Theory and experiment of a fiber loop mirror filter of two-stage polarization-maintaining fibers and polarization controllers for multiwavelength fiber ring laser

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Abstract: A fiber loop mirror (FLM) filter with two-stage polarization-maintaining fibers (PMFs) and polarization controllers (PCs) is presented. The transmission function of this FLM is calculated in detail by Jones matrix. The wavelength interval depends on both the PMFs and the PCs. The side frequencies can be restrained by choosing appropriate length of the PMFs. Furthermore, an erbium-doped fiber ring laser based on this FLM filter is proposed and demonstrated. Stable single-, double- and triple-wavelength are achieved respectively. The 3dB line-width is less than 0.03nm, and the fluctuation of wavelength and peak power is less than 0.05nm and 0.1dB in 30 minutes.

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References and links

1. Introduction

Filters are very important elements for a lot of optical systems, especially in fiber lasers. All-fiber comb filters, using a fiber loop mirror (FLM), have been used extensively in the design of multiwavelength fiber lasers [1-3]. Mortimore D. has made a basic analysis of the FLM [4]. Since then, tons of applications with a FLM have been reported due to their advantages such as low cost, low loss, simple construction, and polarization independence [5-7]. Tuning characteristic is a desired feature of any comb filter when it is used in a multiwavelength light source. A FLM of one-stage polarization-maintaining fiber (PMF) and polarization controller (PC) is a simple filter device (considered as PC-PMF). In this FLM, the filter spectrum depends on the PC and the PMF. However, the wavelength interval only depends on the PMF [8]. The only way of varying the filter interval is to use different PMF in the FLM; it is unfeasible in real optical systems. To avoid the disadvantage, a new real FLM is proposed and studied.

In this letter, a FLM of two-stage PMFs and PCs is demonstrated, and the characteristics of this FLM are investigated both theoretically and experimentally. A PC has been used in most designs to tune the filter spectrum and a PMF is a high-birefringence fiber which can bring the phase shift. Two-stage of them are connected to be an optic PC-PMF-PC-PMF cascade (considered as PCs-PMFs). Although the operation principle of the FLM has been studied [9,10], the transmission characteristics of the FLM with both the PMF and the PC have not been investigated in detail. In this letter, with Jones matrix, the transmission function of the PC-PMF FLM and the PCs-PMFs FLM are calculated and simulated. Both of the FLMs are proved to be polarization independent. It is a significant characteristic in most optical applications, especially in fiber lasers. The transmission spectrum of the PCs-PMFs FLM is more flexible. The side frequencies can be restrained; and the restrain ability depends on the length ratio of the PMFs. The wavelength interval depends on both PMFs and PCs. Later that was confirmed by experimental filter results in this letter. Furthermore, an erbium-doped fiber ring laser based on this FLM is proposed. Stable single-, dual-, triple-wavelength lasing are obtained by adjusting the PCs. The 3dB and 30dB line-widths of each lasing wavelength of the laser are less than 0.03nm and 0.06nm respectively. The fluctuation of lasing wavelength is less than 0.05nm and that of the peak power is less than 0.1dB in 30 minutes.

2. Experimental setup and principle

![Diagram](image)

Fig. 1. Fiber loop mirror (FLM) of two-stage polarization-maintaining fibers (PMF) and polarization controllers (PC).

The PCs-PMFs FLM is schematically shown in Fig. 1. A polarization-insensitive 3dB coupler is used to connect the ring cavity and the FLM. The beam travels towards the 3dB coupler at...
port 1, and the incident beam is split into two propagating beams. Fifty percent of output beams from port 3 travel clockwise around the loop; and the other fifty percent output beams from port 4 travel counterclockwise with a phase difference of $\pi/2$. Two beams contrarily pass through PCs and PMFs and the transmission beam output at 3dB coupler from port 2.

The transmission characteristics are analyzed by Jones matrix. It describes efficiently the polarization state of a plane wave. In this representation, the electric field is expressed in terms of its complex amplitudes as a column vector:

$$E = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} E \cos \theta \\ E \sin \theta \end{bmatrix}$$  \hspace{1cm} (1)$$

Where, $\theta$ is the angle of the incident light polarization orientation with x-axis. Firstly, we analyze the PC-PMF FLM, ignoring the PC$_2$ and the PMF$_2$ of Fig.1. There are two different Jones matrices depending on the direction of propagation around the loop: clockwise (from port 3 to port 4) and counterclockwise (from port 4 to port 3). The incident lights are coupled into the fiber loop by a 3dB coupler, and the Jones matrix is $M_C$. The output electric fields vector can be represented as:

$$\begin{bmatrix} E_3 \\ E_4 \end{bmatrix} = M_C \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}$$  \hspace{1cm} (2)$$

Where, $E_3$, $E_4$ are the output electric fields of port 3 and port 4, and $E_1$, $E_2$ are the incident electric fields of port 1 and port 2. The incident lights of FLM only input from port 1, so there is $E_2=0$.

The light of port 3 clockwise goes through the PC first. An all fiber PC is made from a half-wave plate (HWP) coil and two quarter-wave plates (QWPs) coils at both ends. The Jones matrices of the three plates are [11]:

$$T(\theta_j) = \begin{bmatrix} \cos \frac{\phi_j}{2} + i \sin \frac{\phi_j}{2} \cos 2\theta_j & i \sin \frac{\phi_j}{2} \sin 2\theta_j \\ i \sin \frac{\phi_j}{2} \cos 2\theta_j & \cos \frac{\phi_j}{2} - i \sin \frac{\phi_j}{2} \cos 2\theta_j \end{bmatrix}$$  \hspace{1cm} (3)$$

Where $(j=1, 2, 3)$, $\theta_1$, $\theta_2$, $\theta_3$ are the angular orientations of the three wave-plates, and $\phi_1=2\pi/m$, $\phi_2=2\pi/l$ and $\phi_3=2\pi/n$. For most commercial PCs, $l$, $m$ and $n$ are respectively designed to be 4, 2 and 4. When lights travel from port 3 to port 4, they go through the QWP, the HWP and the QWP in sequence, and then the Jones matrix of a PC is represented as the product of three Jones matrices

$$M_{PC}(\theta_1, \theta_2, \theta_3) = T(\theta_3)T(\theta_2)T(\theta_1) = \frac{i}{2} \begin{bmatrix} A + iB & C + iD \\ C - iD & -A + iB \end{bmatrix}$$  \hspace{1cm} (4)$$

Where

$$\begin{align*}
A &= \cos(2\theta_1) - \cos(2\theta_1 - 2\theta_2 + 2\theta_3) \\
B &= \cos(2\theta_1 - 2\theta_2) + \cos(2\theta_2 - 2\theta_3) \\
C &= \sin(2\theta_2) - \sin(2\theta_1 - 2\theta_2 + 2\theta_3) \\
D &= \sin(2\theta_2 - 2\theta_3) + \sin(2\theta_3 - 2\theta_1)
\end{align*}$$  \hspace{1cm} (5)$$

From the Eq. (4), it is obviously observed that the angles of $\theta_1$, $\theta_2$ and $\theta_3$ can completely represent a certain state of the PC, so we use a array $(\theta_1, \theta_2, \theta_3)$ to represent a PC state, and a array $(\theta_{11}, \theta_{12}, \theta_{13}, \theta_{21}, \theta_{22}, \theta_{23})$ for two PCs. Where, $(\theta_{11}, \theta_{12}, \theta_{13})$ is for the first-stage (PC$_1$) and $(\theta_{21}, \theta_{22}, \theta_{23})$ is for the second one (PC$_2$). A PMF is a high-birefringence fiber which brings the phase shift ($\Delta \rho$), the Jones matrix of a PMF is represented as:
When \( \Delta \varphi = (2\pi/\lambda)L \Delta n \), which is the retardance of the PMF. \( \Delta n \) is the refractive index difference of the fast-axis and the slow-axis; it represents the birefringence of the PMF. \( L \) is the length of the PMF. The Jones matrix from port 3 to port 4 is the matrices product of \( M_{\text{PMF}} \) and \( M_{\text{PC}} \), shown as:

\[
M = M_{\text{PMF}} \cdot M_{\text{PC}}
\]  

(7)

Where, Fig. 2(a) is the PC-PMF FLM, the PC is (\( 2x \, \phi \)) and \( M_{\text{PC}} \), shown as:

\[
M_{\text{PC}}(\varphi) = \begin{bmatrix} 1 & 0 \\ 0 & e^{i \varphi} \end{bmatrix}
\]

(6)

When counterclockwise lights travel from port 4 to port 3 they go through the PMF firstly, the Jones matrix is represented as:

\[
M = M'_{\text{PC}} \cdot M_{\text{PMF}} = T(-\theta_2)T(-\theta_1)T(-\theta_1) \cdot M_{\text{PMF}}
\]

(8)

The electric field \( E_3 \) at the port 3 will go through the PC and the PMF, arriving at the port 4 represented as an electric field of \( E_4 \), and vice versa. After propagation in fiber loop, the electric field at port 3 and port 4 is \( E_3 = M' E_3 \) and \( E_4 = M' E_4 \).

Then \( E_1 \) and \( E_2 \) are coupled into the coupler again, the output lights are:

\[
\begin{bmatrix} E_1' \\ E_2' \end{bmatrix} = M_c \begin{bmatrix} E_3' \\ E_4' \end{bmatrix} = \frac{1}{2} \begin{bmatrix} i(M' + M)E_3' \\ 2(M' - M)E_4' \end{bmatrix}
\]

(9)

Where, \( E_1' \) and \( E_2' \) are the reflected light (port 1) and the transmitted light (port 2) respectively. \( M_c \) is the matrix when lights go through the 3dB coupler inversely. It is obviously that \( E_2' = (M' \cdot M) \cdot E_1' / 2 \). Then the transmission function is

\[
T(\lambda) = |E_1'| / |E_1|
\]

(10)

The Jones matrix of the PCPs-PMFs FLM is the matrices product in series, and then the Jones matrix of \( M \) and \( M' \) are \( M = M_2 \cdot M_1 \) and \( M' = M'_2 \cdot M'_1 \). Where \( M_1, M_1', M_2, M_2' \) is defined by Eq. (7) and (8). \( M_1, M_1' \) is the clockwise and counterclockwise Jones matrix of the first stage, and \( M_2, M_2' \) is the second one. For multi-stage, \( M \) and \( M' \) is the product of multi-stage. The transmission also can be represented by the Eq. (10). In generally situation, two PMFs are unparallel. We assumed that the optical axes are the fast and slow axis of the first stage PMF; and the angle of two PMFs is arbitrary \( \alpha \). The phase contributions of the second PMF in optical axes are \( \phi_2 = \varphi_2 \cos \alpha + \varphi_2 \cos (90^\circ + \alpha) \) and \( \phi_2' = \varphi_2 \sin \alpha + \varphi_2 \sin (90^\circ + \alpha) \) respectively. Where, \( \varphi_2 \) and \( \varphi_2' \) are the phase of the second PMF. So, an unparallel PMF is equivalent to a parallel PMF with phase shift \( \Delta \varphi = \phi_2 - \phi_2' \), replaces \( \varphi_2 \rightarrow \phi_2 - \phi_2' \) in Eq. (6).

With this theory we simulate and compare the transmission spectrum of the PC-PMF FLM and the PCs-PMFs FLM. For simplifying the calculation, we assumed that the fast axis of PMF is x-axis, and two PMFs are parallel.

Polarization independent is very important for its application in optical fiber systems. Fig. 2 shows the transmission spectrum with different polarization direction of incident lights. Where, Fig. 2(a) is the PC-PMF FLM, the PC is \( (\pi/9, \pi/4, \pi/2) \), L is 3m, \( \Delta n \) is 5x10^{-5}. Fig.2 (2) is a PCs-PMFs FLM, the PCs are \( (\pi/9, \pi/3, \pi/6, \pi/3, \pi/4, \pi/4) \), \( L_1 = 2m \) and \( L_2 = 3m \), \( \Delta n_1 = \Delta n_2 = 5x10^{-4} \), and the polarization angle \( \theta \) is \( \pi/3, \pi/4 \) and \( 5 \pi/5 \). From Fig. 2, we observe that the three curves are completely superposed both of two FLMs. This polarization independent characteristic is significant in most optical applications, especially in fiber lasers. In the fiber ring laser of this letter, the polarization state is variable when traveling through the laser cavity; however, the FLM can be a wavelength selector with polarization independent characteristic.
Comparing with Fig. 2(a) and Fig. 2(b), the more characteristics are obtained. The PC-PMF FLM is a uniform amplitude comb filter. That means the wavelength interval equals to a period. However, the side frequencies of the PCs-PMFs FLM can be restrained. It is more flexible in optical applications. In this letter, we study the transmission characteristic dependence of both of two FLMs in detail. Fig. 3 and Fig. 4 show the wavelength interval dependence of two FLMs; Fig. 5 shows that the restrain ability and period dependence of the PCs-PMFs FLM.

The tunable wavelength interval is crucial in optical fiber systems. The interval dependence of the PC-PMF FLM is shown in Fig. 3. The central wavelength interval (equals to a period) only depends on different PMF ($L$ and $\Delta n$) as shown in Fig. 3(a) and 3(b). $L$ is 0.5m, 1m and 3m in Fig. 3(a) and $\Delta n$ is $5 \times 10^{-4}$, $4 \times 10^{-4}$ and $3 \times 10^{-4}$ in Fig. 3(b) respectively. The interval reduces as $L$ and $\Delta n$ increases. Due to the interval dependence only for different PMF, it is unfeasible to tune interval in real optical fiber systems. However, the PCs-PMFs FLM can be a uniform amplitude comb filter in some certain PCs states; and the interval of the PCs-PMFs FLM can be tuned by adjusting the PCs as shown in Fig. 4.
Fig. 4. Interval dependence of the PCs-PMFs FLM for (a) different PMFs, and (b) different PCs.

The wavelength interval depends on both the PMFs and the PCs in the PCs-PMFs FLM. Fig. 4(a) is for different PMFs and Fig. 4(b) is for different PCs. We set PCs states as $(0, \pi/4, 0, \pi/6, \pi/4, \pi/3)$ in order to obtain uniform amplitude spectrum in Fig. 4(a). And $L_1, L_2$ are 2m 1m, 5m 3m, and 4m 7m of three curves in Fig. 4(a). PCs states are $(\pi/9, \pi/3, \pi/6, 0, \pi/4, 0), (0, \pi/4, 0, \pi/3, \pi/4, \pi/9)$ and $(\pi/9, \pi/3, \pi/6, \pi/3, \pi/4, \pi/9)$ in Fig. 4(b). In Fig. 4(b), the maximum and minimum interval (curve “I” and “II”) can be obtained by adjusting the PCs. Although the tunable range of the PCs is smaller than that of the PMFs, it is feasible for the PCs tuning in real system. In Fig. 5(b), the bandwidth of maximum interval is broad, which is a disadvantage for some optical systems. However, the side frequencies restrain ability is an effective method to reduce the bandwidth. Curve “Ⅲ” of Fig. 4(b) shows that the bandwidth is narrow and interval is wide.

Fig. 5. Transmission dependence for different PMFs length with (a) $L_2/L_1\neq$constant and (b) $L_2/L_1=$constant.

The side frequencies restrain ability and transmission period depend on the PMFs as shown in Fig. 5(a) and 5(b). $L_1, L_2$ are 2m 1m, 2m 3m, and 2m 5m of three curves in Fig. 5(a). We can see from Fig. 5(a), the side frequencies restrain ability is the best of curve “I”. It is calculated that the side frequencies restrain ability is optimal while $L_1/L_2=2$ or 1/2. We set $L_1/L_2$ as a constant in Fig. 5(b), $L_1, L_2$ of Fig. 5(b) are 3m 2m, 4.5m 3m, and 6m 4m. It is obtained that the period depends on the length of PMFs. The period multiple reduce as the length multiple increase. And the bandwidth is becoming narrower with the increasing length of the PMF in both of two Figs.
Fig. 6. Transmission spectrum of the PC-PMF FLM in (a) PC \((\theta_1, \pi/4, \pi/6)\), (b) PC \((\pi/2, \theta_2, \pi/9)\) and (c) PC \((\pi/6, \pi/4, \theta_3)\).

The transmission dependence for PC is studied in detail; we plot 3-D Fig of the transmission. Firstly, the transmission spectrum of the PC-PMF FLM is simulated with \(\theta_j\) changing \((j=1, 2, 3)\). \(\theta_j\) only can be adjusted from 0 to \(\pi\) in experiment. The transmission spectrum is shown in Fig. 6. Where \(L=1\text{m}, \Delta n=5\times10^{-4}\), the PC states of Fig. 6(a)-6(c) are \((\theta_1, \pi/4, \pi/6), (\pi/2, \theta_2, \pi/9)\) and \((\pi/6, \pi/4, \theta_3)\). The period (interval) is settled while the angles tuning. Fig. 6(b) is the transmission spectrum by adjusting the HWP. In \(\theta_2\)-axis direction, there are two periods; that means for a fixed wavelength, there are two absolute maxima and minima. In wavelength-axis direction, the peak wavelengths shift with \(\theta_2\). Both Fig. 6(a) and 6(c) are QWP. They show one period in \(\theta_j\)-axis \((j=1, 3)\) direction and the peak wavelengths also shift with \(\theta_j\). However, the shift direction is contrary in two Figs.

We also simulate the transmission spectrum of the PCs-PMFs FLM in different PCs states, as shown in Fig. 7. Here we discuss two typical situation. Fig. 7(a) represents adjusting first QWP of PC1, where the PCs is \((\theta_{11}, \pi/3, \pi/6, \pi/3, \pi/4, \pi/9)\), \(L_1=1\text{m}, L_2=2\text{m}\), and \(\Delta n_1=\Delta n_2=5\times10^{-4}\). Fig. 7(b) represents adjusting the HWP of PC1, where the PCs is \((\pi/9, \theta_{12}, \pi/6, \pi/3, \pi/4, \pi/9)\). When adjusting the HWP and QWP, Fig. 7 shows common characteristic with Fig. 6. However, in wavelength-axis direction, the spectrum is more variable like we discuss in Fig. 2(b). The spectrum is confirmed with a certain PCs state, with that conclusion, we can obtain the expected filter spectrum by adjusting the three plates of PC.
3. Experiment result and discussions

The filter characteristics are described by testing the transmission spectra of the structure of Fig. 1 and the results are accordant very well. The optical spectrum analyzer (OSA, AQ6317) with 0.01nm resolution is a principal component in the measurement system. An amplified spontaneous emission (ASE) light source is connected to port 1 as incident lights. An OSA is connected to port 2 to detect transmission lights. We test two stage PMFs of 4m and 6m and Δn=3.1×10^{-4}.

The measured transmission spectra from 1540nm to 1570nm are shown in four pictures of Fig. 8, which represent the PCs in different states. Fig. 8(a) and 8(b) show the uniform amplitude and the wavelength interval is tuned by adjusting PCs. Fig. 8(a) and 8(d) show another different PCs states. The spectrum can change by adjusting PCs states, and the period is always a constant which is about 6nm in our experiment. Fig. 8(a) is the tunable minimum interval (about 1nm) and Fig. 8(b) is the maximum interval (about 6nm) in experiment. The results agree with the discussion in Fig. 4.
A significant application of the FLM is for multiwavelength fiber lasers; in this letter, a fiber ring laser is set up with the PCs-PMFs FLM filter as a wavelength selection element. Fig. 9 shows the scheme of the erbium-doped fiber ring laser based on this PCs-PMFs FLM. To avoid the instability of the output influenced by the factor of the environment, all the parts are fixed on the experimental platform. In the configuration, a 980nm-pump diode laser with 250mW maximum output and a 976.8nm central wavelength is coupled into the ring cavity by a 980/1550nm wavelength-division multiplexer (WDM coupler). The gain is provided by a 6m home made erbium-doped fiber with an absorption coefficient of 16 dB/m at 1530 nm. An optical isolator (ISO) is set in the ring cavity to achieve the unidirectional ring oscillation. The PC3 is used in the cavity to adjust the polarization state. A PCs-PMFs FLM was connected together with the ring cavity through a 3dB coupler (50:50). The stable tunable output of laser is adjusted by two PCs (PC1 and PC2). The home made PMFs with $\Delta n=3.1\times10^{-4}$ are 4m and 6m respectively. The laser power is coupled out using a 95:5 coupler which provides 5% for the output and 95% for feedback inside the cavity. The proposed arrangement in this case can let the fiber loop mirror act merely as a transmission-type spectral filter to modulate the light in the ring cavity, simplifying the laser cavity configuration.
Figure 10 shows the laser output measured by the OSA with 0.01-nm resolution. In experiment, we find that the fiber laser output can be tuned by adjusting PCs of the FLM. As the PCs are adjusted, the stable single-, double- and triple-wavelengths lasers are observed at the output under the pump power of about 200mW. Sixteen times repeated scans at 2 min intervals in nearly half an hour are shown in Fig. 10(a)-10(c). Figure 10 (a) indicates the single wavelength of 1532.068nm, the 3dB line-width is 0.027nm; 30dB line-width is 0.05nm. Double and triple wavelengths lasers repeated scanning spectrum per 2 minutes are shown in Fig. 10(b) and 10(c), the output wavelengths are 1531.420nm and 1553.280nm in Fig. 10(b) and 1530.854nm, 1533.204nm, 1534.01nm in Fig. 10(c). The fluctuation of lasing wavelength is less than 0.05nm and that of the peak power is less than 0.1dB within 30 minutes in the free-running mode at room temperature. The output lasing depends on the PCs state, that means we can control the output lasing by adjusting the PCs state with the above theory and simulated results.

Stability has been a problem in multiwavelength fiber lasers. Although the PCs-PMFs FLM takes some unstable factors caused by more devices inserted, this is not the main factor of instability in erbium-doped fiber ring laser. Erbium-doped fiber is a homogeneous gain medium at room temperature [12] and the length of whole cavity is long (about 20m in this letter), which leads to strong mode competition and unstable lasing. This mode competition is represented that one mode is lasing at a cost of others vanishing. So it is difficult to obtain simultaneous multiwavelength lasing in erbium-doped fiber lasers. The number of the stable lasing mode depends on the structure of lasers and the operation condition, such as the concentration of erbium fiber, the length of cavity, and the gain media and so on; we got triple wavelength stable lasing with the configuration of Fig. 9 in this experiment setting. In order to achieve more stable wavelength operation, several methods have been proposed: by using frequency shift and polarization hole burning [13]; nonlinear Brillouin gain and four-wave mixing (FWM) effect [14,15]; EDF cooled by liquid nitrogen [16], etc. These methods would
be taken in future work.

4. Conclusion

In summary, a FLM filter of two-stage PMFs and PCs (PCs-PMFs) is presented and an erbium-doped fiber ring laser based on this FLM is proposed. The polarization independent of both the FLMS is a significant characteristic in optical applications. The PCs-PMFs FLM spectrum is more flexible than PC-PMF FLM: the interval depends is determined by both the PCs and the PMFs; the side frequencies restrain ability is optimal while $L_1/L_2=2$ (or $1/2$); and the bandwidth is becoming narrower with the increasing length of PMF. The 3-D plot shows the transmission dependence on PC in detail. Later experimental filter results confirmed the discussion in this letter. Stable single-, dual-, triple-wavelength are obtained in the fiber ring laser. The 3dB and 30dB line-widths of each lasing wavelength of the laser are less than 0.03nm and 0.06nm respectively. The fluctuation of lasing wavelength is less than 0.05nm, and that of the peak power is less than 0.1dB within 30 minutes in the free-running mode at room temperature.

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