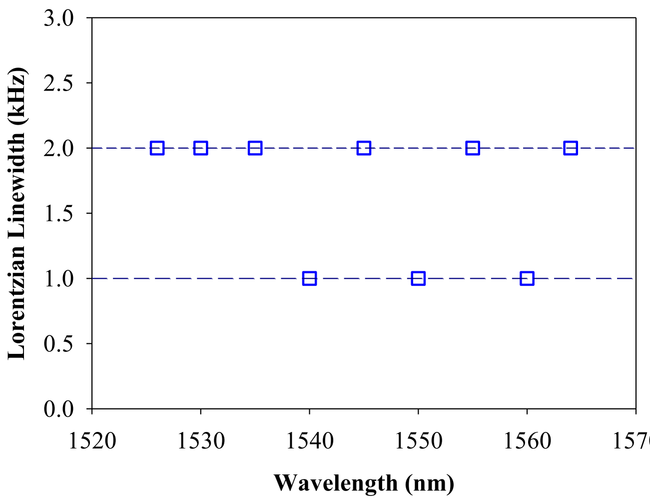

Fig. 8. Measured Lorentzian linewidth of the presented EDF laser in the achievable tuning scope of 1526.0 to 1564.0 nm.

III. Conclusion

In summary, we demonstrated experimentally an EDF based laser by using the blended configuration of MZI design and RB-induced injection loop for wavelength-tunable and stable SLM operations. In the demonstration, the proposed EDF laser structure reached the output powers and corresponding OSNRs between –16.2 and –10.6 dBm and 48.4 and 56.7 dB, respectively, over a wavelength-tuning bandwidth of 1526.0 to 1564.0 nm. The SLM behavior of each lasing wavelength also be verified in the whole output bandwidth by using the self-homodyne measurement. Moreover, the obtainable 3 dB Lorentzian linewidths were between 1 and 2 kHz in the achievable wavelength-tuning span of 1526.0 to 1564.0 nm.

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