Stabilization of Dual-Wavelength Erbium-Doped Fiber Ring Lasers by Single-Mode Operation

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***Abstract*—In this work, a novel single-longitudinal-mode (SLM) dual-wavelength laser configuration is proposed and demonstrated. This laser is based on ring resonators, and employs fiber Bragg gratings to select the operation wavelengths. It includes a short piece of highly doped Er-fiber that acts as the active medium. The stable SLM operation is guaranteed when the two lasing channels present similar output powers. This behavior is shown for different pump powers.**

***Index Terms*—Erbium-doped fiber (EDF), fiber Bragg grating (FBG), multiwavelength lasing, optical fiber amplifier, optical fiber ring laser.**

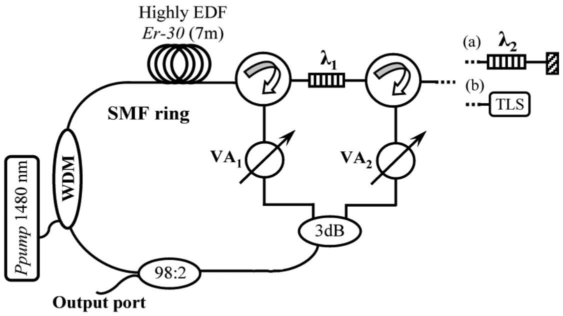

Fig. 1. Experimental setup of the EDFRL using a serial topology (a) by using two FBGs and (b) by using and an external source instead of one of the FBGs. TLS: tunable laser source.

I. INTRODUCTION

STABLE multiwalength single-mode erbium-doped fiber ring lasers (MEDFRL) are very attractive sources for many applications in optical fiber sensing, sensor network multiplexing schemes, and instrument testing due to their advantages; simple structures, narrow linewidth, and compatibility with other optical fiber components [1], [2]. The selection of its operation wavelengths has been achieved by using different optical filtering techniques: Mach–Zehnder filter, arrayed waveguide gratings, or fiber Bragg gratings (FBGs) [3]–[5]. In addition to this, a variety of methods have been employed to try maximizing the number stable emission lines.

The erbium-doped fiber ring lasers (EDFRLs) usually generate multiple longitudinal modes around the central lasing wavelength due to its long cavity length. This aspect can limit their practical applications because of the mode competition and the mode hopping. To achieve single-longitudinal-mode (SLM) operation, several approaches have been proposed [6]–[8]. The ring fiber lasers are also known to be susceptible to output power instabilities. These instabilities can degrade the performance characteristics of a sensor multiplexing network based on a laser interrogation scheme. The optimization of the ring laser configuration can improve considerably the characteristics of these lasers.

In this letter, a stable dual-wavelength EDFRL that operates in SLM condition is experimentally proposed and demonstrated. The laser configuration is based on the serial connection of the FBG using optical circulators and the active medium is a highly doped Er-fiber. This topology was previously reported by the authors in [9]–[11]. However, in this letter, the possibility to obtain a single-mode behavior is experimentally demonstrated by using a high-resolution optical spectrum analyzer. Experimental results of the good time stability obtained in the single-mode regime are also presented.

II. EXPERIMENTAL SETUP

The experimental setup of the proposed MEDFRL is shown in Fig. 1(a). This is a serial configuration based on circulators. The wavelength selection is carried out by means of FBGs with a reflectivity of about 98%. These FBGs are centered at 1543.6 and 1550.9 nm with a corresponding full-width at half-maximum (FWHM) of 0.842 and 0.61 nm, respectively.

A highly erbium-doped fiber (EDF) (Er-30 by Liekki, with an absorption of 30 dB/m at $\lambda = 1530$ nm) is used, acting as the active medium. The length of this EDF was 7 m and the total cavity length was 14 m. Because of the high concentration of erbium, the fiber length needed for the cavity was shorter than in other cases [10]. This configuration was also composed by a 1480/1550-nm wavelength-division multiplexer (WDM), a 1480-nm pump source and a 3-dB coupler to incorporate the two FBGs into the laser cavity. To extract 2% of the laser output power from the ring, a 98% coupler is used.

In this configuration, two circulators were used to insert the FBGs' reflected signals into the ring, ensuring unidirectional operation and therefore avoiding the spatial hole-burning (SHB)

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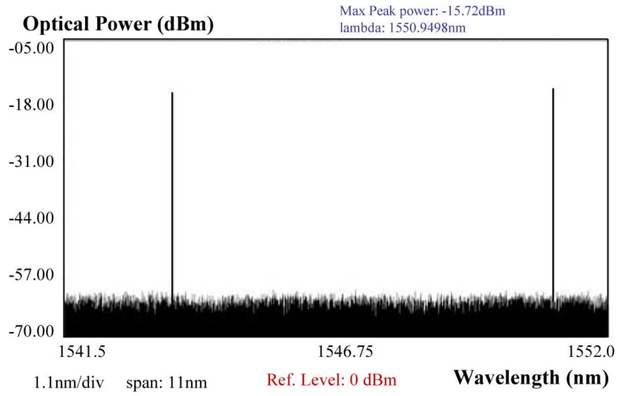

Fig. 2. Output optical spectrum measured by the BOSA for the MEDFRL circulators configuration and a pump power of 90 mW.

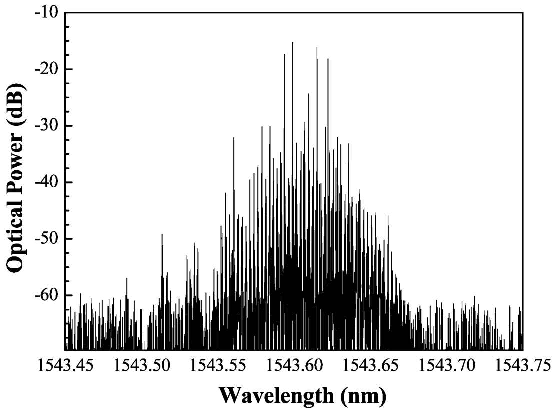

Fig. 3. Detail of the output optical spectrum for the first channel ($\lambda_1 = 1543.6$ nm) at single-wavelength operation.

effect. Because of the use of circulators, it was not necessary to introduce isolators inside the cavity.

One of the major problems in multiwavelength ring lasers is that the oscillation threshold power for each wavelength is different due to the nonuniform shape of the EDF gain profile. As a consequence, variable attenuators (VAs) have been connected to each FBG in order to correctly adjust the cavity losses on each wavelength to achieve oscillation of the system in all the desired channels. All the free terminations on both systems have been immersed in refractive-index-matching gel to avoid undesired reflections.

III. EXPERIMENTAL DEMONSTRATION

The output spectrum of the MEDFRL for a 90-mW pump power is shown in Fig. 2. The experimental results of this work were obtained by using a high-resolution optical spectrum analyzer (BOSA-C Aragon Photonics) which offers simultaneously a high resolution (0.08 pm) and a high dynamic range (>80 dB). As can be shown in Fig. 2, using two FBGs, two lasing channels are obtained. The power of each of the two output channels is around -16 dBm. For the two channels, the signal power is more than 45 dB higher than the amplified spontaneous emission (ASE) noise floor. The pumping threshold needed to obtain laser emission was around 45 mW. However, we worked with higher pump power levels to increment the output power stability, as reported in [11].

The behavior of the longitudinal modes of this fiber laser was experimentally analyzed using this high-resolution optical spectrum analyzer. Its spectral resolution has a lower value than the mode spacing between the longitudinal modes of the ring, given by

$$\Delta\lambda = \frac{\lambda^2}{nL} \tag{1}$$

where n is the refractive index, L is the ring length, and λ is the central mode wavelength. As a consequence, we can verify the SLM operation condition.

We have measured different optical spectra corresponding to different values of pump powers and working conditions (dual- or single-wavelength operations at λ_1 or λ_2). The optical spectrum of the first lasing channel ($\lambda_1 = 1543.6$ nm) around centered mode wavelength in a single-wavelength operation for a pump power of 90 mW is shown by Fig. 3. As can be shown, multiple longitudinal modes are supported by the cavity. This spectral measurement was tested for several levels of pump power. We observed a broadening of the laser linewidth when the pump power increases. For example, for a pump power of 75 mW, an FWHM linewidth of 3.25 GHz was measured; however, when a pump power of 90 mW was used, the FWHM linewidth increases to 4.5 GHz. The broadening of the laser linewidth is related with the irruption of additional longitudinal modes when the gain value rises. Fig. 4 shows the output spectra of the two lasing channels in a dual-wavelength operation with similar output powers for a reduced wavelength span around each single-mode emitted wavelength. In this case, the pump power is 90 mW and the power difference between both channels is about 0.5 dB. The optical spectrum of the first channel ($\lambda_1 = 1543.6$ nm) for a wavelength span of 56.4 pm with 5.64 pm/div is shown in Fig. 4(a). The one of the second channel ($\lambda_2 = 1550.9$ nm) for a wavelength span of 47 pm with 4.7 pm/div is shown in Fig. 4(b). Also for this pump power level, FWHM linewidths of 7.5 and 6 MHz were measured for the first and second channels in that order.

As can be shown in these figures, this laser presents an SLM operation condition in both channels. These measurements have been repeated at different pump powers from 45 to 100 mW. In all cases, an SLM operation in both channels is achieved when the two lasing wavelengths are oscillating simultaneously with similar output powers by using the VAs to adjust the cavity losses. As it was previously proposed by the authors [11], using this configuration, a good stability both in emission power and wavelength were obtained from a pump power of about 90 mW.

This SLM operation can also be obtained by using an external source instead of the one of the FBGs [see Fig. 1(b)] or even by means of different wavelength spacing between the FBGs whenever similar output powers in both channels are obtained simultaneously, as we experimentally carried out in a number of preliminary studies. A possible explanation of this behavior is the self-injection seeding.

As reported in previous works [12], an SLM fiber ring laser can be made to annihilate the mode competition with an auxiliary lasing. In this work, owing to the interaction of the seed light

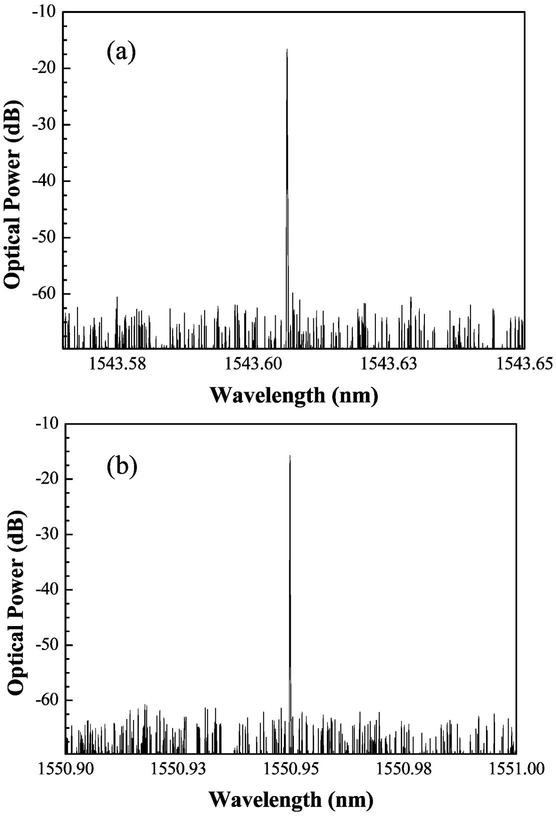

Fig. 4. Details of the output optical spectrum (a) for the first channel ($\lambda_1 = 1543.6$ nm) and (b) for the second channel ($\lambda_1 = 1550.9$ nm) at dual-wavelength operation.

produced from one channel to the other one and vice versa, multiple-longitudinal-mode oscillation can be suppressed, as can be seen in Fig. 4(a) and (b), and thus the mode competition and mode hopping is not produced. Therefore, the laser oscillation is rather stable.

The power of the laser output can suffer some changes with time. For this reason, the temporal variations of the output power were also measured and analyzed on this MEDFRL. The instability is defined as the output power for a given interval of time (hours) and a specific confidence level (CL). This is the probability value associated with a confidence interval (CI), given as a percentage. The CI is the estimated range of values where the parameter of interest is included. We have tested the laser during a period of 6 h. The measured data have been stored each 15 s and a CL of 90% was considered. Just to give data, at room temperature the power averaged variation with CL $= 90\%$ and Pump $=$ 100 mW was about 1.2 dB for $\lambda_1 = 1543.6$ nm, and about 0.9 dB for $\lambda_2 = 1550.9$ nm. Thus, we can conclude that both channels present good output power stability.

IV. CONCLUSION

A stable dual-wavelength EDFRL has been achieved by using FBGs to perform wavelength selection on the systems. In a single-wavelength operation of this laser, we have experimentally demonstrated that multiple longitudinal modes are supported by the cavity. However, for similar pumping levels, we achieve a single-mode operation of the laser when we emit simultaneously two wavelengths using a special ring cavity configuration. The stable SLM operation is guaranteed if the output power of both channels is similar. This implies that it is possible to avoid the utilization of additional optical filtering techniques (that reduce the optical efficiency) to achieve the SLM operation. There is also good power stability of this laser that uses a serial topology involving circulators.

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