Tunable multiwavelength fiber laser using a comb filter based on erbium-ytterbium co-doped polarization maintaining fiber loop mirror

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Abstract: A tunable comb filter based on a fiber loop mirror setup, which incorporates a piece of pumped erbium-ytterbium co-doped polarization maintaining fiber, is newly presented. It is accomplished by controlling the pump power or adjusting a polarization controller in the loop mirror, which results from the fact that the effective birefringence of the erbium-ytterbium co-doped polarization maintaining fiber depends on the pump power and polarization state of the traversing signal. By using the proposed comb filter, a continuously tunable multiwavelength fiber ring laser in the L-band is successfully demonstrated.

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1. Introduction

Multiwavelength lasers are of considerable interest due to their potential applications in test and measurement, optical sensing and optical communications [1-4]. Many research groups have been investigating multiwavelength fiber lasers by employing a variety of comb filters, which incorporate an erbium-doped fiber with suppressed homogeneous gain broadening [5] or a semiconductor optical amplifier (SOA) as the gain medium [6, 7]. For practical applications, tunability is often required of multiwavelength fiber lasers, for which many techniques have been implemented, such as fiber Bragg gratings subject to axial strain [8] and unbalanced Mach-Zehnder interferometer driven by electronic signal [9]. However, the fiber Bragg grating is fragile and easily destroyed during a long-time run. The Mach-Zehnder interferometer is prone to environmental perturbation, which may induce unexpected shift of the lasing wavelengths.

Recently, a fiber loop mirror incorporating a piece of polarization maintaining fiber (PMF) has attracted much attention as an optical comb filter due to its intrinsic advantages such as easy fabrication, stability and flexibility. The device can be tuned by adjusting the effective birefringence of the loop arm, which can be accomplished by adjusting the polarization controllers (PCs) in cascaded sections of PMFs and PCs [10]. The comb filter can also be tuned by changing the operating temperature [11] or applying axial strain to the PMF. Besides these, an active device such as a phase modulator [12] or SOA [13] is also inserted in the fiber loop mirror to tailor the effective birefringence of the loop, which enables continuous shift of the transmission comb spectrum. Tunable multiwavelength fiber lasers have been obtained based on these approaches [11, 12].

In this work, we demonstrate a novel concept of tunable transmission comb filter based on a pumped erbium-ytterbium co-doped polarization maintaining fiber (EYD-PMF) loop mirror. Unlike the passive single-mode PMF, effective birefringence of the EYD-PMF depends on the pump power and the polarization state of the traversing signal [14, 15]. As a result, the comb filter can be tuned by changing the pump power or adjusting a PC adjacent to the EYD-PMF in the loop. Based on the proposed technique, an L-band tunable multi-wavelength SOA-based fiber ring laser is successfully demonstrated at room temperature.

2. Experimental configuration and operational principle

Figure 1 illustrates the experimental setup of our proposed tunable multiwavelength SOA-based fiber ring laser in the L-band. It is composed of two SOAs (SOA_1 and SOA_2) as the gain media and a fiber loop mirror as the all-fiber comb filter. The fiber loop mirror is constructed by connecting a polarization controller (PC_1) and a piece of EYD-PMF to the two ports on the same side of a 3-dB optical coupler (OC_1). The EYD-PMF is pumped by a 980-

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nm laser diode (LD) through a 980/1550 nm wavelength division multiplexing (WDM) coupler. Another polarization controller (PC_2) and an 80/20 optical coupler (OC_2) are also inserted in the ring cavity for output coupling. In addition, two optical isolators (OIs) are used to force the unidirectional operation of the ring cavity. Moreover, OI_1 prevents the amplified spontaneous emission of the SOA_2 into the fiber loop mirror and OI_2 prevents the optical power reflected by the fiber loop mirror into the SOA_1. All connection points in the cavity are fusion-spliced together except that between the OC_2 and SOA_2.

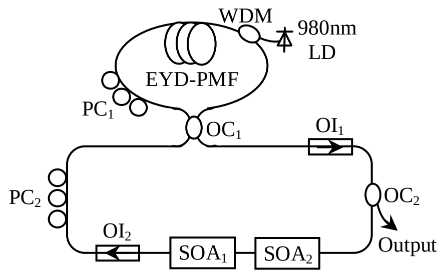

Fig. 1. The experimental setup of our proposed L-band tunable multiwavelength fiber ring laser.

The conventional PMF loop mirror including one PC can act as a transmission comb filter, in which the input light is split into two beams counter-propagating along the loop arm. The polarization states of the two beams are altered by the PC. However, the two beams traverse the cascaded PMF and PC in opposite directions. Consequently, they experience different phase delays and the phase difference is proportional to the product of the PMF length and the effective birefringence, which induces constructive or destructive interference when they are recombined at OC_1. Therefore, the spectral response of the loop mirror is similar to an unbalanced Mach-Zehnder interferometer, but the stability is enhanced since the two beams involved travel the same fiber. For an undoped single-mode PMF, the birefringence hardly depends on the polarization state of the input signal. Accordingly, the PC state has negligible effect on the peak and dip wavelengths in the transmission spectrum of the undoped single-mode PMF loop mirror although it affects the transmission level [16]. In contrast, the effective birefringence of a pumped EYD-PMF depends on the pump power and polarization state of the traversing signal. It is attributed to the fact that the effective refractive index of the fast or slow axis in the EYD-PMF can be changed by absorbing the signal or pump components polarized along the respective axis. In return, the traversing signals with different polarization states will experience different phase delays. A similar statement can be made if the pump power for the EYD-PMF is varied. It follows that the transmission comb spectrum of the loop mirror can be shifted by rotating the PC adjacent to the EYD-PMF or by adjusting the pump power.

3. Experimental results and discussions

The EYD-PMF used in our experiment is a commercial fiber (EYD-PMF 7/130) made by Nufern Company with core erbium absorption coefficient 30 dB/m near 1530 nm, cladding ytterbium absorption 0.60 dB/m near 915 nm. Its birefringence is measured to be $\sim 7.1\times10^{-5}$ near 1600 nm. Considering the low birefringence of the EYD-PMF, a comparatively longer EYD-PMF length is used to obtain narrower comb spacing of the fiber loop mirror. Due to the high absorption coefficient of the EYD-PMF, two SOAs were needed to achieve laser output.

During the measurements in our experiment the bias current and controlled temperature of the SOA_1 and SOA_2 are both fixed at 200 mA and 25 °C, respectively. The SOA_1 and SOA_2 are the same. Their gain is 28.7 dB and polarization sensitivity 0.5 dB at 1550 nm. The saturated output power is 9.6 dBm. Figure 2 illustrates the amplified spontaneous emission

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spectra of one SOA and two cascaded SOAs by use of an optical spectrum analyzer with 0.1-nm resolution. Obviously, the gain peak of two cascaded SOAs is red-shifted compared with that of one SOA.

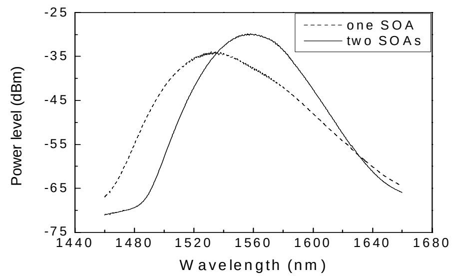

Fig. 2. Optical spectra of the amplified spontaneous emissions for one SOA and two cascaded SOAs.

To illustrate the tunable properties of the EYD-PMF loop mirror as described above, we first disconnect the joint between the OC_2 and SOA_2, and then add the outputs measured from the two ports of the OC_2. Figure 3 shows the comb spectrum under different settings of PC_1 without pumping the EYD-PMF. Obviously, the comb spacing is about 10 nm with 3.6-m EYD-PMF and 3.6 nm with 10-m EYD-PMF. It can be seen that the spectrum can be continuously tuned with the tunable range as large as the comb spacing irrespective of the EYD-PMF length. For the 3.6-m EYD-PMF, the comb spectrum can be observed at wavelengths longer than 1550 nm. It is ascribed to the fact that the amplified spontaneous emission power from the two SOAs at wavelengths shorter than 1550 nm is strongly absorbed by the EYD-PMF. On the other hand, for the 10-m EYD-PMF, the comb spectrum can be observed at wavelengths longer than 1570 nm and peak powers of the comb spectrum drop down compared with that for the 3.6-m EYD-PMF. The common characteristic between the two cases is that the peak powers vary with the setting of the PC_1 since the transmission level of the PMF loop mirror depends on the PC state [16]. It is worth mentioning that adjusting PC_2 only has little impact on the comb spectrum, which contributes to elimination of the potential instability of the laser output arising from the use of a polarization-dependent filter in the cavity.

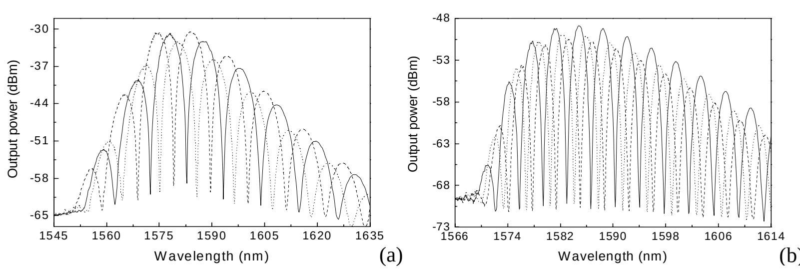

Fig. 3. Measured output spectra under different settings of the PC_1 with (a) 3.6 m; (b) 10 m EYD-PMF.

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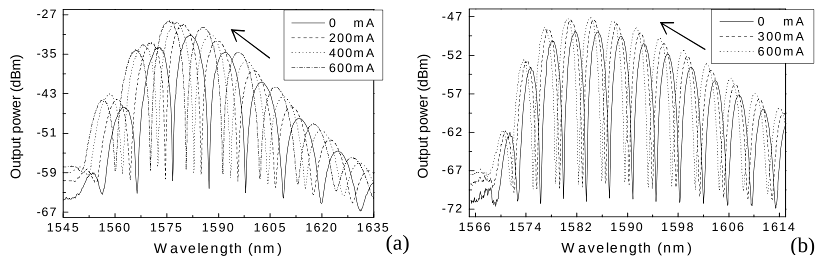

Fig. 4. Measured output spectra under different injection currents for the 980 nm LD with (a) 3.6-m EYD-PMF and (b) 10-m EYD-PMF.

As pointed out in a previous work [17], the refractive index of the erbium-ytterbium co-doped fiber decreases with the pump power. Based on this observation, it follows that adjustment of the pump power or the pump polarization along the fast and slow axes of the EYD-PMF can shift the comb spectrum of the fiber loop mirror. In the absence of a polarizer working at 980 nm, we changed the injection current of the 980-nm LD to tune the comb spectrum as illustrated in Fig. 4. It can be seen that the comb spectrum shifts toward the short wavelength with increase of the pump power. For the 3.6-m EYD-PMF, the amount of the comb spectrum shift can reach 6.3 nm, which is limited by the attainable injection current of the pump LD, at a step of 2.1 nm per 200 mA. However, the shift is smaller for the 10-m EYD-PMF. The reason may be that the pump power is not sufficient to bleach the 10-m EYD-PMF. As a result, the average refractive index changes along the fast and slow axes are small.

Compared with the previously proposed tunable comb filters reported in Refs. 10 and 11, our proposed fiber loop mirror provides better characteristics such as simple configuration and easy tunability. It is not necessary to incorporate other devices in the loop mirror except the EYD-PMF since the effective birefringence of the loop arm can be directly controlled through the EYD-PMF. Of course, the tunability can be improved by substituting an electronically controlled PC using lithium niobate [18] for the mechanically controlled PC_1 for more precise and rapid tuning. A cascaded optical polarizer and PC at 980 nm can be used to change the polarization state of the pump source on demand. Therefore, the refractive indexes of the fast and slow axes can be individually or simultaneously changed. It follows that the comb spectrum can be flexibly tuned with reduced pump power. For example, increase of the pump power polarized along the fast or slow axis in the EYD-PMF red- or blue-shift the comb spectrum, respectively. Furthermore, the comb spacing also can be varied provided the pump power polarized along the primary axes of the EYD-PMF is sufficiently high.

Now we connect the OC_2 and SOA_2. Using the 10-m EYD-PMF loop mirror as the comb filter, a tunable multiwavelength fiber ring laser in the L-band is realized. The laser output spectra are depicted in Fig. 5, which clearly shows that the multiwavelength oscillation is successfully obtained. The tuning range is the same as the comb spacing in case PC_1 is adjusted (Fig. 5(a)) and 1.1 nm in case the injection current of the 980 nm LD is varied between 0 and 600 mA (Fig. 5(b)). Comparing Figs. 4(b) and 5, it is obvious that the lasing wavelengths are longer than the peak wavelengths in the transmission spectra of the fiber loop mirror. It is attributed to the fact that the transmission peak of the fiber loop mirror shifts toward the longer wavelength due to the inherent absorption property of the EYD-PMF when the traversing signal in the EYD-PMF is increased as it evolves from the amplified spontaneous emission to lasing state.

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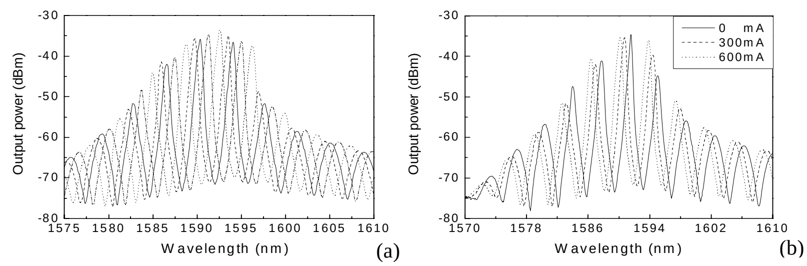

Fig. 5. The output spectra shift of the tunable multiwavelength fiber ring laser: (a) different settings of PC_1 with 600 mA injection current for the 980 nm LD; (b) different injection currents for the 980 nm LD with PC_1 fixed.

Finally, we investigate the operation stability of the proposed fiber laser. After optimally setting the states of PC_1 and PC_2, a flatter output spectrum can be obtained as shown in Fig. 6(a). There are three lasing lines with the power difference less than 2 dB and side-mode suppression ratio larger than 35 dB. The output power fluctuation is within ±0.5 dB for all lasing wavelengths as shown in Fig. 6(b), which may originate from the gain fluctuation of the SOAs. Since the birefringence of the EYD-PMF is low, a long length is used to reduce the comb spacing of the proposed fiber loop mirror and thus to increase the number of the lasing lines. On the other hand, while the large absorption coefficient of the EYD-PMF implies increased cavity loss and thus limitation on the number of the lasing wavelengths, it can also induce larger refractive index change with the pump power [19]. Hence, a compromise should be made between the birefringence and absorption coefficient of the EYD-PMF for obtaining the maximum number of lasing wavelengths and broader tuning range with reduced pump power.

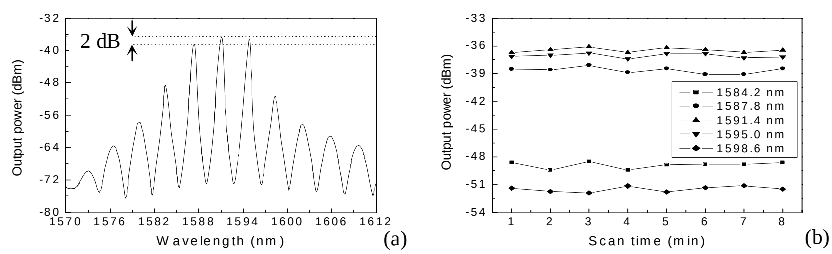

Fig. 6. (a) The optimal output spectrum of the fiber laser with 600 mA injection current for the 980 nm LD; (b) Repeated scans of the output power at lasing wavelengths at time interval of 1 minute.

Employing the fiber loop mirror structure as the optical filter, the stability of the fiber ring laser is potentially improved over competing techniques. Although the number of lasing wavelength is small and the flatness has room for improvement, which can be achieved by optimizing the properties of the used EYD-PMF as analysis above for practical optical communication or sensor application. On the other hand, fiber ring lasers based on the gain medium of erbium-doped fiber can offer other configurations of multiwavelength fiber lasers [3-5]. To overcome the predominantly homogenous line broadening at room temperature, the additional techniques must be used such as frequency shifter [5], highly nonlinear photonic crystal fiber [3, 4]. Obviously, our multiwavelength fiber lasers are much simpler and more stable due to the fact that the SOA is an inhomogeneous gain medium. Therefore, our configuration of tunable multiwavelength fiber lasers can find more potential applications.

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4. Conclusion

We propose and experimentally demonstrate in this work a novel configuration of continuously tunable multiwavelength fiber ring laser in the L-band by use of an EYD-PMF based fiber loop mirror. By adjusting the PC next to the pumped EYD-PMF in the loop mirror, the lasing wavelengths can be tuned over the comb spacing. In addition, the lasing wavelengths also can be shifted by controlling the pump power. It has been shown that the laser output stability is significantly improved by employing the loop mirror setup of the tunable comb filter. The proposed technique provides an alternative solution for making a tunable multiwavelength laser source.

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