IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 3, Number 2, April 2011

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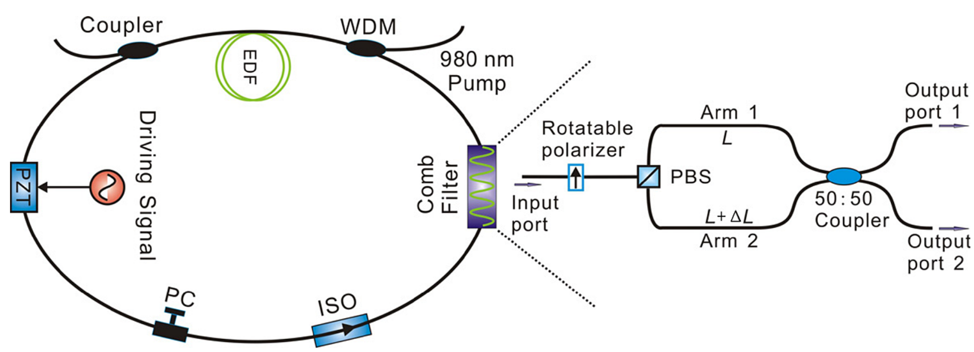

DOI: 10.1109/JPHOT.2011.2120601
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Multiwavelength Switchable Erbium-Doped Fiber Ring Laser With a PBS-Based Mach–Zehnder Comb Filter

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DOI: 10.1109/JPHOT.2011.2120601
1943-0655/$26.00 ©2011 IEEE

Manuscript received January 24, 2011; revised February 18, 2011; accepted February 21, 2011. Date of publication February 28, 2011; date of current version March 15, 2011. This work was supported by the National Natural Science Foundation of China under Grant 11074078, the Specialized Research Fund for the Doctoral Program of Higher Education, China, under Grant 20094407110002, the Foundation for Distinguished Young Talents in Higher Education of Guangdong, China, under Grant C10183, and the Key Program for Scientific and Technological Innovations of Higher Education Institutes in Guangdong Province under Grant cxzd1011. Corresponding authors: Z.-C. Luo and W.-C. Xu (e-mail: zcluo@scnu.edu.cn; xuwch@scnu.edu.cn).

Abstract: We propose and demonstrate a multiwavelength switchable fiber ring laser by employing a simple but novel polarization beam splitter (PBS)-based Mach–Zehnder (M–Z) comb filter. The proposed comb filter consists of a rotatable polarizer, a PBS, and a 3-dB fiber coupler. By adjusting the polarization state of the lasing light launched into the PBS, the multiwavelength switchable operation can be easily achieved. When the proposed comb filter was incorporated into the laser cavity, up to 11 multiwavelength switchable lasing lines with a channel spacing of 1.2 nm were obtained. In addition, the lasing locations and the number of the lasing lines can be flexibly tuned by exploiting the wavelength-dependent loss mechanism.

Index Terms: Fiber lasers, multiwavelength, switchable, comb filter, Mach–Zehnder.

1. Introduction

Multiwavelength fiber lasers have attracted much attention due to their widely potential applications in optical fiber sensing, fiber device testing, and wavelength-division-multiplexing (WDM) transmission system [1]–[7]. In particular, as the capacity of the communication system increases, the multiwavelength switchable fiber laser is considered as a useful light source for the wavelength-routed WDM optical network using optical cross-connects (OXCs) to avoid channel collisions and make full use of the traffic bandwidth [8]. Conventionally, the multiwavelength switchable function of the fiber laser is determined by the characteristics of the comb filter. Therefore, much effort has been directed toward investigating the comb filter with multiwavelength switchable function. To date, several methods have been proposed to achieve the multiwavelength switchable lasing in fiber lasers based on various comb filters, such as using sampled Hi-Bi fiber grating [8], the Sagnac birefringence loop [9]–[11], the unbalanced in-line Sagnac interferometer [12], the polarization diversity loop [13], [14], and a phase modulator in the loop mirror [15].

The standard Mach–Zehnder (M–Z) comb filter is always deemed to be a nontunable comb filter [16]. Although the two output ports of a standard M–Z interferometer have a switching relationship, the dynamic switchable operation of a single output port cannot be achieved. Recently, we demonstrated

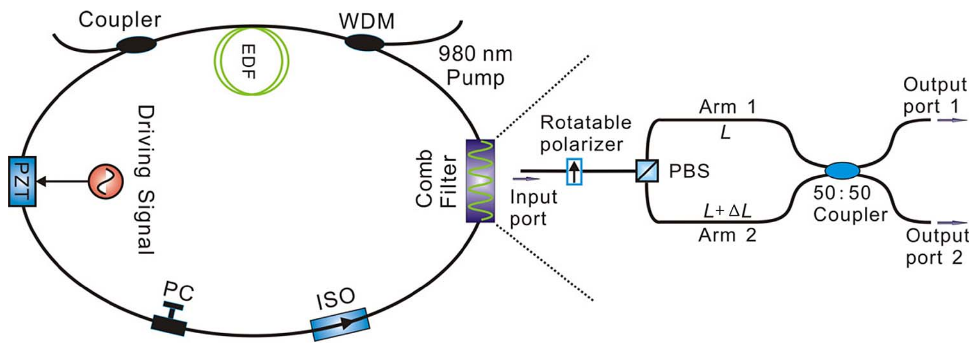

Fig. 1. Schematic of the proposed multiwavelength switchable fiber laser.

a multiwavelength fiber laser with a wavelength switchable function based on a modified dual-pass M–Z interferometer composed of a 3-dB and a non-3-dB coupler [17]. However, since the wavelength switchable operation of the comb filter is related to the polarization states of the light propagating along the interferometer arms, a polarization controller (PC) should be employed in one arm to finely control the polarization states. Therefore, it is less efficient to achieve the wavelength switchable function. In this paper, we propose and demonstrate a multiwavelength switchable fiber ring laser by using a polarization beam splitter (PBS)-based M–Z comb filter. The wavelength switchable operation of the proposed comb filter can be efficiently achieved by changing the polarization state of the light launched into the PBS, which results in the intensity change of the light propagating in the two arms. By incorporating the proposed comb filter into the laser ring cavity, up to 11 multiwavelength switchable lasing lines with 1.2-nm channel spacing were obtained. Moreover, by employing the wavelength-dependent loss mechanism, the lasing locations and the number of lasing lines can be flexibly tuned.

2. Experimental Setup and Operation Principle

Fig. 1 shows the schematic of the proposed multiwavelength switchable fiber ring laser. A 4.5-m long erbium-doped fiber (EDF) pumped by a 980-nm laser diode serves as the gain medium. A PC is employed to adjust the polarization state of the propagating light. The isolator (ISO) assures the unidirectional operation. Since the EDF is a strong homogenous line broadening gain medium at room temperature, a phase modulator composed of a 4-m-long single-mode fiber (SMF) wrapped around a cylindrical piezoelectric transducer (PZT) is used to suppress the mode competition. The multiwavelength switchable comb filter, which is developed from a standard M–Z interferometer, consists of a rotatable polarizer, a fiber PBS, and a 50:50 fiber coupler. The output is taken by a 10% fiber coupler and measured by an optical spectrum analyzer (OSA).

First, the transmission characteristics of the proposed comb filter are analyzed. Since a rotatable polarizer is placed before the PBS, the initial polarization state of the input light is forced into alignment with the orientation of the polarizer, provided that the linearly polarized light after the polarizer at an angle α with respect to one of the principal axes of the fiber is launched into the PBS. Then, the input light is split into two orthogonal polarized components after passing the PBS. The two polarized components experience path difference when they propagate in the two arms of the filter and finally interfere in the fiber coupler. The electric field in the two output ports can be expressed by the following Jones matrix representation:

$$\begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = \begin{bmatrix} \sqrt{1-c} & j\sqrt{c} \\ j\sqrt{c} & \sqrt{1-c} \end{bmatrix} \begin{bmatrix} e^{j\phi} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A\cos\alpha \\ A\sin\alpha \end{bmatrix}. \quad (1)$$

Here, A is the amplitude of the initial input field, $\phi = kn\Delta L$ is the phase difference caused by the path difference ΔL between the two arms of the comb filter, where n is the effective refractive index

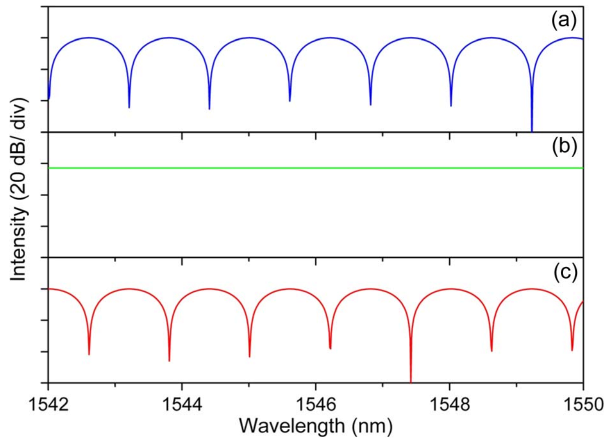

Fig. 2. Calculated evolution spectra of switchable operation with 1.2-nm channel spacing.

of the fiber, and k is the wavenumber. c is the coupling ratio of the fiber coupler. According to (1), E_1 and E_2 are obtained as

$$\begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = A\begin{bmatrix} \sqrt{1-c}\cos\alpha e^{j\phi} + j\sqrt{c}\sin\alpha \\ j\sqrt{c}\cos\alpha e^{j\phi} + \sqrt{1-c}\sin\alpha \end{bmatrix}. \tag{2}$$

Then, the transmission function of the two output ports of the filter can be deduced from (2)

$$T_1 = \frac{|E_1|^2}{|A|^2} = \cos^2\alpha - c\cos2\alpha + \sqrt{c(1-c)}\sin2\alpha\sin\phi \tag{3}$$

$$T_2 = \frac{|E_2|^2}{|A|^2} = \sin^2\alpha + c\cos2\alpha - \sqrt{c(1-c)}\sin2\alpha\sin\phi. \tag{4}$$

From (3) and (4), we can see that the two ports have a switching relationship with each other, just like a standard M–Z interferometer. However, the characteristics of the proposed comb filter are not only dependent on ϕ but on α and c as well. Among these three parameters, c mainly affects the contrast ratio of the filter, and ϕ is the phase difference which determines the channel spacing. In the calculation, supposing that α and ϕ are fixed, the contrast ratio of the comb filter reaches its maximum value when c is set to be 0.5, namely, the fiber coupler is a 3-dB one. Therefore, we choose $c = 0.5$ in the following theoretical analysis and the experiment. As can be analyzed from (3) and (4), one knows that the comb filter can realize dynamic switchable function in either port 1 or port 2 by simply adjusting the rotatable angle of the polarizer (α), i.e., the switchable operation can be achieved by setting $\alpha = \pi/4$ and $\alpha = 3\pi/4$. Moreover, it is worth noting that the wavelength switchable operation has a period of $\pi/2$ of the input polarization angle.

3. Results and Discussions

Based on the theoretical analysis above, we showed the calculated transmission spectra of output port 1 of the proposed comb filter in Fig. 2. The evolution of the switchable operation is illustrated from Fig. 2(a)–(c). Correspondingly, the input polarization angle α was set to be $3\pi/4$, π and $5\pi/4$, respectively. The channel spacing is 1.2 nm, which is determined by the path difference between the two arms. Here, $n = 1.46$ and $\Delta L = 1.37$ mm are used in the calculation. During the process of the switchable operation, the contrast ratio of the comb filter varied. Note that the contrast ratio can be tuned to be 0, as shown in Fig. 2(b).

To verify the spectral response of the proposed comb filter in the theoretical prediction, we measured the filter's transmission characteristics at different input polarization states. An amplified spontaneous emission (ASE) light source was used as the input. Fig. 3 presents the measured

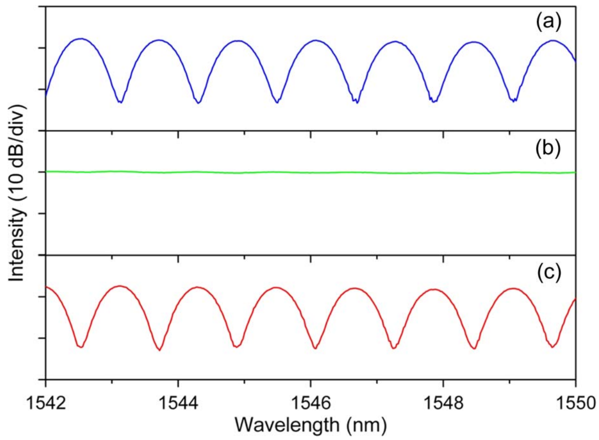

Fig. 3. Experimentally measured transmission curves corresponding to Fig. 2.

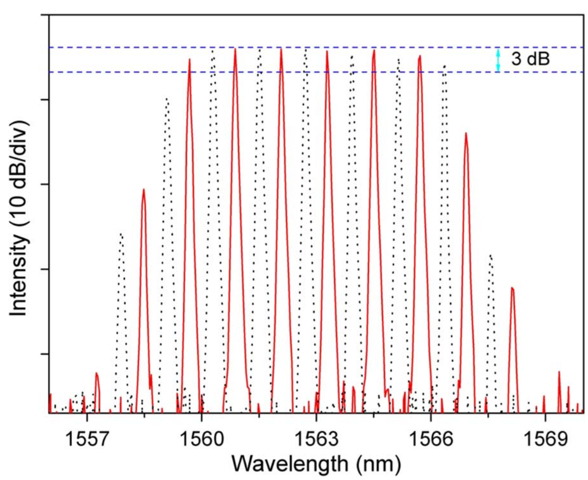

Fig. 4. Output spectra of the lasing wavelength switchable operation (red and black dotted curves) centered at ~1563 nm.

transmission spectra with different orientations of the polarizer. As predicted in the theoretical calculation, the wavelength switchable comb spectra with a channel spacing of 1.2 nm can be obtained by simply rotating the polarizer with a period of $\pi/2$. Note that the channel spacing of the proposed comb filter can be finely tuned by controlling the path difference between two interferometer arms. The experimental results are well consistent with the theoretically calculated results. Therefore, the proposed comb filter can be employed in multiwavelength fiber lasers to achieve multiwavelength switchable lasing operation.

Then, we incorporated the proposed comb filter into the fiber ring laser to generate multiwavelength switchable lasing. The lasing threshold of the fiber laser was about 18 mW, and we fixed the pump power at 100 mW in the following experiment. As the PZT was driven by a sinusoidal signal waveform with a frequency of 14.7 kHz, the multiwavelength fiber laser operated stably at room temperature. Since a polarizer was inserted into the cavity, the ring cavity produced a wavelength-dependent loss mechanism, which can optimize the multiwavelength operation, including the lasing locations and the number of lasing lines by rotating the PC [18]. Fig. 4 presents the output spectra of multiwavelength switchable lasing operation centered at ~1563 nm when the PC was not adjusted at the optimum position. As can be seen in Fig. 4, the red and black dotted curves have a wavelength switchable relationship, and there are six lasing wavelengths in the 3-dB spectral bandwidth.

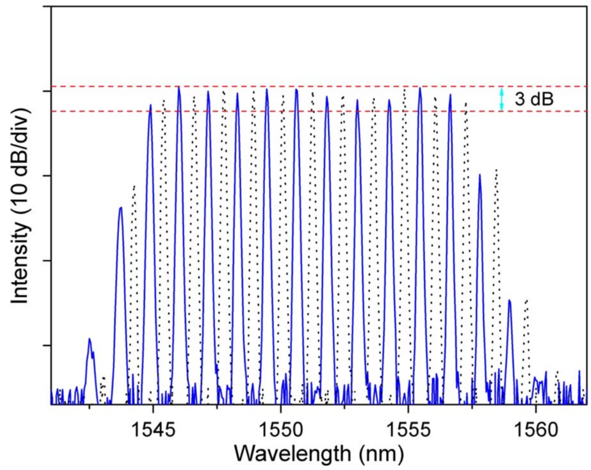

Fig. 5. Output spectra of the multiwavelength switchable operation (blue and black dotted curves) centered at ∼1552 nm.

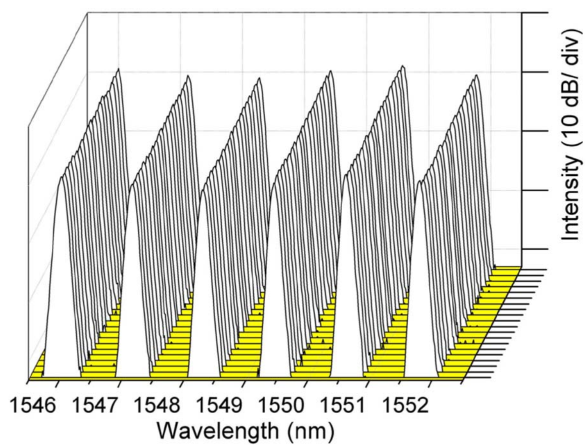

Fig. 6. Repeatedly scanned output 20 times with a 3-min interval.

The channel spacing is 1.2 nm, which is in agreement with the comb spacing shown in Fig. 3. Here, the output power was about 1.95 mW.

When we further rotated the PC, the lasing locations and the number of lasing lines could be tuned. Therefore, after the optimized rotation of the PC, up to 11 wavelength switchable lasing lines in 3-dB bandwidth centered at ∼1552 nm were obtained, as shown in Fig. 5 with blue and black dotted curves. In this case, the output power was about 1.83 mW. Then, we observed the stability of the multiwavelength fiber laser at room temperature. We repeatedly scanned the output of the main six lasing wavelengths with a 3-min interval 20 times. The results are shown in Fig. 6. In the experimental observation, the maximum wavelength drift of the main six lasing channels was less than 0.02 nm, and the maximum power fluctuation was less than 1.1 dB, indicating that the fiber laser operated stably at room temperature.

4. Conclusion

In conclusion, we have proposed and demonstrated a multiwavelength switchable fiber laser based on a novel PBS-based M–Z comb filter. The proposed comb filter, which consists of a rotatable polarizer, a PBS, and a 3-dB coupler, provides the multiwavelength switchable function by simply adjusting the input polarization states. Up to 11 multiwavelength switchable lasing lines in 3-dB bandwidth with 1.2-nm channel spacing were obtained. Moreover, the lasing locations and the number of the lasing lines can be flexibly adjusted by employing the wavelength-dependent loss mechanism.

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