Single-Longitudinal-Mode Multiwavelength Fiber Ring Laser

Jian Liu, *Member, IEEE*, Jianping Yao, *Senior Member, IEEE*, Jian Yao, and Tet Hin Yeap

***Abstract*—A single-longitudinal-mode multiwavelength fiber ring laser is proposed and demonstrated. The single-longitudinal-mode operation is realized using a fiber loop mirror with a saturable absorber. The fiber loop mirror acts as a passive self-tracking narrow multiband optical filter. Single-longitudinal-mode multiwavelength lasing is generated by using either a Lyot–Sagnac filter or a fiber grating array.**

***Index Terms*—Fiber Bragg grating (FBG), fiber loop mirror, fiber ring laser, Lyot–Sagnac loop, single-longitudinal mode, spatial hole burning.**

I. Introduction

MULTIWAVELENGTH fiber ring lasers are attractive for applications such as wavelength-division-multiplexing (WDM) communications, fiber-optic sensors, high-resolution spectroscopy, and microwave photonics systems, thanks to the numerous advantages such as narrow linewidth, high power, low intensity noise, and compatibility with other optical fiber components. Some multiwavelength fiber ring lasers have been proposed and demonstrated recently [1]–[4]. However, those fiber ring lasers suffer from densely spaced multiple longitudinal modes lying beneath the gain curve because of the long lasing cavity (typically longer than 10 m), which limits their applications due to multimode oscillation, mode hopping, and relatively large linewidth. Therefore, single-longitudinal-mode operation is highly desirable.

Several techniques have been proposed to achieve single-longitudinal-mode operation for fiber ring lasers [5]–[8]. These include the use of a compound ring [5], passive multiple ring cavity [6], or intracavity etalon [7]. Fiber lasers based on these approaches can generate a single-longitudinal-mode lasing with a single wavelength. For many applications, however, multiwavelength operation is required. In this letter, we propose and demonstrate a fiber ring laser that can generate single-longitudinal-mode multiwavelength lasing. In the proposed configuration, the single-longitudinal-mode operation is realized using a fiber loop mirror with a saturable absorber (SA). Spatial-hole burning effect is generated in the absorber when counterpropagating light waves are launched into the loop mirror. The spatial-hole burning effect leads to slight refractive index change in the absorber, and a weak Bragg grating with very narrow reflection bandwidth is, thus, generated [8]–[10]. Single-longitudinal-mode operation is achieved when the absorber-based loop mirror is incorporated into the fiber ring cavity. In this letter, we also demonstrate that narrow multiband filter could be generated in the SA when multiwavelength lasing signals counterpropagate in the loop mirror. With the proposed loop mirror structure, single-longitudinal-mode multiwavelength lasing can be realized by using either a Lyot–Sagnac filter or a fiber Bragg grating (FBG) array in the ring cavity as a wavelength selector. A major advantage of the proposed loop mirror structure is that it does not require an external injection source or a physical mirror [8], [9], which simplifies greatly the structure of the whole laser system.

Manuscript received August 4, 2003; revised December 17, 2003. This work was supported by the National Capital Institute of Telecommunications of Canada.

J. Liu was with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada. He is now with the Institute for National Measurement Standards, National Research Council of Canada (NRC), Ottawa, ON K1A 0R6, Canada.

J. Yao, J. Yao, and T. H. Yeap 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).

Digital Object Identifier 10.1109/LPT.2004.824975

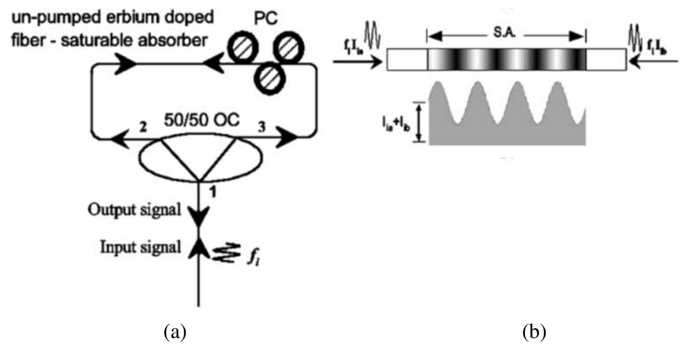

Fig. 1. (a) Schematic diagram of the self-tracking narrow-band filter. (b) Spatial interference pattern generated by two counterpropagation optical waves.

II. Principle

The schematic of the proposed absorber-based fiber loop mirror, which forms a passive self-tracking narrow-band optical filter for single-longitudinal-mode operation, is shown in Fig. 1(a). The loop mirror consists of a 3-dB optical coupler (OC) and a length of unpumped erbium-doped fiber (EDF) that serves as an SA. When the multiwavelength light wave is launched into the loop mirror through the 3-dB coupler from Port 1, the light wave is split into two equal parts, and the two split light waves counterpropagate in the absorber.

The optical power distribution of the ith wavelength in the absorber is given by

$$I_i = I_{ia} + I_{ib} + 2(I_{ia}I_{ib})^{1/2} * \cos(2\beta z) \tag{1}$$

where I_{ia} and I_{ib} are the optical intensity of the ith wavelength in Branches 2 and 3, z is the propagation distance, and β is the propagation constant. Therefore, a standing wave for the ith wavelength, which leads to a spatial interference pattern, is generated in the loop mirror, as shown in Fig. 1(b).

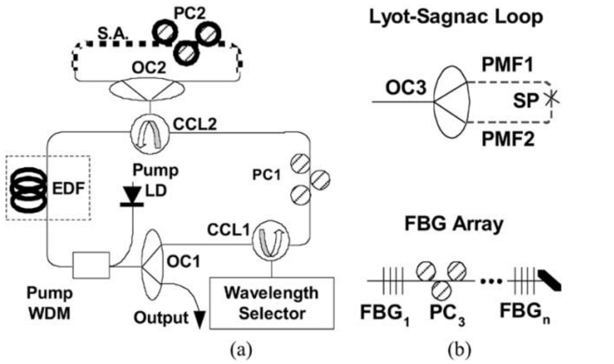

Fig. 2. (a) Configuration of the single-longitudinal-mode multiwavelength fiber ring laser. (b) Wavelength selectors. LD: laser diode. SP: splicing point. CCL: circulator.

In the experiment, a 2-m-long EDF is used as an SA. It is known that the absorption coefficient of an EDF is inversely proportional to the intensity of the optical power. For a given wavelength, the higher the intensity, the lower the absorption. Therefore, when the spatial interference pattern is generated by the counterpropagation optical waves, absorption coefficient with periodic variation which leads to spatial hole burning is formed. The spatial hole burning results in slight refractive index changes ($\sim 10^{-7}$) in the absorber, thus, a weak FBG with very narrow bandwidth is generated [13].

When a multiwavelength light wave signal propagates in the absorber, since the frequency difference between any two wavelengths with frequencies of f_i and f_j is much greater than the cutoff frequency f_c [9], [11], [12], which is determined by erbium–ion dynamics, there is no spatial interference between the two wavelengths. Therefore, the overall intensity is simply the sum of the intensities of the wavelengths

$$I_{ij} = I_i + I_j \quad (f_i - f_j \gg f_c). \tag{2}$$

In other words, the standing waves generated by the different wavelengths can exist independently in the absorber without interaction. These standing waves in the absorber induce the spatial hole burning effect, which leads to the refractive index changes. The periodic variations of the refractive index create a superstructured Bragg grating, acting as a narrow multiband filter in the laser cavity. This narrow multiband filter confines the multiwavelength lasing to a single-longitudinal mode; single-mode multiwavelength lasing is, thus, realized.

III. Experimental Results

As shown in Fig. 2(a), the proposed fiber laser is based on a ring structure. The unidirectional traveling wave in the main cavity is realized by using two circulators. A length of 12-m-long EDF is used as the active medium, which is pumped by a 976-nm semiconductor laser via a $980/1550$-nm WDM. Circulator 2 also acts as a pump isolator to block the residual pump signal from the EDF, to ensure that the SA in the loop mirror is unpumped. Two in-line polarization controllers (PCs) in the main ring and the loop mirror ensure that the state of polarization of the light in the ring cavity is properly controlled. The wavelength selection is realized using either a Lyot–Sagnac loop mirror or an FBG array, shown in Fig. 2(b). The whole cavity component loss is 9.5 dB and the cavity length is 34.4 m. To achieve single-longitudinal-mode operation, a very narrow-band optical filter would be incorporated into the laser cavity. This is achieved by using a fiber loop mirror with an SA. In the experiment, a 2-m-long EDF with erbium concentration of 600 ppm is used as the SA.

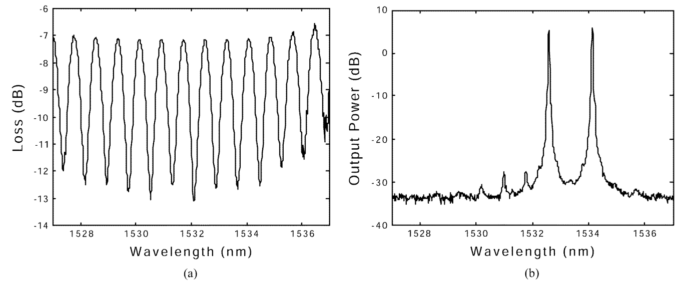

Fig. 3. (a) Reflection spectrum of the Lyot–Sagnac filter. (b) The optical spectrum of dual wavelength fiber laser when the Lyot–Sagnac filter is used as the wavelength selector.

The polarization-maintaining fiber (PMF) Lyot–Sagnac filter has a number of potential applications [14]. By using a Lyot–Sagnac filter as the wavelength selector, the required wavelength spacing can be obtained by simply adjusting the length difference Δl between two segments of PMF. The interval of the contiguous frequency is given by

$$\Delta\nu = \frac{c}{B\Delta l}$$

where c is the light speed in vacuum and $B(\sim 4.0 \times 10^{-4})$ is the birefringence of the PMF. The Lyot–Sagnac filter consists of a $50/50$ single-mode OC, two segments of Corning PMF of 4.79 and 12.17 m with a rotation angle of 52° between two principle axes. Therefore, a 100-GHz contiguous frequency interval (corresponding to a wavelength interval of 0.8 nm) is obtained. Fig. 3(a) shows the optical spectrum of the Lyot–Sagnac filter and Fig. 3(b) shows the optical spectrum of the dual-wavelength lasing of the fiber laser using the Lyot–Sagnac filter. The 3-dB linewidth is measured to be 0.05 nm for both wavelengths, limited by the optical spectrum analyzer resolution. The total output power is 9.08 dBm. It can be seen that the lasing occurs at 1532.57 and 1534.14 nm. The peak powers of the two wavelengths are 5.95 and 5.3 dBm, respectively, achieved by pumping the EDF using a 250-mW pumping laser. The side-mode suppression ratios (SMSRs) are 34.8 and 35.2 dB.

The single-longitudinal-mode operation is verified by using an Exfo laser spectrum analyzer. It is observed that a number of unstable longitudinal modes and mode hopping exist for the two wavelengths when the absorber-based fiber loop mirror is not incorporated in the laser cavity, as can be seen in Fig. 4(a). Fig. 4(b) shows the mode structure of the dual-wavelength fiber laser with the absorber-based fiber loop mirror incorporated. Only two peaks, which correspond to the two lasing wavelengths, are observed. By adjusting the state of polarization, one of two peaks disappear from the oscilloscope display, at the same time one of two wavelengths disappear from the optical spectrum analyzer screen, which indicates that the two peaks on the oscilloscope represent the two single longitudinal modes of the two wavelengths. The 3-dB linewidth of the two wavelengths is measured to be 11.7 MHz, limited by the 7-MHz resolution of the laser spectrum analyzer.

The single-longitudinal-mode operation is also verified by applying the laser output to a photodetector. A beating signal

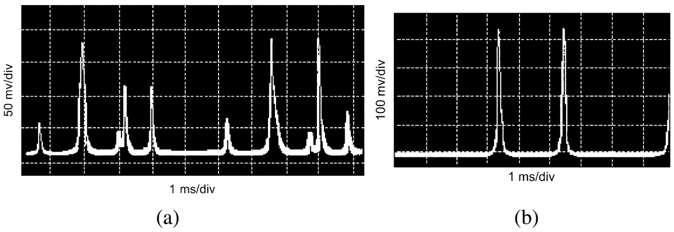

Fig. 4. (a) Multiple mode oscillation in the dual-wavelength fiber laser without mode confinement. (b) Mode structure of the single-longitudinal-mode dual-wavelength fiber laser.

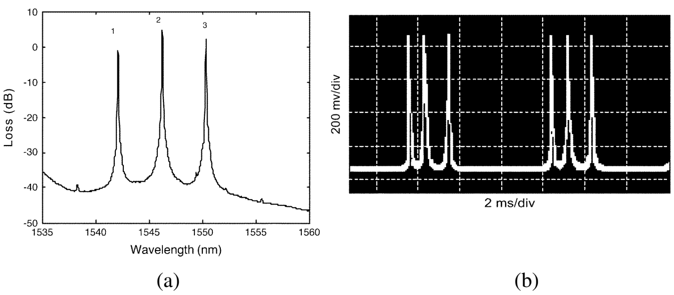

Fig. 5. (a) Optical spectrum of the single-longitudinal-mode triple-wavelength fiber laser. (b) The corresponding mode structure.

at 25 GHz is observed when the spacing of the two wavelengths is tuned to 0.2 nm. This further confirms that the laser is operating at single longitudinal mode. Note that to obtain stable simultaneous multiple wavelength lasing with small wavelength spacing, the active EDF is cooled in Liquid Nitrogen to eliminate the homogenous gain broadening and a bandpass filter is employed to control the lasing wavelengths. The use of this dual-wavelength laser to generate microwave signals is a direct application of this fiber laser, but the discussion of microwave signal generation using this laser is beyond the scope of this letter and will be reported elsewhere.

In the experiment, the SA length in relation to the single-longitudinal-mode property is experimentally investigated. It is observed that a 0.5-m-long absorber could not guarantee a single-longitudinal-mode oscillation, since the filter linewidth increases when the grating length decreases. On the other hand, a very long absorber results in larger cavity loss, which increases the laser threshold and reduces the output power. In the experiment, a 2-m length absorber is chosen since it ensures single-longitudinal-mode lasing and allows an acceptable output power as well.

Multiple wavelength selection can also be implemented using an FBG array. By using an FBG array as the wavelength selector, selection of multiple wavelengths is more flexible. In the experiment, the FBG array consists of three cascaded FBGs with different center reflection wavelengths. Fig. 5(a) shows the optical spectrum of the triple-wavelength fiber laser. The fiber laser total output power is measured to be 8.2 dBm. The mode structure measured using the laser spectrum analyzer is shown in Fig. 5(b). As can be seen, the fiber laser is operating in single longitudinal mode for the three lasing wavelengths.

IV. Discussions

We should note that stable multiwavelength lasing is obtained once the laser starts to lase. This means that the SA ensures a single-longitudinal-mode lasing when the lasing power is above the threshold. We also notice that single-longitudinal-mode lasing is maintained when the pumping power is increased. In the experiment, a stable single-longitudinal-mode lasing is maintained when the lasing power is increased to its maximum.

Based on the experiments, we find that the key factors that affect the maximum number of wavelengths are the polarization sensitivity and the gain homogenous broadening. In the experiment, to achieve stable multiwavelength lasing, the state of polarization must be properly adjusted. In addition, to achieve multiwavelength lasing, the wavelength spacing cannot be too small. At room temperature, a wavelength spacing of less than 1 nm leads to a poor stability.

V. Conclusion

We have demonstrated a novel single-longitudinal-mode multiwavelength fiber ring laser. The single-longitudinal-mode operation was realized by using a fiber loop mirror with an SA, which acts as a self-tracking narrow multiband optical filter. It was demonstrated that narrow multiband optical filtering was generated in the single SA when multiwavelength lasing signals were counterpropagating in the absorber. Multiple wavelength lasing was demonstrated by using either a Lyot–Sagnac filter or an FBG array.

References

[1] R. M. Sova, C. S. Kim, and J. U. Kang, "Tunable dual-wavelength all-PM fiber ring laser," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 287–289, Mar. 2002.

[2] K. Zhou, D. Zhou, F. Dong, and N. Q. Ngo, "Room-temperature multiwavelength erbium-doped fiber ring laser employing sinusoidal phase-modulation feedback," *Opt. Lett.*, vol. 28, no. 11, pp. 893–895, June 2003.

[3] Q. Mao and J. W. Y. Lit, "Switchable multiwavelength erbium-doped fiber laser with cascaded fiber grating cavities," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 612–614, May 2002.

[4] J. Yao, J. P. Yao, Y. Wang, S. C. Tjin, Y. Zhou, Y. L. Lam, J. Liu, and C. Lu, "Tunable active mode-locked multi-wavelength fiber ring laser," in *Optics Communications*. New York: Elsevier, May 2001, vol. 191, pp. 341–345.

[5] J. L. Zhang, C. Y. Yue, G. W. Schinn, W. R. Clements, and J. W. Lit, "Stable single-mode compound-ring erbium-doped fiber laser," *J. Lightwave Technol.*, vol. 14, pp. 104–109, Jan. 1996.

[6] C. C. Lee, Y. K. Chen, and S. K. Liaw, "Single-longitudinal-mode fiber laser with a passive multiple-ring cavity and its application for video transmission," *Opt. Lett.*, vol. 23, no. 5, pp. 358–360, 1998.

[7] Y. Takushima, S. Yamashita, K. Kikuchi, and K. Hotate, "Polarization-stable and single-frequency fiber lasers," *J. Lightwave Technol.*, vol. 16, pp. 661–669, Apr. 1998.

[8] H. Chen, F. Babin, M. Leblanc, and G. W. Schinne, "Widely tunable single-frequency erbium-doped fiber lasers," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 185–187, Feb. 2003.

[9] N. Kishi and T. Yazaki, "Frequency control of a single-frequency fiber laser by cooperatively induced spatial-hole burning," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 182–184, Feb. 1999.

[10] Y. Cheng, J. T. Kringlebotn, W. H. Loh, R. I. Laming, and D. N. Payne, "Stable single-frequency traveling-wave fiber loop laser with integral saturable-absorber-based tracking narrow-band filter," *Opt. Lett.*, vol. 20, pp. 875–877, Apr. 1995.

[11] R. Schatz, "Dynamics of spatial hole burning effects in DFB lasers," *IEEE J. Quantum Electron.*, vol. 31, pp. 1981–1993, Nov. 1995.

[12] M. Matsuura and N. Kishi, "Frequency control characteristics of a single frequency fiber laser with an external light injection," *IEEE J. Select. Topics Quantum Electron.*, vol. 7, pp. 55–58, Feb. 2001.

[13] A. Othonos and K. Kalli, *Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing*, London, U.K.: Artech House, 1999.

[14] K. Zhou, J. Yang, J. Ngo, and J. P. Yao, "Comb filter based on all polarization maintaining fiber loop and its applications," *Proc. SPIE*, vol. 4833, pp. 988–994, June 2002.