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基于多模干涉滤波器和双折射滤波器的四波长可开关光纤激光器

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摘 要:设计了一种基于多模干涉滤波器和双折射滤波器的四波长可开关光纤激光器,理论分析了多模干涉滤波器和双折射滤波器及其级联结构的滤波特性.双折射滤波器能有效地抑制多模干涉滤波器的不规则边模.保偏掺铒光纤同时作为增益介质和滤波元件,优化多模光纤长度和保偏掺铒光纤长度保证了波长间隔的最佳匹配,级联滤波器的滤波周期为 4.89 nm.调节偏振控制器,光纤激光器实现了单波长、双波长、三波长以及四波长可开关激光输出,输出激光的边模抑制比均大于 40 dB,1 h 内波长波动均小于 0.1 nm.

关键词:光纤激光器;多模光纤滤波器;双折射滤波器;偏振控制

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Switchable Quadruple-wavelength Fiber Laser Based on Multimode Interference Filter and Birefringent Filter

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Abstract: In order to realize the switchable multi-wavelength oscillation, a fiber ring laser based on a multimode interference filter and a birefringent filter was proposed and demonstrated. The filtering characteristic of the cascaded fiber filters was analyzed theoretically, and the irregular side modes of the multimode interference filter can be effectively restrained by cascading birefringent filter. The Polarization Maintaining Erbium Doped Fiber (PM-EDF) is utilized to serve as gain medium and a part of birefringent filter simultaneously, the length of the multimode fiber and PM-EDF are optimized to match the same wavelength spacing, the filtering period of the cascaded fiber filter is 4.89 nm. The laser could switch to output single-, dual-, triple- and quadruple-wavelength by finely adjusting polarization controller in the experiment, side-mode suppression ratios of lasing wavelengths are more than 40dB, and wavelength fluctuations are less than 0.1 nm during a period of 1h.

Key words: Fiber laser; Multimode interference filter; Birefringent filter; Polarization control

OCIS Codes: 060.3510; 060.2320; 260.1440; 260.5430

0 Introduction

There has been sustained interest towards the development of multi-wavelength fiber laser due to its potential application in optical fiber sensing, fiber optic communication, optical instruments testing[1-5], switchable multi-wavelength fiber laser is very attractive for optical add and drop multiplexer and

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optical routing. In recent years, various methods have been proposed to realize the switchable multi-wavelength fiber laser, such as utilizing polarization maintaining erbium doped fiber[6], erbium doped photonic crystal fiber [7], non-adiabatic microfiber[8], Sagnac loop mirror incorporating polarization maintaining fiber[9], high birefringence few mode fiber[10], Fiber Bragg Grating (FBG)[11], sampled FBG[12], uniform FBG combining with tunable FBG[13], multimode FBG[14], modal interferometer[15]. However, the fabrication of specialty fiber and complex structured FBG is difficult and high cost, the lasing wavelength is fundamentally not tunable. Multimode Interference (MMI) filter has been widely used in salinity sensor and temperature sensor due to its simple structure and high sensitivity[16-17], however, report on fiber laser utilizing MMI filter[18-19] is still limited, equalized output peak power is difficult to obtain due to the irregular side modes of MMI filter.

In this paper, a simple switchable quadruple-wavelength erbium doped fiber laser was proposed and demonstrated. The filtering characteristic of the cascaded fiber filters is analyzed theoretically, some irregular side modes occur in the transmission spectrum of MMI filter, and birefringent filter is utilized to restrain irregular side modes and control lasing wavelength. The proposed fiber laser has the advantage of compact structure due to the double function of Polarization Maintaining Erbium Doped Fiber (PM-EDF), and single-, dual-, triple-, quadruple- wavelength oscillation with good power uniformity are obtained in the experiment.

1 Experimental setup

The schematic diagram of the proposed fiber laser is shown in Fig. 1. The laser consists of a 980 nm Laser Diode (LD), a 980/1 550 nm Wavelength Division Multiplexer (WDM), a PC, a segment of PM-EDF, a polarizer, a segment of Multi-Mode-Fiber (MMF), an isolator and a 1×2 coupler with splitting ratio of 50:50. PC is used to change polarization state in the ring cavity, polarizer is adopted to obtain linearly polarized light and form birefringent filter together with PC and PM-EDF. The 4.09m-long PM-EDF with a birefringence coefficient of 1.2×10^{-4} at 1550 nm serves as both gain medium and a part of birefringent filter, and it is pumped by a 980nm LD with a pump power of 90mW through a 980/1 550 nm WDM. The 4.68 m-long MMF is spliced between input Single Mode Fiber (SMF) and output SMF to form a MMI filter, numerical aperture and core radius of MMF are 0.22 and 31.25 μm, respectively. Note that the length of polarization maintaining erbium doped fiber and multimode fiber are optimized to match the same wavelength spacing, thus benefiting the flexible switching operation and good power uniformity. The isolator is used to guarantee that the light in the ring cavity travels along anti-clockwise direction. The output is monitored through the 50% port of a 1×2 coupler, and the residual 50% port is used for feedback.

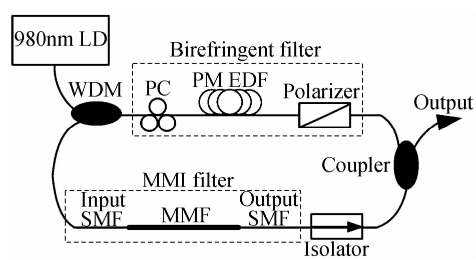

Fig. 1 Schematic diagram of the proposed fiber laser

2 Theoretical analysis

Only Linear Polarization (LP) modes in MMF can be excited by LP_{01} without core offset between SMF and MMF, the power distribution of modes in MMF is determined by power coupling coefficient. Under the condition of linearly polarized mode approximation, the power coupling coefficient η_ν can be calculated by[20]

$$\eta_\nu=\frac{2\left(\frac{\bar{\omega}}{a}\right)^2\exp\left[-\frac{1}{2}\left(\frac{\bar{\omega}}{a}\right)^2\left(\left(2\nu-\frac{1}{2}\right)\frac{\pi}{2}\right)^2\right]}{\mathrm{J}_0^2\left(\left(2\nu-\frac{1}{2}\right)\frac{\pi}{2}\right)+\mathrm{J}_1^2\left(\left(2\nu-\frac{1}{2}\right)\frac{\pi}{2}\right)+\left[\frac{\mathrm{K}_1^2\left(\sqrt{\left(\frac{2\pi a}{\lambda}\mathrm{NA}\right)^2-\left(\left(2\nu-\frac{1}{2}\right)\frac{\pi}{2}\right)^2}\right)}{\mathrm{K}_0^2\left(\sqrt{\left(\frac{2\pi a}{\lambda}\mathrm{NA}\right)^2-\left(\left(2\nu-\frac{1}{2}\right)\frac{\pi}{2}\right)^2}\right)}-1\right]\mathrm{J}_0^2\left(\left(2\nu-\frac{1}{2}\right)\frac{\pi}{2}\right)} \tag{1}$$

where a and NA are core radius and numerical aperture of MMF, ν is mode number of guide mode propagating along MMF, $\bar{\omega}$ is half-width at half-maximum spot size of LP_{01} in SMF, J and K are Bessel function and Hankel function.

As shown in Fig. 2, the calculated power coupling coefficients of first several linear polarization modes are 0.2170, 0.3456, 0.2597, 0.1214 and 0.0379, respectively. Therefore, $LP_{01} \sim LP_{04}$ are the dominant modes in MMF, other high order modes can be ignored due to small power coupling coefficients. The dominant modes propagate along MMF and couple into LP_{01} in output SMF, the transmittance of MMI filter considering four dominant modes can be written as[21]

$$T_1 = \sum_{i,j=1}^{4} \eta_i \cdot \eta_j \cdot \cos[(\beta_{LP_{0i}} - \beta_{LP_{0j}}) L_{MMF}] \tag{2}$$

where $\beta_{LP_{0i}}$ and $\beta_{LP_{0j}}$ are the longitudinal propagation constants of LP_{0i} and LP_{0j}, L_{MMF} is the length of MMF. The wavelength spacing of MMI filter can be calculated by $\Delta\lambda = \dfrac{16 n_{core} a^2}{L_{MMF}}$, where n_{core} is refractive index of MMF core.

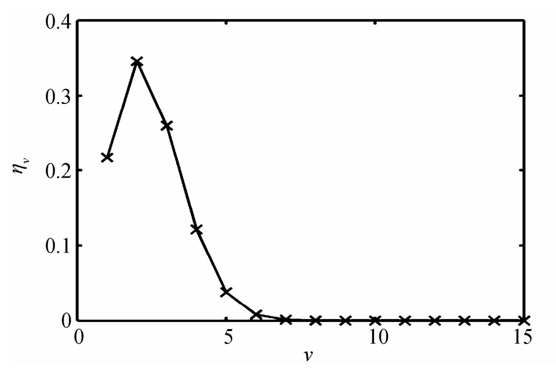

Fig. 2 Power coupling coefficient of LP modes

As shown in Fig. 3, the calculated transmission spectrum of MMI filter is comb with a wavelength spacing of 4.89nm, some irregular side modes occur in the comb spectrum. MMI filter serves as mode selective element in the ring cavity, any side mode with different transmittance can be oscillated, thus the output peak power of lasing wavelengths is probably not equalized. Therefore, birefringent filter is adopted to restrain undesired side modes and select the dominant modes with high transmittance. The transmittance of birefringent filter can be given as

$$T_2 = \sin^2\alpha \sin^2\beta + \cos^2\alpha \cos^2\beta + \frac{1}{2}\sin(2\alpha)\sin(2\beta) \cdot \cos(\Delta\varphi_{LB} + \Delta\varphi_{PC}) \tag{3}$$

where α is the angle between slow axis of PM-EDF and polarized direction of the polarizer, and β is the angle between slow axis of PC and polarized direction of the polarizer, $\Delta\phi_{LB}$ is the phase difference caused by PM-EDF, and $\Delta\phi_{PC}$ is the phase difference caused by PC.

The wavelength spacing of birefringent filter can be calculated by $\Delta\lambda = \dfrac{\lambda^2}{\Delta n \cdot L_{PMF}}$, where Δn is birefringence coefficient of PM-EDF, L_{PMF} is the length of PM-EDF. Fig. 4 shows the calculated transmission spectrum of birefringent filter with $\Delta\phi_{PC}$ equal to π and $\pi/8$, respectively. The value of $\Delta\phi_{PC}$ can be changed by adjusting PC, thus the envelope of birefringent filter will be shifted to shorter wavelength or longer wavelength.

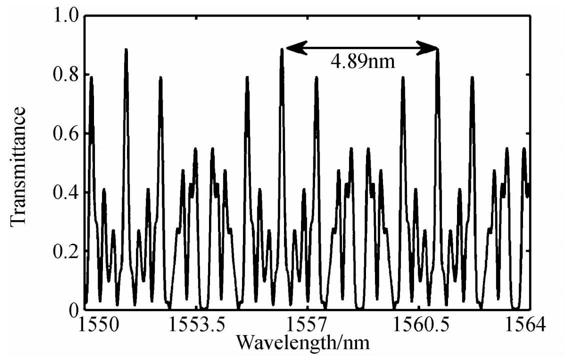

Fig. 3 Transmission spectrum of MMI filter

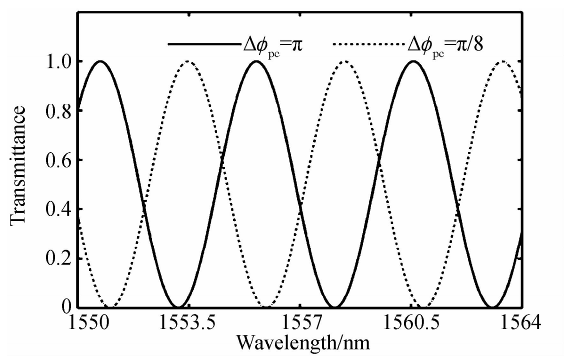

Fig. 4 Transmission spectrum of birefringent filter

In order to restrain undesired side modes and equalize output peak power of different modes within each spectrum period of MMI filter effectively, the length of MMF and PM-EDF are optimized to ensure that the wavelength spacing of MMI filter and birefringent filter is consistent with each other. Assuming that input gain spectrum is flat and normalized, the calculated transmission spectrum of cascaded fiber filter is shown in Fig. 5. The transmission peak of birefringent filter coincides with the transmission peak of MMI filter with $\Delta\phi_{PC}$ equal to 1.56π, dual-wavelength oscillation can be obtained, as shown in Fig. 5(a). The envelope of birefringent filter is shifted to the shorter wavelength by varying the value of $\Delta\phi_{PC}$, the calculated transmission spectrum of cascaded fiber filter with $\Delta\phi_{PC}$ equal to 1.29π is shown in Fig. 5(b). The transmittance of different modes are equalized, quadruple-wavelength oscillation can be obtained simultaneously.

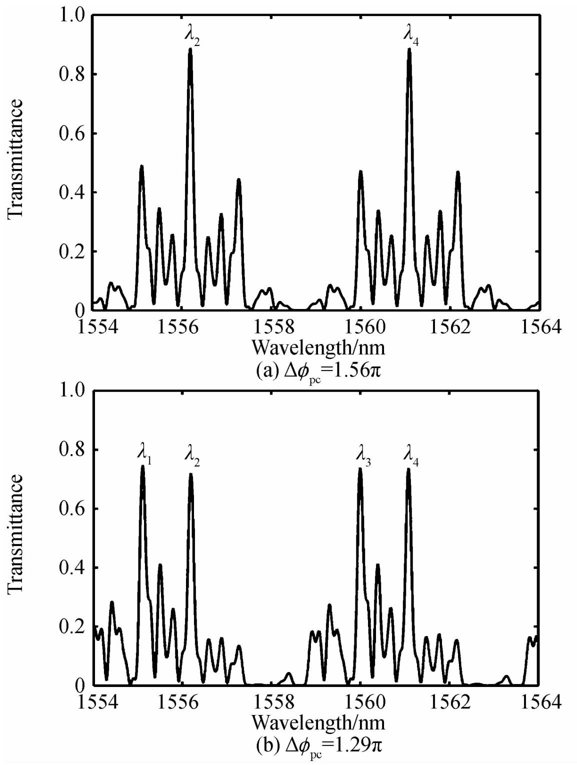

Fig. 5 Transmission spectrum of cascaded fiber filter

3 Experimental results and discussion

To testify the switching operation of fiber laser, output spectrum is observed by a traditional optical spectrum analyzer (Anritsu MS9710B) with a resolution of 0.07 nm. Four different kinds of wavelength oscillation are obtained in the experiment, including single-, dual-, triple- and quadruple-wavelength oscillation. Fig. 6(a) shows single-wavelength oscillation with central wavelength of 1 561.09 nm, output peak power and SMSR are 2.12 dBm and 46.16 dB, respectively. Fig. 6(b) shows dual-wavelength oscillation with central wavelength of 1 556.23 nm and 1 561.09 nm, output peak powers are −0.53dBm and −0.54 dBm, and SMSR are 42.55 dB and 42.54 dB, respectively. Fig. 6(c) shows triple-wavelength oscillation with central wavelength of 1 556.23 nm, 1 560.34 nm and 1 561.09 nm, output peak powers are −0.5 dBm, −2.1 dBm and −1.92 dBm, and SMSR are 47.01 dB, 45.41 dB and 45.59 dB, respectively. Fig. 6(d) shows quadruple-wavelength oscillation with central wavelength of 1 555.42 nm, 1 556.29 nm, 1 560.37 and 1561.36 nm, output peak powers are −6.12 dBm, −3.88 dBm −1.28 dBm, and −5.16 dBm, and SMSR are 40.99 dB, 43.23 dB, 45.83 dB and 41.95 dB, respectively.

The wavelength stability of the proposed fiber laser is measured every 6 minutes during a period of 1h. As shown in Fig. 7, the wavelength fluctuation for

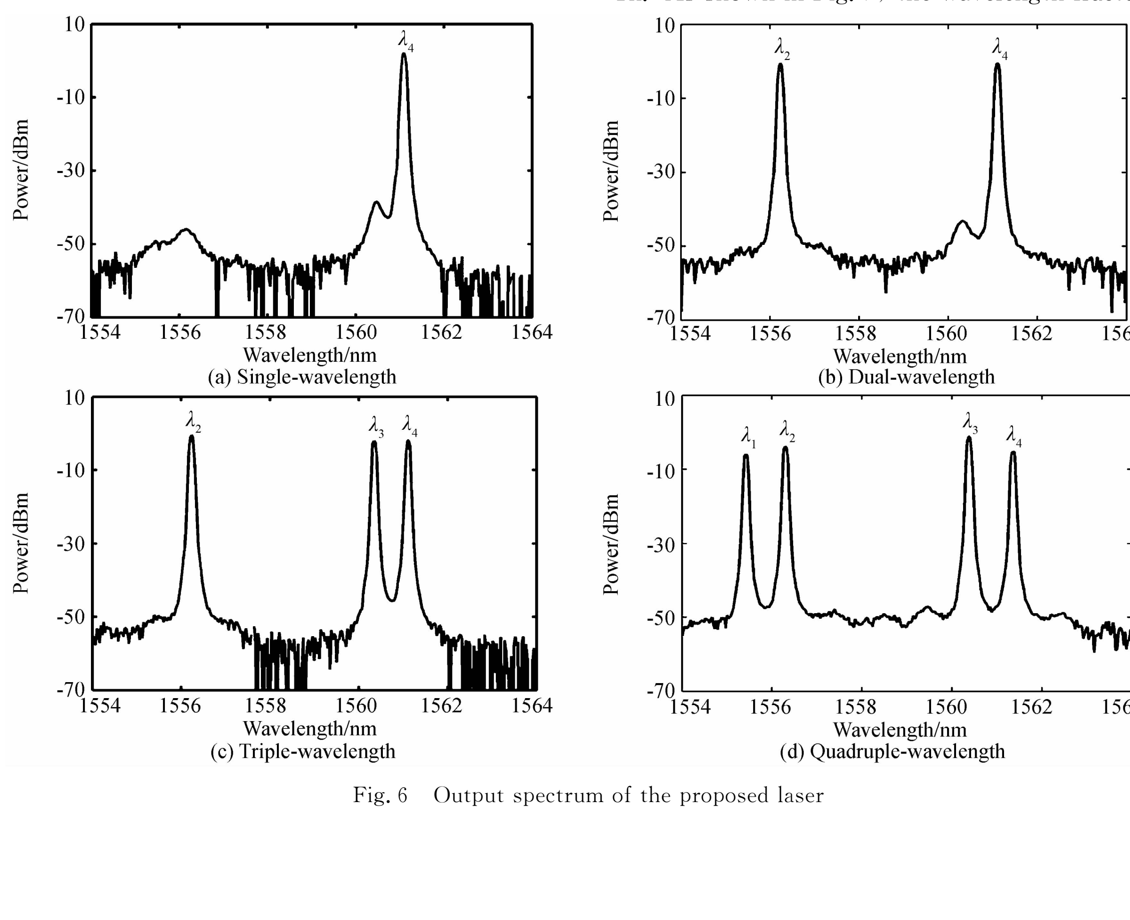

Fig. 6 Output spectrum of the proposed laser

1 561.09 nm of single-wavelength oscillation, 1 556.23 nm of dual-wavelength oscillation, 1 560.34 nm of triple-wavelength oscillation and 1 555.42 nm of quadruple-wavelength oscillation are 0.03 nm, 0.03 nm, 0.06 nm and 0.09 nm, respectively.

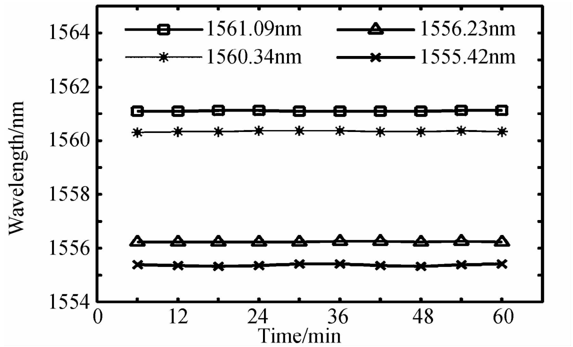

Fig. 7 Wavelength fluctuations of the proposed laser

According to the theoretical analysis, different wavelength spacing can be also obtained by changing the length of MMF and PM-EDF correspondingly, but a proper length of PM-EDF is required to balance the gain and loss in the ring cavity. The polarization state of LP_{01} in input SMF will be changed by adjusting PC, the mode interference between different polarized modes in MMF is changed correspondingly. Moreover, the envelope of birefringent filter will be shifted by adjusting PC, the transmittance of different modes is equalized, gain and loss of different wavelengths in the ring cavity are balanced, thus switchable multi-wavelength oscillation can be obtained. The input gain spectrum is assumed to be flat and normalized in theoretical analysis, however, the gain spectrum of PM-EDF is not ideally flat in the experiment, and the polarization state is also affected by other optical devices in the ring cavity besides PC, single-, triple-wavelength oscillation are also obtained besides dual-, quadruple-wavelength oscillation in the experiment. The proposed laser has good wavelength stability for single- and dual-wavelength oscillation, however, the stability of triple-, quadruple- wavelength oscillation become a little worse, it is attributed to greater mode competition between two adjacent lasing wavelengths with smaller wavelength spacing.

4 Conclusion

We have demonstrated a simple switchable quadruple-wavelength fiber laser experimentally. The filtering characteristic of the cascaded fiber filters is analyzed theoretically, the irregular side modes of MMI filter is effectively restrained by cascading birefringent filter. In order to obtain flexible switching operation and good power uniformity, the length of MMF and PM-EDF are calculated precisely to match the same wavelength spacing. The laser realizes single-, dual-, triple-, and quadruple-wavelength oscillation by adjusting PC in the experiment, side-mode suppression ratios of lasing wavelengths are more than 40dB, and wavelength fluctuations are less than 0.1nm during a period of 1h.

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