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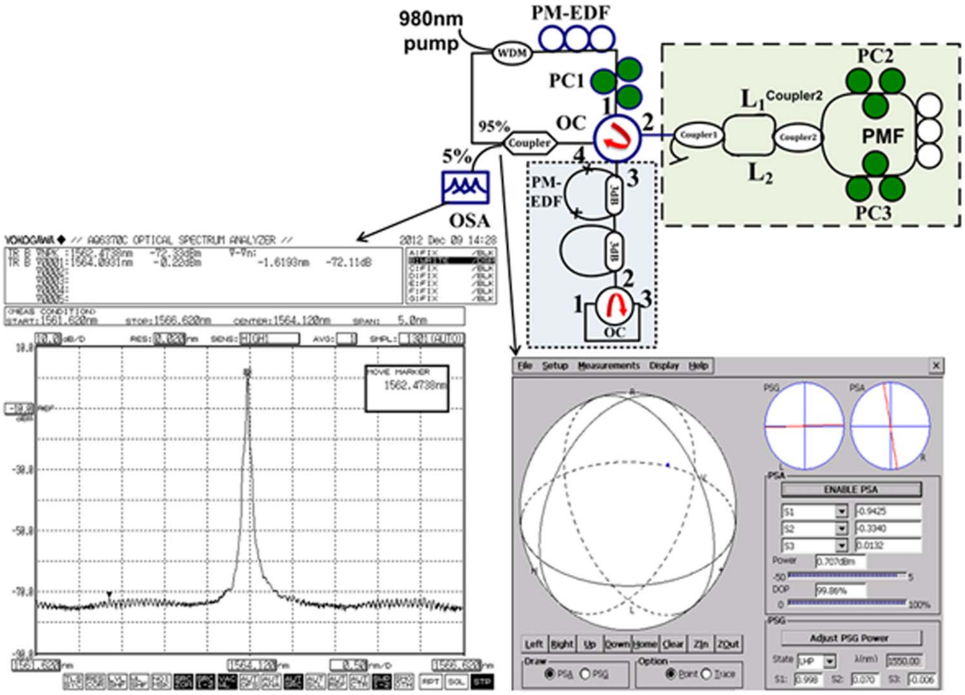

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A Stable and Tunable Linear-Polarization Fiber Ring Laser With a High SMSR by Using a Compounded Fiber Filter

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Abstract: A stable and tunable linear-polarization fiber ring laser with a high side-mode-suppression ratio (SMSR) is proposed and experimentally demonstrated by using a compounded fiber filter, which is composed of a dual-pass Mach–Zehnder interferometer filter incorporating one segment of polarization-maintaining fiber and a high finesse filter. By adjusting the polarization controllers, the output laser can be tuned from 1560.37 to 1568.56 nm and an SMSR as high as 72 dB is achieved. In addition, the peak power fluctuation and wavelength shift are monitored to be less than 0.08 dB and 0.02 nm over an hour. Due to the introduction of the compounded fiber filter as a wavelength selector, the side mode of lasing output can be effectively suppressed and mode competition can be weakened. As a result, the SMSR of lasing output is increased and power stability is improved.

Index Terms: Compounded fiber filter, fiber laser, high SMSR, linear-polarization, stable tunable.

1. Introduction

Stable and tunable linear-polarization erbium-doped fiber ring lasers are very attractive sources for many applications in optical communications, spectroscopy, and optical fibers sensors. Especially, high power stability tunable fiber lasers with high SMSR are considered to be a desirable candidate as a valuable source for wavelength-division-multiplexing (WDM) [1]. The fiber ring lasers with such properties could easily reduce the occurrence of intolerable mode partition noise or crosstalk in WDM communications system, and further improve dynamic range in an optical measurement system. Generally, fiber ring lasers have the possibility of multimode operation with mode hopping due to long cavity, which would lead to the generation of a number of densely spaced longitudinal modes [2]. These will result in mode competition and affect the stability of lasing output. Besides, at room temperature, the homogeneous broadening gains medium of the erbium-doped fiber results in strong mode competition. To overcome this obstacle, many different methods have been proposed. Except for the impractical cooling EDF in liquid nitrogen [3], other methods have also been investigated. These include the introduction of, utilizing polarization hole burning [4], and Spatial-Hole Burning (SHB) [5], using an unpumped EDF as the saturable absorber [6]. Meanwhile, in order to obtain stable single-wavelength oscillation, various filters are also indispensable at room temperature. Many studies have been focused on the techniques by using versatile filters for obtaining tunable and stable power fiber lasers. These filters such as fiber Bragg gratings (FBGs), the optical band-pass filter

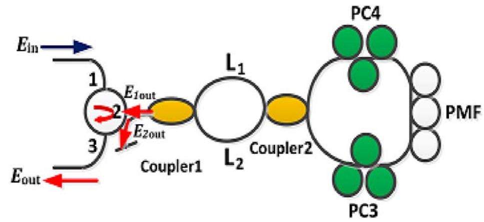


Fig. 1. Schematic of measuring reflectivity spectrum of the D-P-M-Z-PMF filter.

(OBPF), the Fabry-Perot tunable filter (FFP-TF), and the saturable absorbers have been employed to suppress multimode operation in ring laser cavity. However, in order to obtain stable and high SMSR lasing output in the ring fiber lasers, it is insufficient for using the above single filter to suppress mode competition and reduce the mode-hopping. Recently, some ring fiber lasers with a compound-ring resonator have been reported to suppress multimode oscillation, improve power stability and increase SMSR [7]–[11]. Yeh *et al.* designed a triple-ring cavity which consisted of a main ring cavity imbedding a FFP-TF and two subring cavities with different lengths. Due to the combination of a FFP-TF and triple-ring cavity, the side-mode could be effectively suppressed. But, the SMSR was only $\sim$55 dB for single-wavelength [2]. Chou *et al.* reported double-ring cavity with the introduction of a FFP-TF into the ring laser. Experimental results showed that the SMSR of the output single-wavelength laser was $\sim$70.2 dB (an optical spectrum analyzer with a 0.05 nm resolution) [7]. However, the power fluctuation was $\sim$1 dB, and the central wavelength variation was $\sim$0.04 nm. Pan *et al.* introduced a high finesse ring filter, which was formed from one 2×2 3-dB optical coupler, 0.6-merer EDF and a 20 : 80 optical coupler. By using the high finesse ring filter and an OBPF were inserted into the ring cavity, a single-wavelength laser with SMSR of 68 dB was realized (an optical spectrum analyzer with a 0.01 nm resolution) [10]. For the above reported configurations, the FFPF or the OBPF as the comb filter were also necessarily inserted into the ring cavity to restrict side mode. These would cause the cost increased and confine the integration of laser system. In the view of the cost and the easy integration in practical application, developing compounded filters with low cost and high performance has attracted considerable interests in developing a linear-polarization wavelength lasing with more stable and high SMSR for the application of WDM communication system and optical measurement system.

In this paper, a compounded filter which is formed of a dual-pass Mach-Zehnder interferometer filter incorporating one segment of PMF (D-P-M-Z-PMF) and a finesse filter is developed. Based on this compounded filter, we propose and experimentally demonstrate a stable and tunable linear-polarization fiber ring laser. Experimental results illustrate that introduction of the compounded filter into ring fiber laser cavity is helpful to suppress the side-modes and reduce the mode competition effectively. With 200 mW pump power, a linear-polarization laser with SMSR higher than 72 dB is successfully obtained, and its peak power fluctuation and wavelength shift are monitored to be less than 0.08 dB and 0.02 nm over an hour, respectively. By adjusting the PCs carefully, the output laser can be tunable from1560.37 nm to 1568.56 nm.

2. A Compounded Fiber Filter

The compounded fiber filter consists of a D-P-M-Z-PMF filter and a high finesse filter. To investigate the characteristics of the two filters, we deduce the expression of the reflectivity of the two filters theoretically.

2.1. The D-P M-Z-PMF Filter

Fig. 1 show the structure of D-P-M-Z-PMF filter which is formed of a dual-pass Mach-Zehnder interferometer filter incorporating one segment of PMF. The optical circulator (OC) is used to assist the D-P-M-Z-PMF filter inserted into ring cavity. Supposing that the beam is launched into the Port1 of the OC, the spectral response of the proposed filter can be analyzed by the following Jones matrix representation:

$$\begin{bmatrix}[\boldsymbol{E}_{1out}]\\ [\boldsymbol{E}_{2out}]\end{bmatrix} = [C_1][T][C_2]\begin{bmatrix}0,1\\ 1,0\end{bmatrix}\begin{bmatrix}[P_2^s][J][P_1^s],0\\ 0,[P_1^k][J][P_2^k]\end{bmatrix}[C_2][T][C_1]\begin{bmatrix}[\boldsymbol{E}_{in}]\\ 0\end{bmatrix}$$

where $[\boldsymbol{E}_{in}]$ is the input field of the filter, and $[\boldsymbol{C}_m]$ $(\mathrm{m}=1,2)$, $[\boldsymbol{T}]$, $[\boldsymbol{P}_\mathbf{n}](\mathrm{n}=1,2)$, $[\boldsymbol{J}]$ are the matrices of the fiber couplers, the interferometer arms of the dual-pass M-Z interferometer, the PCs and the PMF, respectively. These matrices can be expressed as

$$[\boldsymbol{C}_m] = \begin{bmatrix}\sqrt{1-k_m}, j\sqrt{k_m}\\ j\sqrt{k_m}, \sqrt{1-k_m}\end{bmatrix},\quad [T] = \begin{bmatrix}e^{jL_1\beta},0\\ 0,e^{jL_2\beta}\end{bmatrix},$$

$$[P_n^s] = \begin{bmatrix}\cos\theta_n, \sin\theta_n\\ -\sin\theta_n, \cos\theta_n\end{bmatrix},\quad [J] = \begin{bmatrix}e^{-j\varphi},0\\ 0,e^{j\varphi}\end{bmatrix},\quad [P_n^k] = \begin{bmatrix}\cos\theta_n, -\sin\theta_n\\ \sin\theta_n\ \ ,\cos\theta_n\end{bmatrix}.$$

Here, $\boldsymbol{k}_\mathbf{m}$ $(\mathrm{m}=1,2)$ is the coupling ratio of the coupler and the propagation constant β is denoted by $2\pi\boldsymbol{n}_{\boldsymbol{eff}}/\lambda$ where $\boldsymbol{n}_{\boldsymbol{eff}}$ is the effective refractive index of the fundamental mode and λ is wavelength in vacuum. $\boldsymbol{L}_\mathbf{1}$ and $\boldsymbol{L}_\mathbf{2}$ are corresponding to the length of the two arms in MZI. $\theta_\mathbf{n}$ $(\mathrm{n}=1,2)$ is the rotation angle of the propagating light through the PC3 and PC4 (clockwise and counterclockwise). φ is the phase of the two orthogonal components of the electric field in the PMF, and it can be expressed as

$$\varphi = \frac{2\pi\ L\Delta\mathbf{n}}{\lambda}$$

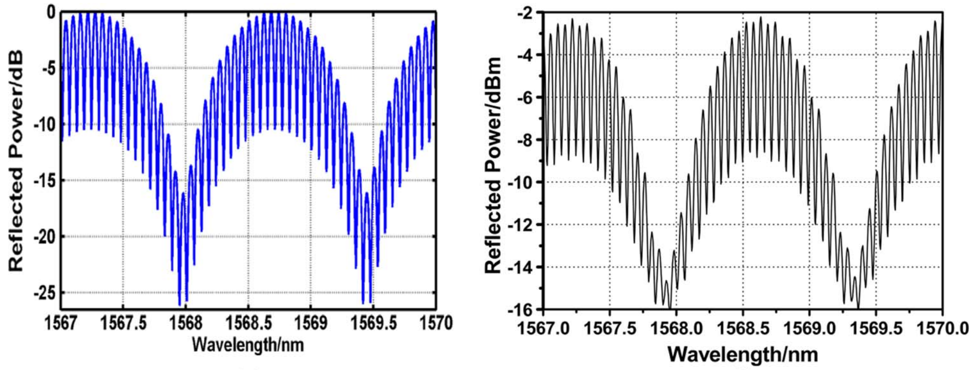
where $\boldsymbol{L}$ is the length of the PMF and $\boldsymbol{n}$ is the refractive index difference between the fast axis and the slow axis of the PMF. The final output $\boldsymbol{E}_\mathbf{out}$ is equal to the electric field $\boldsymbol{E}_\mathbf{1out}$ due to the use of the optical circulator. And thus the reflectivity function in the port3 of the optical circulator (OC) can be obtained:

$$\begin{aligned}R = \left|\frac{E_{out}}{E_{in}}\right|^2 &= 4\left[(1-k_1)(1-k_2)+k_1k_2-2\sqrt{k_1k_2(1-k1)(1-k_2)}\cos(L_1-L_2)\beta\right]\\ &\times\left[(1-k_1)(1-k_2)+k_1k_2+2\sqrt{k_1k_2(1-k1)(1-k_2)}\cos(L_1-L_2)\beta\right]\\ &\times\left[\sin\varphi^2+\cos\varphi^2\cos(\theta_1+\theta_2)^2\right].\end{aligned}$$

Using the above equations, we numerically simulate the reflectivity spectrum of the D-P-M-Z-PMF filter at the parameters: $\boldsymbol{n} = 5.1\times10^{-4}$, $\boldsymbol{L}_\mathbf{1}-\boldsymbol{L}_\mathbf{2} = 1.54$ cm, $\boldsymbol{L} = 1.682$ m, $\theta_\mathbf{1} = -\pi/3$, $\theta_\mathbf{2} = -\pi/5$, $\boldsymbol{k}_\mathbf{1} = 0.5$, $\boldsymbol{k}_\mathbf{2} = 0.3$, $\boldsymbol{n}_\mathbf{eff} = 1.448$, as shown in Fig. 2(a). The theory result shows the wavelength spacing between the adjacent peaks in the envelope peak is approximate to 0.052 nm. With the guidance of theoretical result, we experimentally fabricate the D-P M-Z-PMF filter by using the same parameters in the above simulation. A broadband light source (ASE .ZCN) is adopted to offer the input light injected into port1 and the reflectivity spectrum of the output is monitored by the optical spectrum analyzer with the resolution of 0.02 nm. The measured reflectivity spectrum is given in Fig. 2(b). The measured reflection spectra also exhibited multi-peaks features, and the wavelength spacing between the adjacent peaks in one envelope peak is approximate to ~0.052 nm. Compared the experimental result with the simulation result, we can find that experimental result is well approximate to the theoretical predictions.

2.1. The High-Finesse Filter

The finesse filter is formed of two 3-dB couplers, a ~0.25 m PM-EDF and an OC (3-ports) in Fig. 3. Mathematically, when an input field $\boldsymbol{E}_{in}$ is injected into the left ring in Fig. 3, the power of the



(a) (b)

Fig. 2. (a) Simulation result and (b) experimental measures of reflectivity spectrum of the D-P-M-Z-PMF filter.

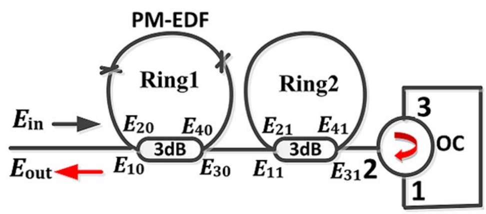


Fig. 3. Schematic of the high finesse filter.

optical field $\boldsymbol{E}_{30}$ can be written as [7]

$$|\boldsymbol{E}_{30}|^2 = \frac{1-\alpha_1+g_1^2-2g_1\sqrt{1-\alpha_1}\cos(\beta_0 S_1)}{1+g_1^2(1-\alpha_1)-2g_1\sqrt{1-\alpha_1}\cos_1(\beta_0 S_1)}|\boldsymbol{E}_{in}|^2$$

where α_1 is the coupling factor of the 2×2 optical coupler1, $\boldsymbol{g}_1$ is the effective gain [9], [10], $\boldsymbol{S}_1$ is the length of the left loop, and β_0 is the propagation constant ($\beta_0 = \boldsymbol{2}\pi \boldsymbol{n}_{eff}/\lambda$). Analogously, $\boldsymbol{E}_{30}$ travels through the right loop, and thus the electric field of the lightwave eventually evolves into $\boldsymbol{E}_{31}$

$$|\boldsymbol{E}_{31}|^2 = \frac{1-\alpha_2+g_2^2-2g_2\sqrt{1-\alpha_2}\cos(\beta_0 S_2)}{1+g_2^2(1-\alpha_2)-2g_1\sqrt{1-\alpha_2}\cos_1(\beta_0 S_2)}|\boldsymbol{E}_{30}|^2.$$

Here, α_2 is the coupling factor of the 2×2 optical coupler2, $\boldsymbol{g}_2$ is the splice intensity loss [5], [6], and $\boldsymbol{S}_2$ is the length of the right loop. After $\boldsymbol{E}_{31}$ propagates through the OC, two loops, the electric field i.e. $\boldsymbol{E}_{out}$ can be expressed as

$$|\boldsymbol{E}_{out}|^2 = \left[\left(\frac{1-\alpha_1+g_1^2-2g_1\sqrt{1-\alpha_1}\cos(\beta_0 S_1)}{1+g_1^2(1-\alpha_1)-2g_1\sqrt{1-\alpha_1}\cos_1(\beta_0 S_1)}\right)\left(\frac{1-\alpha_2+g_2^2-2g_2\sqrt{1-\alpha_2}\cos(\beta_0 S_2)}{1+g_2^2(1-\alpha_2)-2g_1\sqrt{1-\alpha_2}\cos_1(\beta_0 S_2)}\right)\right]^2|\boldsymbol{E}_{in}|^2.$$

The reflectivity function of the high-finesse filter can be deduced as

$$R = \frac{|\boldsymbol{E}_{out}|^2}{|\boldsymbol{E}_{in}|^2} = \left[\left(\frac{1-\alpha_1+g_1^2-2g_1\sqrt{1-\alpha_1}\cos(\beta_0 S_1)}{1+g_1^2(1-\alpha_1)-2g_1\sqrt{1-\alpha_1}\cos_1(\beta_0 S_1)}\right)\left(\frac{1-\alpha_2+g_2^2-2g_2\sqrt{1-\alpha_2}\cos(\beta_0 S_2)}{1+g_2^2(1-\alpha_2)-2g_1\sqrt{1-\alpha_2}\cos_1(\beta_0 S_2)}\right)\right]^2.$$

When the parameters are set as $\alpha_1 = \alpha_2 = 0.5$, $\boldsymbol{g}_1 = 1.25$, $\boldsymbol{g}_2 = 0.04$, $\boldsymbol{S}_1 = 5.21$ m, $\boldsymbol{S}_2 = 4.3$ m, $\boldsymbol{n}_{\mathbf{eff}} = 1.448$, we calculate the reflectivity of the high-finesse filter, as shown in Fig. 4. Fig. 4 also

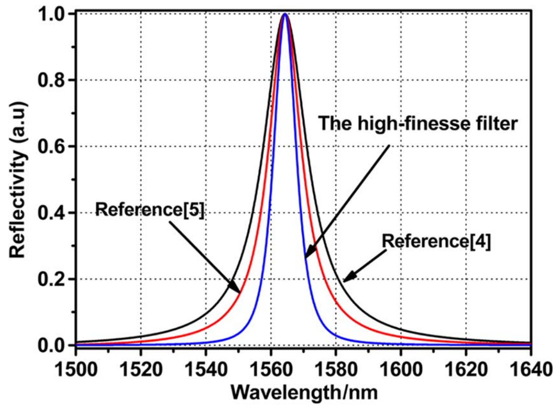


Fig. 4. Reflectivity of the high finesse filter and other different filters reported.

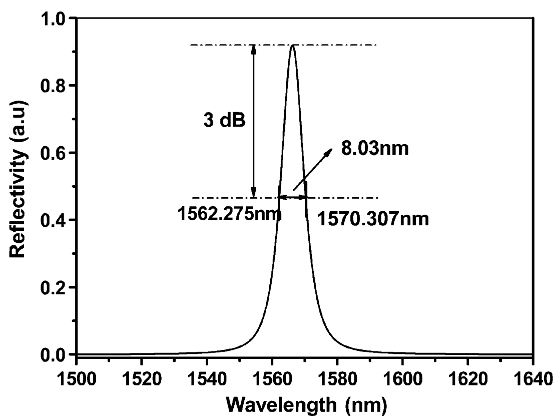


Fig. 5. The 3 dB bandwidth of the high finesse filter.

shows theoretical results of the reflectivity of filter reported in Ref. [4] and Ref. [9]. It can be found that the bandwidth of the proposed high-finesse filter is narrower than that of filter reported in Ref. [8] and Ref. [9]. The 3 dB bandwidth of the high-finesse filter is $\sim$3.08 nm in Fig. 5.

3. Experimental Setup and Results

Fig. 6. shows the experimental configuration of a stable and tunable linear-polarization polarization-maintaining erbium-doped fiber (PM-EDF) ring laser. In the ring cavity, there are a segment of PM-EDF with the length of $\sim$2.5 m serving as the gain medium, a 1550 nm/980 nm WDM used to couple the 980 nm laser as the co-propagating pump into the PM-EDF, PC1 employed to adjust the polarization state of the ring cavity, an OC (4-ports) used to form a unidirectional ring for connecting the compounded filter i.e. the D-P-M-Z-PMF filter and the high finesse filter, and a 95/5 fiber coupler as the laser output. The D-P-M-Z-PMF filter consists of a dual-pass Mach-Zehnder interferometer with a segment of $\sim$1.682 m PMF and two PCs in second loop. The finesse filter is formed of two 3-dB couplers, a $\sim$0.25 m PM-EDF and an OC (3-ports). The lasing output is monitored by the optical spectrum analyzer (OSA, YOKOGAWA, AQ6370C) with resolution of 0.02 nm from the 5% port of 95/5 coupler.

With the 200 mW pump power (980 nm), the output spectrum of laser is recorded by the optical spectrum analyzer as shown in Fig. 7. It can be seen from Fig. 6 that the center wavelength of the output laser is at 1564.09 nm, and its SMSR is greater than 72 dB. The stability tests on output laser

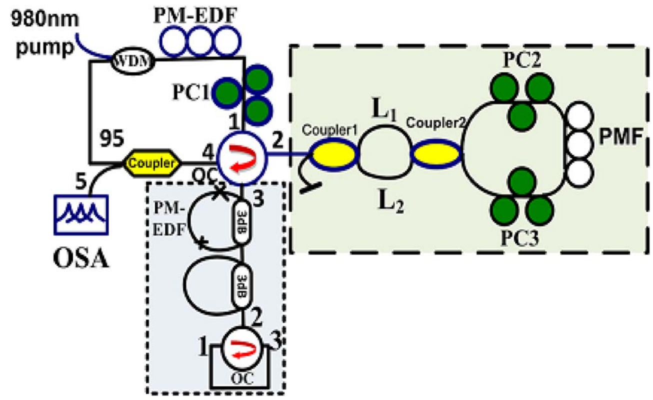


Fig. 6. Schematic of the proposed stable and tunable linear-polarization fiber ring laser.

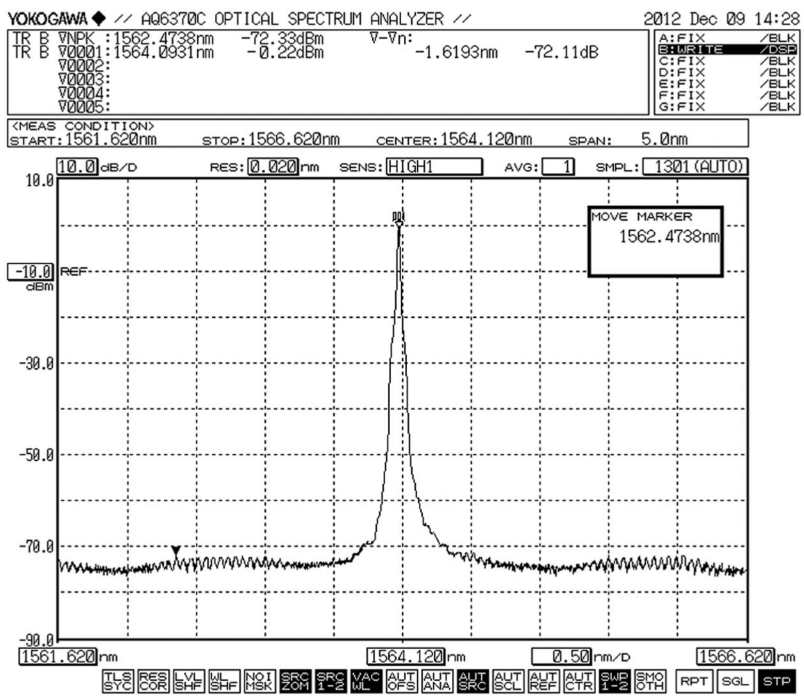


Fig. 7. Output spectra of the fiber laser at the wavelength of 1564.09 nm.

are carried out by recording the spectra with four minutes interval in an hour as shown in Fig. 8(a). The corresponding fluctuation of peak power and the lasing wavelength shift are given in Fig. 7(b). The fluctuation of the average peak power and wavelength shift is less than 0.08 dB and 0.02 nm, respectively.

In order to verify the linear-polarization operation of the output fiber laser, the output-port of the fiber laser is connected to the PA (the General Photonics PSGA-101 Light-wave Polarization Analyzer). Fig. 9. shows the polarization parameters of the fiber laser accumulated in 5 min without external disturbance. The apparent degree of polarization (DOP) in percentage is as high as 99.86%, which indicates that the laser outputs are almost in stable single polarization state. Furthermore, by adjusting PCs carefully, the lasing wavelength can be tuned from 1560.37 nm to 1568.56 nm as shown in Fig. 10. The tunable range is greater than 8 nm, and their SMSRs are all as high as 72 dB. It

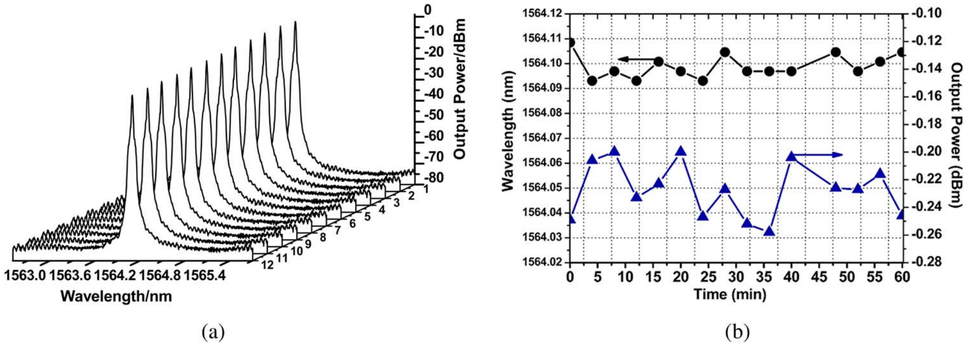


Fig. 8. (a) Repeated scanning spectrum with a time interval of 4 min. (b) Fluctuations of the output wavelength and power over a period of 60 min.

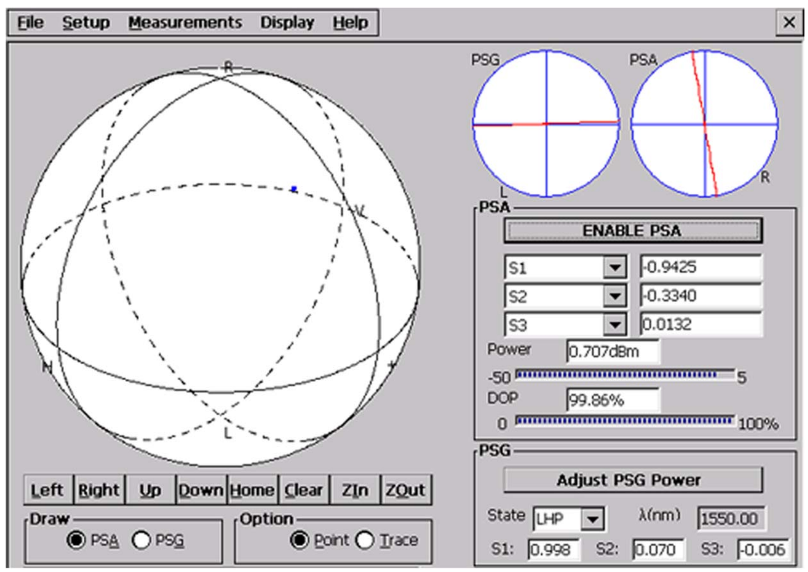


Fig. 9. The polarization parameters of the output laser in 5 min.

should be noted that, the tuning range of the fiber laser is limited by the bandwidth range of the high-finesse filter (1560.2 nm–1569.6 nm). After the lasing wavelength is roughly determined by the D-P M-Z-PMF filter, which selects the homogeneous gain of the PM-EDF. The lasing and the light existing in the Ring1 counter propagate and interfere each other transfers when their state-of-polarizations are optimized in the finesse filter. When the frequency difference between the lasing and the light existing in the Ring1 is equal or close to zero, the SHB is produced, as a result, the mode competition is reduced and the SMSR is improved [13]. Hence, adjusting carefully PCs can be utilized to select of the different state of polarizations wavelengths as well as the different frequency of the resonance wavelengths, with a proper state of polarization adjustment of the two sources i.e. the lasing and the light existing in the Ring1, a linear-polarization laser with SMSR higher than 72 dB is successfully generated and tuned.

In order to further verify the significance of the high-finesse filter for selecting lasing wavelength in the ring cavity, two contrast experiments in the same ring cavity are carried out. In Fig. 11(a), the SMSR of output laser wavelength using the finesse filter is higher than that using the filter reported in reference [4] or reference [5] when the D-P M-Z-PMF filter is also inserted into the ring cavity. As a result, the high-finesse filter can much effectively suppress the side-mode and improve the

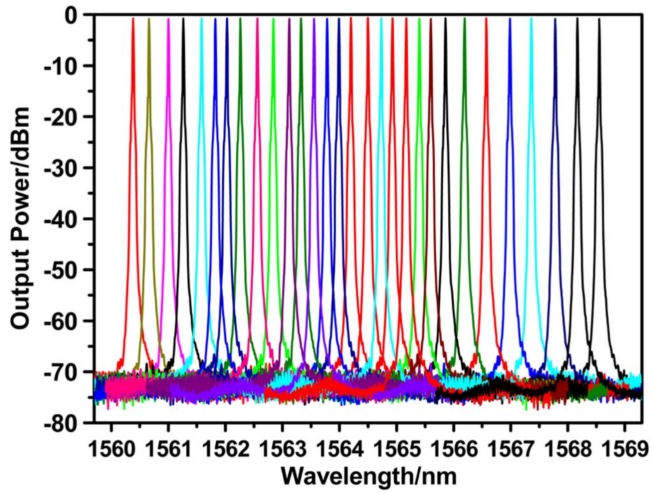


Fig. 10. Output spectra of the output laser with the wavelength tuned from 1560 nm to 1569 nm by adjusting the PCs.

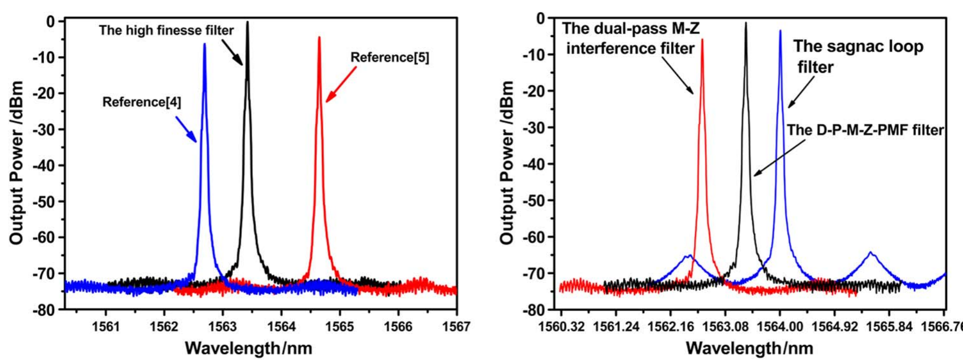


Fig. 11. (a) Output spectra of the output laser using filters reported in reference [4] and [5], the finesse filter. (b) Output spectra of the output laser using the dual-pass Mach-Zehnder interference filter, the Sagnac loop filter and D-P-M-Z-PMF filter.

SMSRs. Meanwhile, compared with the past report [4]–[7], the proposed laser has lower cost, higher SMSR and better stability performance.

To investigate the performance of the D-P-M-Z-PMF filter, we build the same ring cavity only using a Sagnac loop or the dual-pass Mach-Zehnder interference as filter when the high-finesse filter is also inserted into the ring cavity. It can be seen from Fig. 11(b) that the ring laser with the D-P-M-Z-PMF filter can offer higher SMSR than that with only the Sagnac loop filter or the dual-pass Mach-Zehnder interference filter, and the side-mode is also effectively suppressed. So, with the co-operation of the two filters, the power stability is improved, and the SMSR is increased greatly.

4. Conclusion

In summary, we propose and demonstrate a stable and tunable linear-polarization fiber ring laser with a high SMSR using the compounded filter as wavelength selector. The incorporation of filter can also effectively suppress the side-mode, improve the SMSRs and enhance the stability of the output laser. With 200 mw pump power, a linear-polarization laser with SMSR higher than 72 dB is successfully generated, and its peak power fluctuation and wavelength shift are monitored to be less than 0.08 dB and 0.02 nm over an hour. By adjusting the PCs carefully, the output laser can be tunable from1560.37 nm to 1568.56 nm. Thus, this ring laser will have a number of applications in the WDM communication system and the optical measurement system.

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