Switchable multi-wavelength fiber laser based on cascade fiber tapers and phase modulator

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Abstract: An all-fiber switchable multi-wavelength erbium fiber laser was proposed in this paper. A sinusoidal phase modulator composed of a piece of single-mode fiber around a piezoelectric transducer was inserted in the ring cavity, combined with an all-fiber Mach-Zehnder interferometer based on cascade in-line two-taper as the comb filter, which suppressed the mode competition owing to the homogeneous broaden line in erbium-doped fiber and eliminated the unstable wavelength lasing. Simultaneous and stable five-wavelength lasing was observed with 0.804 nm intervals at room temperature. The signal to noise ratio is higher than 40 dB, the 3 dB bandwidth is about 0.023 nm, and the five lasing lines in power differences are less than 14 dB. Meanwhile, the laser has highly flexible wavelength switchable property. By adjusting the driving signal and polarization controller, single wavelength lasing output, switchable dual, triple and ever more wavelengths lasing output could be realized. These advantages enable this laser as a potential candidate for high-capacity wavelength division multiplexing systems and mechanical sensors.

Key words: fiber laser; switchable multi-wavelength; phase modulation; fiber taper

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基于光纤拉锥及相位调制的可切换多波长掺铒光纤激光器

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摘 要:研究了一种全光纤可切换多波长掺铒光纤激光器。该激光器利用一段缠绕在压电陶瓷上的单模光纤作为正弦相位调制器以及基于光纤拉锥的马赫-曾德尔干涉仪作为梳状滤波器,抑制由于掺铒光纤的均匀展宽效应引起的模式竞争,从而避免了在室温下不稳定的单波长激射,实现了多波长掺铒光纤激光器的稳定输出。实验中观察到稳定的 5 个波长的同时激射,相邻波长间隔为 0.804 nm。信噪比大于 40 dB,3 dB 带宽约为 0.023 nm,中心 5 个波长输出功率的平坦度为 14 dB。同时,激光器

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具有灵活的波长可切换特性，通过调整驱动信号和偏振控制器的状态，实现了单波长、双波长、三波长以及更多波长的输出。该激光器可应用于大容量波分复用系统和光纤传感。
关键词：光纤激光器； 可切换多波长； 相位调制； 光纤拉锥

0 Introduction

Optical fiber communication system with large capacity and high rate develops rapidly. Wavelength-division-multiplexed communication system gradually demands for more and more channels. Hence, stable power and wavelength C-band multi-wavelength erbium-doped fiber laser as multi-wavelength light source has attracted much interest. In order to suppress the mode competition owing to the homogeneous broaden line in erbium-doped fiber at room temperature[1], a common method is to immerse the erbium-doped fiber in liquid nitrogen (at 77 K)[2]. To date, several approaches have been reported, including acousto-optic frequency shifter feedback technique[3], nonlinear optical loop mirror (NOLM)[4], nonlinear polarization rotation (NPR)[5], and special structure erbium-doped fiber such as dual-core erbium-doped fiber [6] or elliptic-core erbium-doped fiber[7]. However, methods mentioned above need high-frequency driving source, higher power level or complex fabrication technique. Another key component of the multi-wavelength laser is multichannel wavelength selective filter, such as fiber gratings[8-10], Fabry-Perot etalon[11], Mach-Zehnder interferometer[12], acousto-optic filter[13]. Nevertheless, these devices are generally not all-fiber structure and have a high insertion loss, which don't facilitate to integrate and all-fiber connect. Additionally, researchers found that some lasers have tunable properties, i.e., the lasing light can switch from one wavelength to another wavelength, or output multiple wavelengths at the same time[14-17]. This type of tunable multi-wavelength lasers are useful for sensing and instrument testing.

In this paper, an all-fiber switchable multi-wavelength erbium fiber laser (MEFL) is proposed and demonstrated. A sinusoidal phase modulator composed of a piece of single-mode fiber around a piezoelectric transducer is inserted in the ring cavity, combined with an all-fiber Mach-Zehnder interferometer (MZI) based on cascade in-line two-taper as the comb filter, which suppresses the mode competition owing to the homogeneous broaden line in erbium-doped fiber and eliminates the unstable wavelength lasing. Simultaneous and stable five-wavelength lasing is observed at room temperature. The switchable property of one, two, three or even more wavelengths by adjusting the driving signal and polarization controller which balance the gain and loss of different wavelengths can also be realized. This type of MEFL is simple, stable, cost-effective, and the multi-wavelength switchable property is highly flexible.

1 Experimental setup and principle

An experimental MEFL system was set up using the design shown in Fig.1. A piece of 2 m laboratory-made erbium-doped fiber (EDF), whose absorption coefficient is 16 dB/m at 1 530 nm, pumped from the 980/1 550 nm wavelength division multiplexer (WDM) coupler provided the linear gain for all the lasing lines. The isolator ensured the unidirectional operation in the ring cavity. The laser power was coupled out using a 95:5 coupler that provides 5% for output and 95% for feedback inside the cavity. The spectral characteristics were monitored through an ANDO AQ6317C optical spectrum analyzer (OSA) with a resolution of 0.01 nm. The all-fiber in-line two-taper MZI was made of a standard single mode fiber (SMF), which reshaped the net gain profile in the cavity. A 9.5 m SMF around a cylindrical piezoelectric transducer (PZT) that was driven by a variable frequency sine-wave driving signal played a role as the phase modulator. The outside diameter of PZT is

44 mm, inner diameter 39 mm, length 38 mm and resonance frequency 20 kHz. Sine-wave driving signal was generated by Agilent3312A signal generator (SG) and amplified by TEGAM2340 power amplifier (HVA). The full-power bandwidth of HVA is from DC to 200 kHz. The polarization controller (PC) was used to continuously adjust the polarization state of lasing emissions.

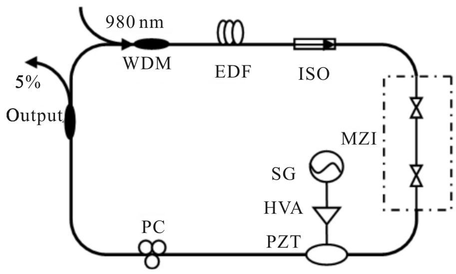


Fig.1 Experimental setup of the switchable MEFL

The in-line two-taper MZI filter is realized by concatenating two abrupt tapers made of standard SMF, plays a role as the comb filter. Two tapers can be considered as the fiber beam combiner/splitter. The core and cladding of the SMF between two tapers are equivalent to two asymmetric interference arms. As shown in Fig.2, at first, the optical signal launches into the first taper region. As the coating of the fiber between two tapers is stripped, the core mode is partly coupled to the cladding modes which can propagate along the jacket-off SMF. Then passing through the second taper region, part of excited cladding modes are coupled back to the core mode. Owing to the different propagation constants between the core mode and the excited cladding modes, a multiple-mode-interferences pattern is observed in transmission spectrum of the in-line two-taper MZI. The transmission spectrum is close to a periodic function of wavelength and the spacing of the comb filter is given by $\Delta\lambda=\lambda^2/\Delta n_{\rm eff}L$. $\Delta n_{\rm eff}$, L and λ are the effective refractive index difference between core and cladding modes, the interferometer length, and the input wavelength in vacuum, respectively. By selecting the appropriate interferometer length, the free spectral range can be designed in line with the International Telecommunication Union (ITU) standard. In the present experiment, the two same abrupt fiber tapers with a typical waist diameter D_t of 40 μm and a taper length L_t of 600 μm, were fabricated in a standard Corning SMF-28 fiber by an Ericssion fusion splicer (FSU-952) using electric arc method. The length of the jack-off SMF (the interferometer length) was 60 cm, corresponding to a free space range (FSR) of 0.806 nm.

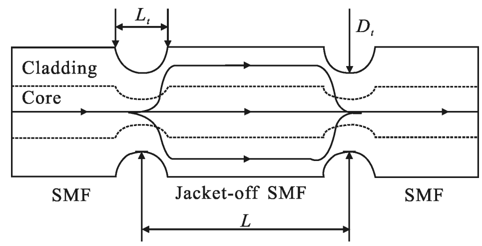


Fig.2 Schematic of an in-line two-taper MZI

A piece of SMF around a cylindrical PZT driven by a variable frequency sine-wave driving signal plays a role as the phase modulator. When periodic sinusoidal modulation is applied to PZT, the phase of the light signal (angular frequency ω_0) in the fiber changes cyclically of the form $\Phi(t)=\eta\cos(\omega_m t)$, where $\omega_m=2\pi/T$ is the angular frequency of the modulation signal and η is the modulation amplitude. Then the modulated signal can be expanded by Fourier series to contain $\omega_0+k\omega_m$ frequency components, $k=0,\pm1, \pm2, \cdots$. The square of the absolute value of Fourier coefficients $|c_k|^2=|J_k(\eta)|^2$ are the intensity component that correspond to the frequency $\omega_0+k\omega_m$, and $J_k(\eta)$ are Bessel functions of the first kind of order k. Therefore, the phase modulation has a frequency shift effect for optical signal. The signal frequency shifts from ω_0 to $\omega_0+\omega_m$, $\omega_0+2\omega_m$, $\cdots$. Meanwhile the phase modulator transfers the energy on one wavelength corresponding to J_0 to other wavelengths corresponding to J_1, J_2, $\cdots$. The modulation amplitude determines the relative magnitude of J_0, J_1, J_2 and so on. So it balances the gain and loss of different wavelengths and suppresses the invariable loss caused by the mode competition, which is beneficial to realize stable multi-wavelength outputs at room temperature.

2 Experimental results and discussion

The amplified spontaneous emission (ASE) light source as a broadband light source, and the filter characteristics of the laboratory-made in-line two-taper MZI are measured by OSA. As shown in Fig.3, the spectrum presents obvious comb filter features with FSR of 0.806 nm. By changing the length of the jack-off SMF, the FSR can be free designed. Reduce the fluctuation of tapered region and keep the cone flat will reduce the excess loss of the filter. However, the sinusoidal band-pass shape needs further consideration for improvement by reasonable optimization to get flat-topped band-pass comb filter.

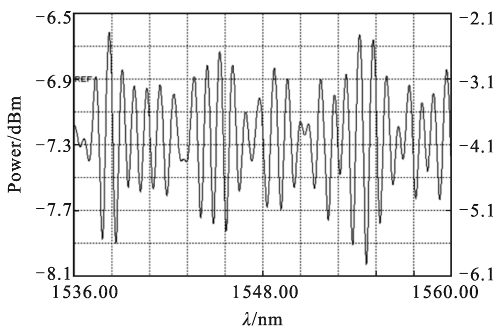
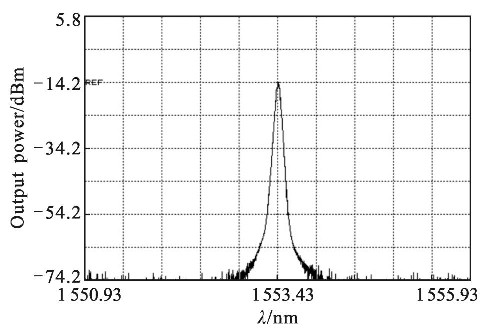
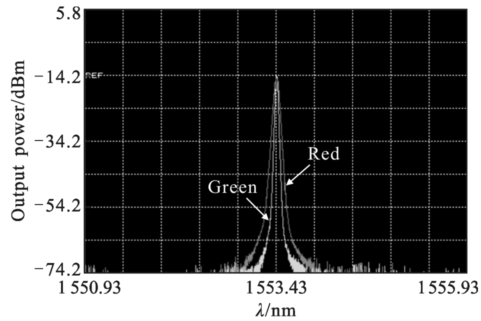


Fig.3 Spectrum of comb filter

Figure 4(a) shows the measured optical spectrum of the laser when the phase modulator is switched off. Without the phase modulation, it generates a single wavelength lasing. The lasing wavelength is 1 554.432 nm with a 3 dB bandwidth of 0.061 nm and signal-to-noise ratio (SNR) of over 50 dB. Although the polarization hole burning effect can suppress the mode



(a) With phase modulator OFF



(b) Before and after 5 kHz, 25 V sine phase modulation

Fig.4 Experimentally measured spectrum

competition to a certain extent by adjusting the PC in the cavity, the multi-wavelength outputs are unstable and spectral intervals are not uniform. Then we add 5 kHz, 25 V sine phase modulation signal, the 3 dB bandwidth of the single wavelength lasing narrows significantly, approximately of 0.031 nm. Fig.4(b) is the comparison chart captured by OSA. The red and green channels are before and after we add phase modulation, respectively. The 3 dB bandwidth is compressed nearly 50%.

As shown in Fig.5 (a), increase the driving voltage to 45 V and keep the modulation frequency of 20 kHz which is the resonant frequency of the PZT, homogeneous line broadening of the gain medium is effectively suppressed. Owing to increasing the modulation frequency, lasing wavelengths deviate faster from the peak wavelengths of comb filter as through PZT each time, which is equivalent to balance the loss in the cavity. Meanwhile the 3 dB bandwidth is effectively compressed. The laser generates simultaneous and stable five lasing wavelengths that occur at 1 551.818 nm, 1 552.623 nm, 1 553.426 nm, 1 554.230 nm, and 1 555.033 nm corresponding to the peak wavelengths of the comb filter with the average 3 dB bandwidth of 0.023 nm, wavelength intervals of about 0.804 nm and SNR of over 40 dB. The wavelength of output multi-wavelength lasing could be tuned by bending the two tapers of MZI filter[18]. By changing the interferometer length, the channel-spacing can be adjusted. In the center, 5 lasing lines in power differences are less than 14 dB. The flatness of the output spectrum depends on many factors, such as the flatness of the comb filter, the length of the EDF and so on. Accordingly, in theory we can obtain more lasing wavelengths through reasonable optimization of the flatness of output spectrum. In the experiment it requires a high driving voltage that may due to the large loss in the cavity, and the spectral extinction ratio of the comb filter is not high enough also should be considered. The most effective and practical method is to reduce the fluctuation of tapered region and keep the cone flat, which will reduce the excess loss of the filter. Compared Fig.5 (a) to Fig.4, the average peak power of five wavelengths is significantly lower than the single wavelength with the same pump power. In order to validate the stability of the MEFL, we measure the peak power and wavelength of each lasing for half an hour with a time interval of one minute. The results are recorded in Fig.5 (b) and (c). The output power fluctuation at each peak wavelength are less than 0.86 dB and the wavelength shift of each lasing are less than 0.02 nm, which indicates a good long-time output power stability and wavelength stability of the MEFL at room temperature.

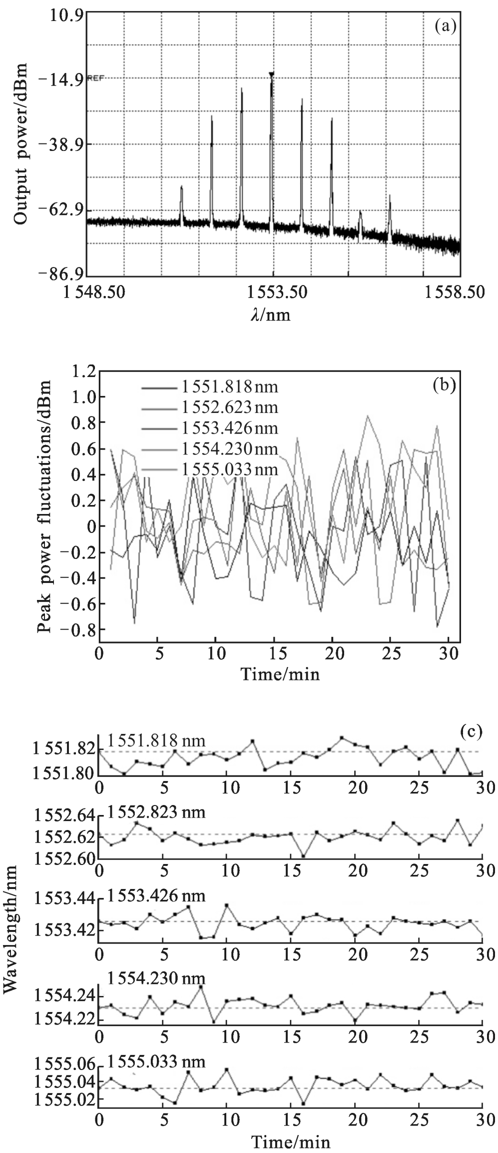
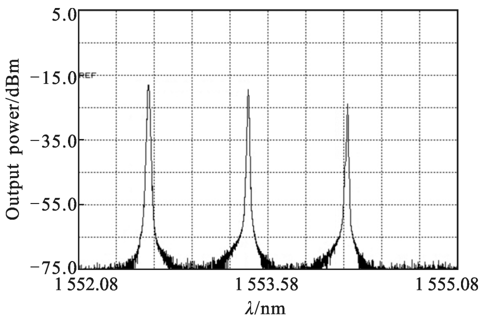
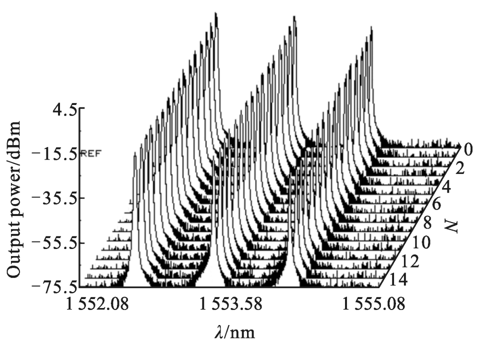


Fig.5 (a) Stable five wavelengths lasing with modulation frequency 20 kHz and driving voltage 45 V. (b) Power stability: the fluctuations of each peak power. (c) Wavelength stability: the shifts of each peak wavelength

From the theoretical analysis and experimental results above, it suggests that this design could realize one, two, three...up to five wavelengths lasing output by adjusting the modulation signal and polarization state. Optimize the experimental conditions, simultaneous more wavelengths lasing could be realized. Adjusting the PC in the cavity to make one wavelength lasing corresponded to one polarization state has overlarge cavity loss, then leading to the wavelength lasing which has overlarge cavity loss being suppressed. In the meantime, the utilization of frequency shift effect of the phase modulator guarantees stability of a variety of laser output. It could achieve stable switching at multi-wavelength lasing state. We take triple-wavelength lasing state for example. Set the frequency of modulation signal at 20 kHz and keep the drive voltage of 25 V. As shown in Fig.6 (a), there are three lasing wavelengths at 1 552.621 nm, 1 553.423 nm and 1 554.222 nm with a average 3 dB bandwidth of 0.021 nm, wavelength intervals of about 0.801 nm and SNR of over 45 dB. Sixteen successive scans of the system output with a time interval of one minute are carried out and the result is recorded in Fig.6(b), which indicates a good long-time power and wavelength stability of the state. The output power fluctuation at each peak wavelength are less than 0.73 dB and the wavelength shift of each lasing are less than 0.012 nm. Then we adjust the polarization state in the cavity, as shown in Fig.7, any lasing of one wavelength position in the triple-wavelength state could be suppressed alone, dual-wavelength lasing in different positions can be observed with the average 3 dB bandwidth of 0.023 nm and SNR of over 48 dB. Sixteen successive scans of the system output with a time interval of one minute are also carried out. As can be seen in the figure, even switching to different output states, the MEFL still maintain good stability at room temperature. In addition, the realization of switchable property of more wavelengths lasing state needs more subtle adjustment of polarization state.

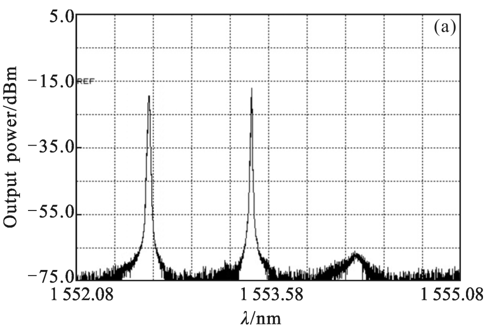


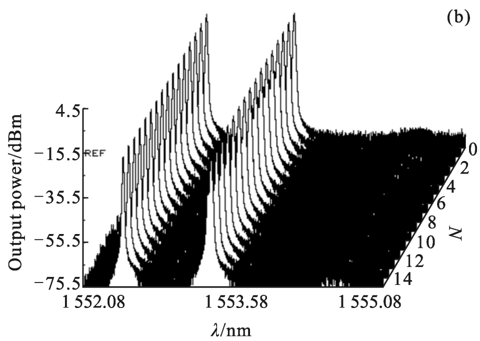
(a) Optical spectrum

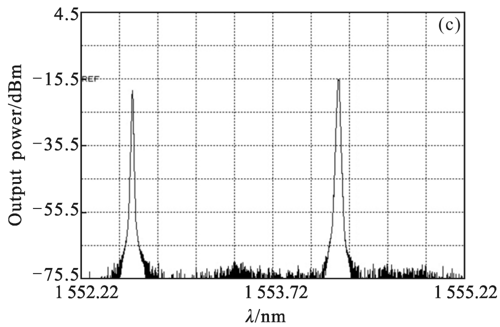


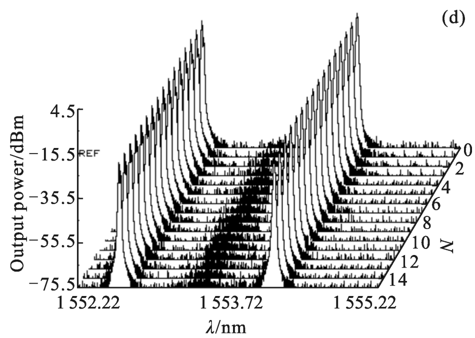
(b) Spectral stability

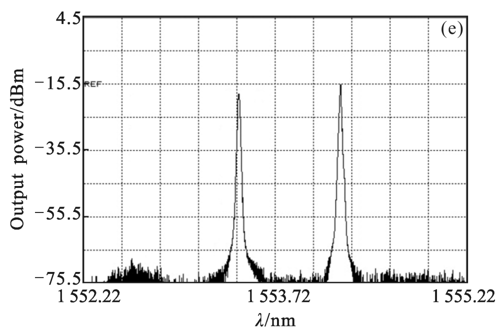
Fig.6 Three wavelengths lasing of MEFL with modulation frequency 20 kHz and driving voltage 25 V











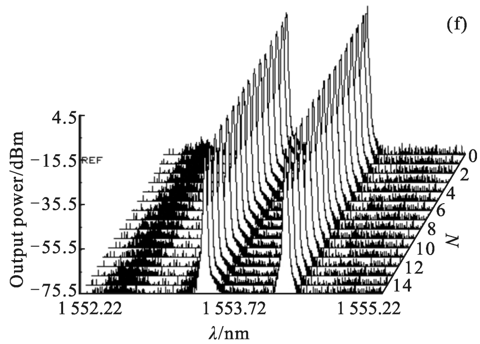


Fig.7 Switchable properties of three wavelengths lasing of MEFL (a),(c),(e) Optical spectrum. (b),(d),(f) Spectral stability

3 Conclusion

We proposed a room-temperature switchable multi-wavelength fiber ring laser in this paper. It used a MZI based on cascade in-line two-taper as the comb filter and a piece of single-mode fiber around a PZT driven by sine-wave signal as the sinusoidal phase modulator. Set modulation frequency at 20 kHz and drive voltage of 45 V, simultaneous five-wavelength lasing with 0.804 nm spacing that was anchored on ITU standard has been generated stably at room temperature, whose peak power differences were less than 14 dB. The SNR was higher than 40 dB, the 3 dB bandwidth which was compressed nearly 50% under the phase modulation was about 0.023 nm. Further bring in partial polarization dependence property, by adjusting the modulation signal and polarization state, single wavelength lasing output, switchable dual, triple and ever more wavelengths lasing output could be realized. Experiment demonstrates the switchable wavelength property of triple-wavelength lasing output state. Even switching to different output states, the MEFL still maintains good stability.

The proposed laser has the advantages such as simple all-fiber configuration, flexibility in channel-spacing and wavelength tuning, narrow bandwidth, and highly flexible wavelength switchable property. These advantages enable this MEFL as a potential candidate for high-capacity WDM systems and mechanical sensors.

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