A Wavelength-Tunable Single-Longitudinal-Mode Fiber Ring Laser With a Large Sidemode Suppression and Improved Stability

Shilong Pan and Jianping Yao, *Senior Member, IEEE*

***Abstract*—A high-performance single-longitudinal-mode (SLM) fiber ring laser incorporating a high finesse ring filter that contains a section of weakly pumped erbium-doped fiber is proposed and experimentally demonstrated. The incorporation of the high finesse ring filter can suppress multimode oscillation, improve power stability, and increase sidemode suppression ratio (SMSR). A stable SLM oscillation with a tunable range from 1522 to 1573 nm and an SMSR as high as 68 dB is experimentally demonstrated.**

***Index Terms*—Fiber lasers, high finesse ring filter, sidemode suppression ratio (SMSR), single longitudinal mode (SLM).**

I. Introduction

WAVELENGTH-TUNABLE single-longitudinal-mode (SLM) fiber lasers have important applications in coherent communications, high-resolution spectroscopy, optical sensing, and optical coherent tomography, thanks to the advantageous features such as broad wavelength tuning range, high output power, and narrow linewidth [1]. An SLM fiber laser can be implemented with a ring structure using a pumped erbium-doped fiber (EDF) as the gain medium. However, a fiber ring laser usually has a long cavity, which would lead to the generation of an enormous number of densely spaced longitudinal modes. To limit the number of longitudinal modes to be one, a compound ring filter with an effective free spectral range (FSR) that is the least common multiple of multiple ring cavities was proposed [2]–[8]. Compared with other approaches such as the use of a saturable absorber [9] or a high finesse fiber Bragg grating Fabry–Pérot etalon [10], [11], an SLM fiber ring laser based on multiple-ring cavities features a higher slope efficiency and better tunability. But the finesse of the compound ring filter is always low, and mode hopping can still be observed. In addition, the power stability is also poor. In a fiber laser, in addition to the requirement for high power stability, the sidemode suppression ratio (SMSR) should also be large. For instance, a low SMSR would lead to intolerable mode partition noise or crosstalk in a wavelength-division-multiplexing (WDM) communications system, and would also cause low dynamic range in an optical measurement system. The SMSR of a conversional SLM fiber laser is always around 50 dB or less [5], [6], [8], [11].

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The authors are with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada (e-mail: jpyao@site.uOttawa.ca).

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Recently, we proposed and developed a novel high-finesse fiber ring filter, which was incorporated into a dual-wavelength SLM fiber ring laser for microwave generation [8]. The ring filter contains a section of EDF that is weakly pumped to generate a small optical gain. Thanks to the optical gain, the ring filter has a frequency response with a significantly increased finesse. Dual-wavelength SLM operation is thus guaranteed. Since the EDF is pumped, the saturation of the EDF should evidently affect the performance of the filter, which is not investigated in [8]. In addition, in [8], the wavelengths can only be tunable in a very limited range, therefore, the influence of the filter to the tunability of a fiber laser is not sufficiently studied.

In this letter, the two issues are addressed. The high-finesse ring filter is used to construct a single-frequency EDF ring laser (EDFRL). By taking into account the saturation property of the EDF when analyzing the transmission function of the filter, we find that the ring filter introduces an automatic gain control (AGC) in the fiber laser which improves the power stability. Since the ring filter also has a frequency response with a high finesse when the EDF in the ring filter is saturated, it can simultaneously suppress multimode oscillation and improve the stability. In addition, the tunability of the laser is investigated, and the best operation wavelength regime for the laser to achieve both a high output power and a large SMSR is obtained. An experiment is performed. A stable SLM operation with a tunable range from 1522 to 1573 nm and an SMSR of up to 68 dB (0.01-nm resolution) is demonstrated. To the best of our knowledge, this is among the highest values reported so far.

II. Principle

The proposed SLM-EDFRL is shown in Fig. 1(a). An 8-m EDF (EDF_1) is used as the gain medium, which is pumped by a 980-nm laser diode (LD) via a 1550/980-nm WDM coupler and a 3-dB optical coupler. To ensure a unidirectional operation, an optical isolator is placed before EDF_1. The 3-dB optical coupler has a splitting ratio of $50:50$ at 1550 nm and of $10:90$ at 980 nm, with 10% of the pump power being injected into a fiber ring loop. The fiber ring loop consists of a 3-dB optical coupler, a 0.6-m EDF (EDF_2), and a $10:90$ optical coupler. Due to the gain introduced by the weakly pumped EDF, the ring filter has a comb spectral response with a high finesse, which is used to effectively suppress the undesirable modes around the transmission peak. A tunable Fabry–Pérot filter with a 3-dB bandwidth of 0.3 nm is incorporated to provide a coarse wavelength selection. To obtain an optimal laser output, a polarization controller (PC) is incorporated to adjust the polarization state of the light

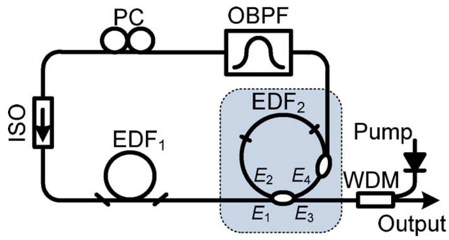


Fig. 1. Configuration of the proposed SLM fiber laser. ISO: isolator; OBPF: optical bandpass filter.

in the cavity. The laser output is monitored by an optical spectrum analyzer (OSA) with a resolution of 0.01 nm.

Mathematically, when an input lightwave with the optical field E_1 is injected into the ring filter, the power of the optical field E_4 in the ring filter can be written as [8]

$$|E_4|^2 = \frac{\gamma |E_1|^2}{1 + g^2(1-\gamma) - 2g\sqrt{1-\gamma}\cos\omega\tau} \tag{1}$$

where γ is the coupling factor of the 2×2 optical coupler, g is the effective gain, and τ is the time delay of the ring filter. Considering the saturation of EDF_2, g is given by

$$g = \frac{g_0}{1 + (1-\alpha)|E_4|^2/P_{\rm sat}} - \alpha \tag{2}$$

where g_0 is the small signal gain provided by EDF_2, α is the coupling factor of the 1×2 optical coupler and $P_{\rm sat}$ is the saturation power of EDF_2. Substituting (1) into (2) yields

$$A_3 g^3 + A_2 g^2 + A_1 g + A_0 = 0 \tag{3}$$

where

$$A_0 = \alpha + \alpha(1-\alpha)\gamma|E_1|^2/P_{\rm sat} - g_0 \tag{3a}$$

$$\begin{aligned} A_1 = {} & 1 + 2(g_0 - \alpha)\sqrt{1-\gamma}\cos\omega\tau \\ & + (1-\alpha)\gamma|E_1|^2/P_{\rm sat} \end{aligned} \tag{3b}$$

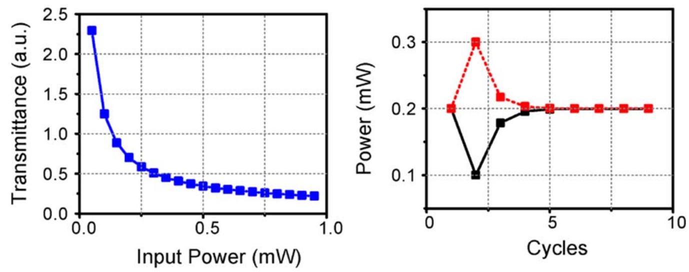
$$A_2 = (\alpha - g_0)(1-\gamma) - 2\sqrt{1-\gamma}\cos\omega\tau \tag{3c}$$

$$A_3 = 1 - \gamma. \tag{3d}$$

From (3), the gain g can be calculated if $\alpha, \gamma, g_0, P_{\rm sat}$ and $|E_1|^2$ are provided. With a given g, the transmission function of the high-finesse ring filter is obtained

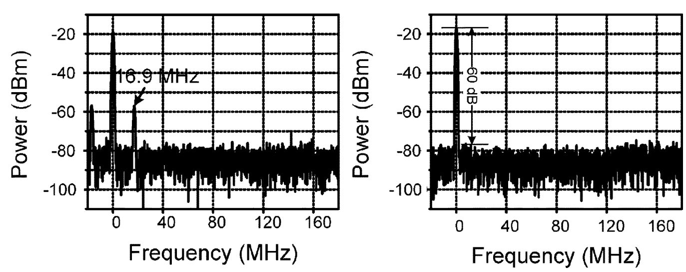
$$T = \frac{\alpha|E_4|^2}{|E_1|^2} = \frac{\alpha\gamma}{1 + g^2(1-\gamma) - 2g\sqrt{1-\gamma}\cos\omega\tau}. \tag{4}$$

With the parameters used in the experiment $\alpha = 0.1, \gamma = 0.5, g_0 = 4, P_{\rm sat} = 0.5$ mW, we have the transmittance of the ring filter as a function of the input optical power, as shown in Fig. 2(a). When the input power increases, the transmittance of the ring filter decreases rapidly. Therefore, the incorporation of the ring filter also functions to provide an AGC, which is essential to the power stability of the fiber laser. To investigate the effect of the AGC, we assume that the laser is operating at a steady state and then a sudden increase or decrease in the lasing power is introduced due to environment fluctuations. The evolution of the oscillating power is calculated using (3) and (4) with the results shown in Fig. 2(b). In the first cycle, the laser operates at a steady state with an oscillating power of 0.2 mW. Then, the power of the oscillating mode is increased (decreased) to 0.3 (0.1) mW. After only three cycles, the power converges to its steady value. Power fluctuations of the oscillating mode are



(a) (b)

Fig. 2. (a) Transmittance of the ring filter as a function of the input power. (b) Evolution of the output power with a sudden change in the lasing power.



(a) (b)

Fig. 3. Electrical spectra measured by applying the laser output to a PD. RBW = 1 MHz: (a) Spectrum measured when EDF2 is not pumped, and (b) spectrum measured when EDF2 is weakly pumped.

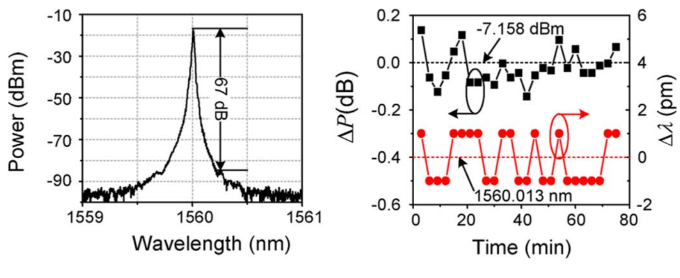
automatically suppressed, indicating that the AGC introduced by the high finesse ring filter greatly improves the power stability of the fiber laser.

In fact, the ring filter with a pumped EDF can also be seen as a fiber laser which is injection locked by another fiber laser formed by the main cavity. As a result, the injection locking would greatly improve the SMSR [12].

III. Experimental Results and Discussion

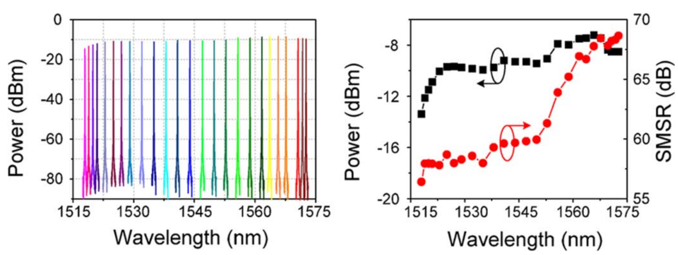
An experiment based on the setup shown in Fig. 1 is performed. To verify the performance of the high finesse ring filter, the RF spectra by applying the laser output to a photodetector (PD) is measured in a frequency range of 0–180 MHz. When EDF_2 is not pumped, i.e., moving the pump LD and the WDM to the location right after EDF_1, a strong beat note at 16.9 MHz is observed, as shown in Fig. 3(a), which indicates that the laser is not operating in SLM. On the other hand, when a pump with a proper pump power is injected into the ring filter, the finesse of the filter is greatly increased [8], and an SLM operation is thus established, as shown in Fig. 3(b).

Fig. 4(a) shows the optical spectra at the laser output. A single wavelength at 1560.012 nm is observed. The SMSR for the wavelength is 67.2 dB (0.01-nm resolution), much higher than that reported in the dual-wavelength EDFRL [8]. We should note that an SLM fiber laser with an SMSR of 70.2 dB was reported [4], but the value was obtained using an OSA with a resolution of 0.05 nm. In our experiment, if the spectrum is measured using the OSA but with a poorer resolution of 0.05 nm, the SMSR reading is dramatically increased to 75.4 dB. It should be noted that it is very hard to resolve the nearest sidemodes with the OSA since the OSA has a highest resolution of 0.01 nm. Since the electrical spectrum has a



(a) (b)

Fig. 4. (a) Optical spectra of the fiber laser output with an SMSR of 67 dB (0.01-nm resolution). (b) Fluctuations of the output power and wavelength over a period of 75 min.



(a) (b)

Fig. 5. (a) Output spectra of the proposed laser with the wavelength tuned from 1520 to1573 nm. (b) Output power and SMSR when the wavelength is tuned from 1518 to 1566 nm.

resolution bandwidth (RBW $=$ 1 MHz) much less than the spacing of the nearest sidemodes ($\sim$8.5 MHz), it can be used to evaluate the actual sidemode suppression. From Fig. 3(b), we can see the DC component is nearly 60 dB over the noise floor, which indicates that the power of the undesirable modes are at least 60-dB lower than the power of the oscillating mode. The output power is only -7.2 dBm. This is because the EDF in the ring filter is very short (0.6 m), which leads to a low small-signal gain. To maintain a high effective gain which is required to obtain a high finesse, from (4) the injection optical power is controlled to be small. Recently, Er–Yb codoped fiber was developed to provide large small-signal gain within a very short length. If an Er–Yb codoped fiber is used to replace the EDF in the ring filter, the power should be greatly increased. Since the effective gain can be greatly increase by use of an Er–Yb codoped fiber, the finesse of the ring filter would also be increased. Then, a higher SMSR would be expected.

The power and wavelength stability is also investigated. To do so, we let the system operate in a room environment for a period of 75 min. The fluctuations of the output power and wavelength are shown in Fig. 4(b). The wavelength shift is less than 2 pm and the optical power fluctuation is smaller than $\pm$0.2 dB. It should be noted that the OSA used in our experiment has a wavelength accuracy of $\pm$0.02 nm and a power accuracy of $\pm$0.3 dB. The wavelength shift and the power fluctuation are within the measurement accuracy of the OSA, confirming that the proposed fiber laser has a high lasing stability.

By simply tuning the OBPF, the lasing wavelength can be continuously tuned in the whole C-band. Fig. 5(a) shows the output spectra of the laser with the wavelength tuned from 1520 to 1573 nm. The maximum and minimum output power is -13.2 and -7.2 dBm at the wavelength of 1518 and 1566 nm, as shown in Fig. 5(b). If the power variation is within 3 dB, the tunable range is greater than 51 nm (1522–1573 nm). The SMSR increases as the wavelength increases, from 56.4 dB at 1518 nm to 68.6 dB at $\sim$1573 nm. This feature is related to the different noise figures and large-signal gains of the EDFs at different wavelengths. From Fig. 5(a) and (b), the best operation wavelength regime to achieve both a high output power and a high SMSR is 1556 to 1573 nm. Note that the PC is finely adjusted to obtain the optimal SMSR for each wavelength. If the cavity is implemented with all polarization maintaining components, the use of the PC would be avoided.

IV. Conclusion

A novel SLM EDFRL incorporating a high-finesse ring filter has been proposed and demonstrated. Very stable SLM oscillation with a wavelength-tunable range from 1522 to 1573 nm and an SMSR of up to 68 dB (0.01-nm resolution) was obtained. The proposed SLM-EDFRL features a simple configuration, stable operation, and broad wavelength tunable range, which may find applications in optical communications, instrumentation, and other systems.

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