Temperature tunable multiwavelength fiber laser by using compounded filter

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Abstract: A stable multiwavelength erbium-doped fiber laser was proposed and experimentally demonstrated by using a compounded fiber filter, which was composed of a Mach-Zehnder interferometer (MZI) and a birefringence fiber filter-Lyot filter. The MZI was fabricated by using the fiber fusion splicer to splice a section of SMF to form two cascaded spherical structures. The Lyot filter was incorporating a segment of polarization maintaining fiber (PMF) and two polarization controllers (PCs), which provided nonlinear polarization rotation (NPR) and birefringent filter effect to suppress the mode competition and generate multiwavelength. Using cascaded spherical-shape structures MZI and the Lyot filter as mode restricting elements respectively, the transmission spectrum of cascaded spherical-shape structures MZI was modulated by the Lyot filter, which determined the period of the compounded structure. In the experiments, 9-wavelength operation with a side-mode suppression ratio (SMSR) of ~40 dB was achieved, and the space of wavelength was 0.68 nm defined by the Lyot filter. When the stability of proposed structure was observed for 2 hours every 10 minutes, the fluctuation of the central wavelength′s output power was less than 0.67 dB. Furthermore, when the two spherical-shape structures MZI was fixed on a furnace and the temperature varied from 30 ℃ to 110 ℃, the spectrum of output wavelength can be tuned within the range of 6.69 nm.

Key words: multiwavelength fiber laser; compounded; two spherical-shape structures MZI; Lyot filter; tunable

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采用复合滤波器的温度可调谐多波长光纤激光器

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摘 要: 提出了一种基于复合光纤滤波器的在室温下稳定输出多波长掺铒光纤激光器,该激光器由两个级联球状结构的马赫-增德尔干涉仪(MZI)和一个双折射光纤滤波器-Lyot 滤波器组成。球状结构 MZI 是由光纤熔接机在一段单模光纤(SMF)放电设计而成的。Lyot 双折射光纤滤波器是利用一段

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保偏光纤(PMF)和两个偏振控制器(PC)连接而成,该结构可以诱导非线性偏振旋转效应和双折射光纤效应来抑制模式竞争产生多波长。Lyot 滤波器和球状结构的 MZI 作为模式限制器件,并且 Lyot 滤波器对级联球状结构 MZI 的透射谱进行调制,其透射谱周期决定了复合滤波器结构的透射谱周期。在室温下,该系统实现了边模抑制比约为 40 dB 的九个波长的同时激射,且波长间隔约为 0.68 nm,与 Lyot 滤波器透射谱周期一致。为了验证输出波长的稳定性,在 2 h 内,每隔 10 min 观察输出的波长,实验证明,室温下中心波长输出功率的浮动小于 0.67 dB。此外,将两个球状结构 MZI 放置在高温炉上,使其外界温度从 30 ℃升至 110 ℃时,输出波长光谱的调谐范围可达到 6.69 nm。

关键词: 多波长光纤激光器; 复合; 两个球状结构 MZI; Lyot 滤波器; 可调谐

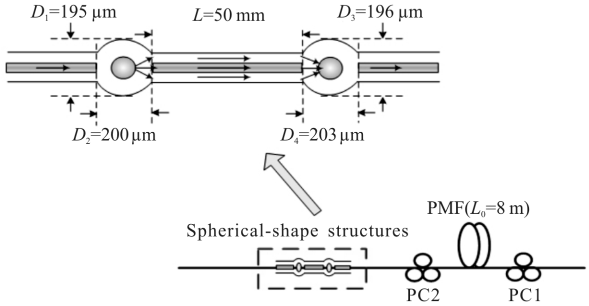
0 Introduction

Multiwavelength erbium-doped fiber lasers (MWEDFLs) have been extensively investigated for their versatile applications in dense wavelength-division-multiplexing(DWDM) communication systems, fiber sensing, and optical instrumentations[1-2]. Thus, numerous approaches have been described in the development and applications of multiwavelength fiber lasers, such as in multiwavelength outputs using polarization hole burning(PHB) effect[3], and the utilization of intensity dependent loss(IDL)[4]. So some passive optical techniques, such as Fabry-Perot filters (FFPs)[5] and birefringence fiber filters[6-7] have been empolyed to produce a comb spectrum, then incorporate into cavity to achieve a multiwavelength fiber laser.

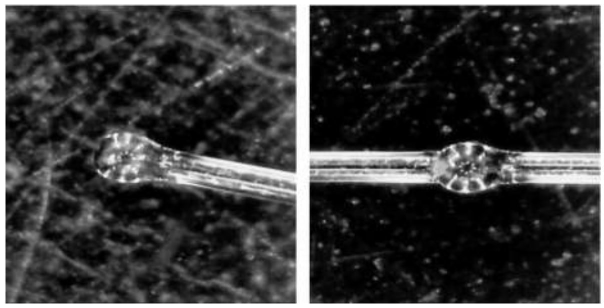
In order to obtain tunable MWEDFL, in addition to above methods, MWEDFLs can be achieved by active optical techniques, such as tuning the transmission spectrum and consequently tuning output characteristics. Some tunable methods have been reported in recent years, such as FBG filter[8], acousto-optic tunable filter[9], mechanical tuning[10], temperature tuning and magnetic tuning. Recently, some ring fiber laser and tunable filters with some techniques have been reported to suppress multimode oscillation and achieve tune. In the reference [11], a cascaded fiber filter is proposed with a nonlinear optical loop mirror (NOLM) and birefringence fiber filter. The spectrum range of lasing lines can be controlled by adjusting the NOLM, but it is not convenient to practical operation to adjust PCs and NOLM. A in-line MZI with SMF-PCF-SMF and FPI superimposed filter is proposed in the reference [10], which can obtain stable multiwavlength lasing line and can be tuned by mechanical tuning to adjust the curvature radius over the MZI. However, this system could only obtain a few lasing lines and the production of FPI is complex. In this paper, a stable and tunable multiwavelength fiber laser based on compounded fiber filters is demonstrated. Among them, the Lyot filter is a birefringence fiber filter, which is composed of a section of PMF and two PCs. The Lyot filter is used to generate comb spectrum, and the two spherical-shape structures MZI is used as a wavelength selection element. The proposed system can relieve multimode oscillation to achieve the multiwavelength output at room temperature. Compared to above references, this system can achieve 9-wavelength with good stability and a high side-mode suppression ratio (SMSR). Moreover, the two spherical-shape structures MZI is sensitive to temperature, and the transmission spectrum will show shift by changing temperature around the two spherical-shape structures MZI. So the different spectrum range of wavelength can be achieved. What's more, the manufacturing method of the two spherical-shape structures is simple and convenient, and made by SMF only. Therefore, a low cost and more simple system is realized.

1 Operation principles of compounded fiber filter

The superimposed fiber filter with the two spherical-shape structures MZI and the Lyot filter, is illustrated in Fig.1(a). The two spherical-shape structures MZI is made by the optical fiber fusion splicer (FURUKAWA S178C). Firstly, the coating layer of standard SMF (8.2 μm/125 μm) is removed, and fiber facets is polished. Then the fiber facet is polished into the optical fiber fusion splicer. In the fusion splicer, the stepper motor is used to control the position of the fiber, and the end face of fiber is placed over the center line of display screen. Afterwards, the splice procedure is clicked, and the parameters of discharge is also modified. Last, the "arc" is clicked for the operation of discharge, thus a spherical-shape structure is manufactured. According to calculation, the approximate value of loss of the two spherical-shape structures MZI is about 1.9 dB. That the real image of the MZI is shown in Fig.1(b). The PC1 is utilized to make linearly polarized lights changed into elliptical polarized lights. The induced wavelength space is proportional to the PMF length. Moreover, the higher transmittance of the transmission spectrum may be discretely tuned by adjusting the PC2 state. In addition to this, when the light transmits in the core mode and launched into the first spherical-shape structure (The longitudinal diameter D_1 of spherical-shape structure is 195 μm and the transverse diameter D_2 is 200 μm), part of the light is coupled to the cladding modes. These cladding modes travel a certain optical path with length of L along the sensing segment, finally re-coupled back to interfere with the core mode at the second spherical-shape structure (The longitudinal diameter D_3 of spherical-shape structure is 196 μm and the transverse diameter D_4 is 203 μm). Therefore, it is also a core-cladding-mode interference generated by the two spherical-shape structures MZI and superimposed with the Lyot filter.



(a) Structure of the compounded fiber filter



(b) Real image of the MZI

Fig.1 Structure diagram of compounded filter

The transmissivity of the two spherical-shape structures MZI can be expressed as[12]

$$T_{\mathrm{MZI}}=1-\frac{4k}{(1+k)^2}\sin^2[\pi(n_{\mathrm{core}}-n_{\mathrm{clad}})L/\lambda] \tag{1}$$

Where L is the length between two spherical-shape structures, n_{core} and n_{clad} are the effective index of the core mode and the cladding mode in the SMF, respectively, Δn_{eff} is the difference between the effective refractive index of the core and the cladding mode, k is the optical amplitude ratio of the light corresponding to the cladding and core mode involved and the value of the parameter k is about 0.5, and λ is the signal wavelength in vacuum. And the phase difference φ between the core mode and the cladding mode is as follows[13]:

$$\varphi(\lambda,\ \Delta n_{\mathrm{eff}},\ L)=2\pi\frac{\Delta n_{\mathrm{eff}}L}{\lambda} \tag{2}$$

When surrounding environment changes, the length, effective refractive index difference and signal wavelength also vary into ΔL, $\delta\Delta n_{\mathrm{eff}}$, $\Delta\lambda$, respectively. And the change of the signal wavelength can be expressed as:

$$\Delta\lambda=\lambda\left(\frac{\Delta L}{L}+\frac{\delta\Delta n_{\mathrm{eff}}}{\Delta n_{\mathrm{eff}}}\right) \tag{3}$$

When it comes to the temperature, we can take the derivative of the Eq.(3) with respect to temperature. It is described as:

$$\Delta\lambda=\lambda\left(\frac{1}{L}\frac{\partial\Delta L}{\partial T}+\frac{1}{\Delta n_{\mathrm{eff}}}\frac{\partial\,\delta\Delta n_{\mathrm{eff}}}{\partial T}\right)\Delta T \tag{4}$$

According to Eq.(4), the temperature applied to the two spherical-shape structures MZI induces a proportional wavelength shift. Therefore, the central wavelength shifts of the two spherical-shape structures MZI based ring cavity laser are proportional to the temperature.

According to Eq.(1), the transmission spectrum of the two spherical-shape structures MZI at room temperature is shown in Fig.2.

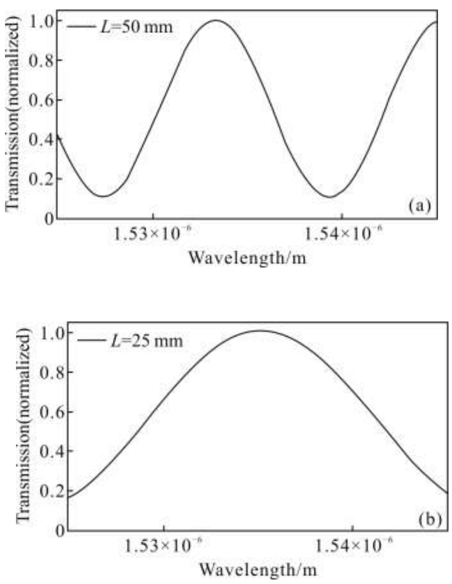


Fig.2 Transmission spectrum of the two spherical-shape structures

According to Fig.2, the free spectral range(FSR) of the two spherical-shape structures MZI is controlled by L, and the two spherical-shape structures MZI acts as the mode coupler in the experiments. The length between two spherical-shape structures MZI is not suitable for too long[14]. Otherwise, the interference will happen in the two spherical-shape structure MZI and influence the transmission spectrum. Also, it had been proved that extinction ratio decreases with the increase of the length between two spherical-shape structures. So the length between two spherical-shape structures is selected for 50 mm in the experiment.

By using the Jones matrix, the transmissivity of the Lyot filter is written as[15]

$$T_L=\cos^2\alpha\cos^2\beta+\sin^2\alpha\sin^2\beta+\frac{1}{2}\sin2\alpha\sin2\beta\cos(\Delta\varphi) \tag{5}$$

$$\Delta\varphi=2\pi\Delta nL_0/\lambda_0 \tag{6}$$

Where α is the angle between the incident light and the fast axis of PMF, β is the angle between the output light and the fast axis of PMF, Δn is the difference of the effective refractive index between the fast axis and slow axis of PMF, and λ_0 is the wavelength of incident light to PMF. The transmission spectrum of the Lyot filter is calculated, as shown in Fig.3.

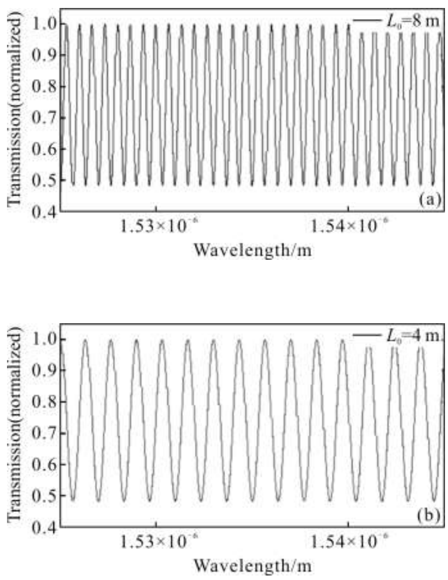


Fig.3 Transmission spectrum of the Lyot filter

From Fig.3, we can know that the length of PMF applied to the Lyot filter induces different wavelength space. When the length of PMF is too long, the wavelength space will become smaller. On the contrary, if the length of PMF is too short, the wavelength space will be so large that can not realize more wavelength output. Therefore, L_0=8 m is used to contribute to the Lyot filter with PCs and its channel space is 0.68 nm in theory.

On account of the uncorrelated superposition between the Lyot filter and the two spherical-shape structures MZI, the transmissivity of the superimposed filter is the direct product of the Lyot filter and the two spherical-shape structures MZI, respectively. The transmissivity may be derived and described as

$$T=T_{MZI}\times T_L \quad (7)$$

According to Eq. (7), we can obtain that the transmission spectrum of the compounded fiber filter is shown in Fig.4.

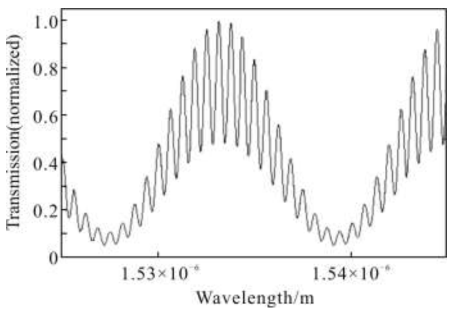


Fig.4 Transmission spectrum of the compounded structure

Compared with Fig.2 and Fig.3, the transmission spectrum of the two spherical-shape structures MZI is the outer envelope of the compounded structure, and it is modulated by the Lyot filter, and then the period of the superimposed structure is determined by the Lyot filter.

2 Experimental results and discussion

The schematic configurations of the proposed tunable MWEDFL based on compounded fiber filter is shown in Fig.5. A 980 nm laser diode is used as the pump source and connected to a 7 m long erbium-doped fiber (EDF) through a 980 nm/1 550 nm wavelength division multiplexer (WDM). After that, the compounded structure is used as the fiber filter, then connected to an optical isolator (ISO) which is used to suppress the undesired reflection and ensure the light transmission in the same direction. Finally, the output from the filter is connected to a 10:90 coupler, where a portion of the output is extracted by the 10% port to an optical spectrum analyzer(OSA) with the resolution of 0.07 nm and the rest is fed back into the cavity.

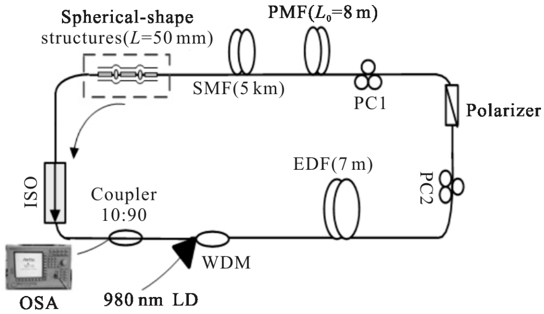


Fig.5 Schematic diagram of the experimental setup

NPR is the key method to achieve multiwavelength output. Linearly polarized lights from the polarizer will become elliptical polarized lights through the adjustment of PC1, and elliptical polarized lights can be considered to be superposition of left circular polarized lights and right circular polarized lights, respectively. Kerr effect which is introduced by the SMF makes the intensity of circular polarized lights have different nonlinear phase shift. Therefore, the polarization state which is synthesis by left and right circular polarized lights occurs rotation when the lights propagate through SMF, and the rotation angle is related to the intensity of light. PC2 can control the intensity of light by adjusting transmittance of the transmission spectrum when the lights pass through the polarizer again. So a intensity of related device is made up by the polarizer, the Lyot filter, and SMF, thus intensity dependent inhomogeneous loss induced by NPR can suppress the mode competition.

A single wavelength begins to emerge when the pump power is 24 mW. And there are several unstable output wavelength when the pump power increases to 102 mW. Stable 9-wavelength at room temperature has been achieved as shown in Fig.6, when the pump power is 205 mW. As can be seen from the figure that the SMSR of the wavelengths are more than 40 dB. The spectrum have a wavelength spacing of about 0.68 nm, which is determined by the longitudinal mode spacing of the Lyot filter, and it is consistent well with the theoretical estimate.

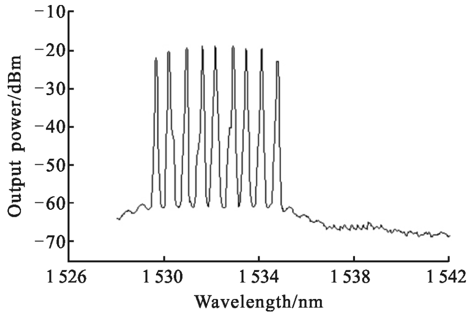


Fig.6 Output laser of experiment

To further investigate the performance of the EDFL, the two spherical-shape structures MZI is fixed on a furnace. The MZI is placed without the effection of the strain, and the temperature is monitored by the thermoelectric thermometer. Moreover, the fiber coating layer is striped within 10 cm close to furnace for the sake of preventing melting the fiber coating layer to change refractive index of fiber surface with the rise of temperature. The temperature is changed from 30 ℃ to 110 ℃, the spectrum under the broadband light source of the two spherical-shape structures MZI at different temperature and is shown in Fig.7.

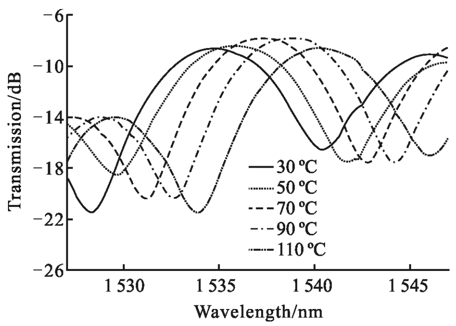


Fig.7 Spectrum of the two spherical-shape structures MZI at different temperature

As can be seen from the figure, with the increase of the temperature, the spectrum of the cascaded spherical-shape structures MZI shows red shift. Also, the output wavelength will change and is shown in Fig.8. As expected, the whole spectrum drifts, the first wavelength is tuned from 1 530.49 nm to 1 537.18 nm, and the SMSR is maintained at 40 dB during the whole tuning process.

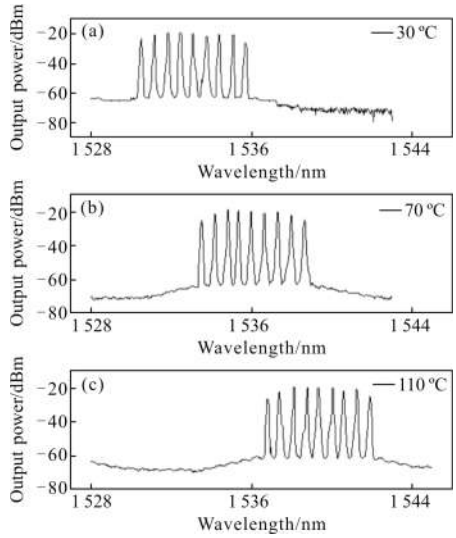


Fig.8 Output laser drift with the increasing temperature

In order to verify the stability of proposed structure, the system has been measured for 2 hours every 10 minutes at room temperature and the results obtained is shown in Fig.9 (a), the output power of multiwavelength are approaching −18 dBm. As shown in Fig.9(b), the output power change of the central

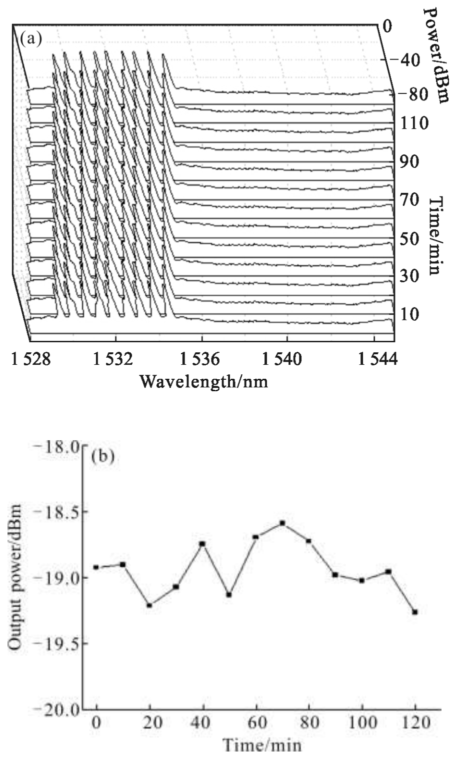


Fig.9 (a) Stability of output power at room temperature, (b) the output power change of the central wavelength

wavelength is less than 0.67 dB. If the stability of the pump LD and the operation surroundings can be improved, a more stable multiwavelength lasing will be expected.

3 Conclusions

A tunable multiwavelength fiber laser with superimposed fiber filter is successfully fabricated. The Lyot filter not only acts as wavelength generate element, but also can effectively alleviate the mode competition induced by the homogeneous gain broadening in the EDF. Furthermore, the two spherical-shape structures MZI is a tunable filter. As a result, stable 9 -wavelength oscillation with a wavelength-spacing of about 0.68 nm at room temperature has been achieved, and with the change of the temperature, the tuning range of the output wavelength can attain 6.69 nm, which can make it potentially applied to many systems.

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