Multi-wavelength Erbium-doped Fiber Laser with Tunable Wavelength Spacing

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Abstract: We demonstrate a stable multi-wavelength ring cavity erbium-doped fiber laser in this paper. A fiber Michelson interferometer is inserted into the ring laser cavity acting as a multi-wavelength filter to realize multi-wavelength operation. The optical path difference of the two arms of the fiber Michelson interferometer is tunable by changing the optical delay line. Thus, the wavelength spacing of the multi-wavelength laser is tunable by tuning the optical delay line in the Michelson interferometer. Eventually, the tunable range of the wavelength spacing is realized from 0.045 nm to 0.7 nm in our experiments. More than 60 wavelengths within 3 dB flatness with wavelength spacing of 0.0474 nm can be achieved.

1 INTRODUCTION

Multi-wavelength laser has found a lot of applications in many filed, such as optical communication, optical fiber sensing, laser measurement, optical component testing and so on (Liu et al., 2011; Salvadé et al., 2008), and many efforts have been made to obtain high-quality multi-wavelength laser. There are two issues to deal with to obtain stable multi-wavelength laser with erbium-doped fiber as the gain medium. Firstly, the erbium-doped fiber laser suffers from homogenous line broadening and cross-saturation in the room temperature which could lead the unstability of the multi-wavelength laser (Yao et al., 2004). Many approaches have been developed to suppress the homogenous line broadening in erbium-doped fiber to obtain stable multi-wavelength laser. For example, cooling the erbium-doped fiber in the liquid nitrogen was proved to be an effective method (Yamashita and Hotate, 1996); Utilizing the nonlinear effects, like stimulated Brillouin scattering or four wave mixing in the fiber, has achieved good results in obtaining multi-wavelength erbium-doped fiber laser (Al-Mansoori et al., 2005, Pan et al.,2006; Xu et al., 2008). Secondly, in the multi-wavelength erbium-doped fiber laser, the multi-wavelength filter is a very important component. Many kinds of multi-wavelength filters are adopted in the multi-wavelength lasers, such as multi fiber Bragg grating (Han et al.,2006), Fabry-Perot cavity (Al-Alimi et al., 2018; Qin et al.,2006), programmable optical filter (DeMiguel-Soto et al.,2014), Lyot-Saganc loop with polarization maintaining fiber (Kim and Kang, 2004; Sugavanam et al., 2014), chirped fiber Bragg grating (Dong et al., 2006) and so on. In some applications, like upgradable optical communication systems, tunability of multi-wavelength laser is very important. For the most widely studied multi-wavelength fiber laser using Lyot-Saganc loop filter consisting of a piece of birefringence fiber, the wavelength spacing is fixed once the length of the birefringence fiber is selected (Wang et al., 2013, Zhang et al., 2008). For the Brillouin-erbium multi-wavelength laser, the wavelength spacing is still fixed by the Brillouin shift and the narrow Brillouin gain bandwidth. Although a wavelength spacing switchable multi-wavelength Brillouin erbium fiber laser was realized utilizing cascaded Brillouin gain fibers, the wavelength spacing is limited by the narrow bandwidth of the stimulated Brillouin scattering (Wang, et al., 2016). A wavelength spacing tunable multi-wavelength laser was demonstrated by using superimposed chirped fiber Bragg grating (Dong et al., 2006). Mach-Zehnder optical fiber interferometer is also demonstrated to be useful in a wavelength spacing tunable multi-wavelength laser (Chen et al., 2007).

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In this paper, we demonstrate a new multi-wavelength erbium-doped fiber laser with tunable wavelength spacing. A tunable Michelson fiber interferometer consisting of an optical delay line is inserted into the ring laser cavity to act as a continuous tunable multi-wavelength filter. Meanwhile, a nonlinear polarization rotation (NPR) structure combined with a piece of long dispersion shift fiber is introduced into this laser to suppress longitudinal mode competition based on its intensity-dependent loss feature. By tuning the optical delay line, the tunability of the wavelength spacing can be realized from 0.045 nm to 0.7 nm continuously. More than 60 wavelengths within 3 dB flatness with wavelength spacing of 0.0474 nm can be achieved.

2 EXPERIMENTAL SETUP

Figure 1(a) shows the schematic configurations of the spacing-adjustable multi-wavelength erbium-doped fiber laser. A 1480 nm laser diode (LD) is connected to a wavelength division multiplexer (WDM) to pump a piece of 2.1 m erbium-doped fiber. The maximum output power of the 1480 nm LD is ~283 mW. A piece of 5 km dispersion shift fiber (DSF) is inserted into the laser cavity to enhance the nonlinear effect. The 10% arm of a 10 dB coupler is used as the output port of the multi-wavelength laser. A polarization dependent isolator and two polarization controllers (PCs) constitute a Nonlinear Polarization Rotation structure (NPR). A fiber Michelson interferometer is inserted into the laser cavity to act as the multi-wavelength filter and realize multi-wavelength operation of the laser. The schematic configuration of the spacing-adjustable Michelson interferometer is shown in the red dashed box in Fig.1 (a). The Michelson interferometer consists of a 3 dB coupler, a tunable optical delay line (ODL) and two wide band optical reflectors (ORs). The mechanism of the Michelson interferometer can be understood as following: The input laser splits into two parts with the same amplitude in the 3dB coupler; The two laser beams propagate forward and are reflected back by the wideband optical reflectors and then interfere with each other in the 3 dB coupler. The interference results in the comb filtering effect due to the different optical path of the two arms. There is a tunable ODL inserted into one arm of the fiber Michelson interferometer, which makes the optical path difference tunable. The Schematic diagram of the optical delay line is shown in Fig.1 (b). The ruler of the ODL marks the position of the corner cube mirror in the ODL. When changing the ODL ruler reading to a position that makes the two arms of the Michelson interferometer have the same length, the optical path difference is zero. The wavelength spacing of the transmission peaks of the Michelson interferometer can be calculated by:

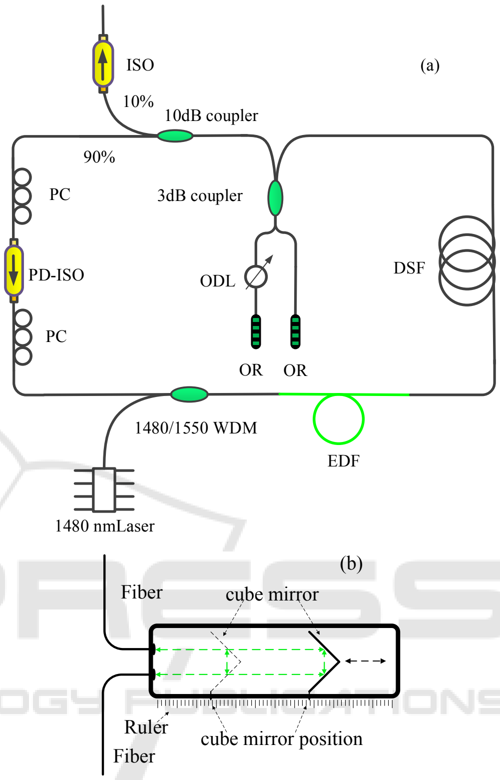

Figure 1: (a) Schematic diagram of the tunable multi-wavelength laser with Michelson interferometer. EDF: erbium-doped fiber; DSF: dispersion shift fiber; ODL: optical delay line; OR: optical reflector; PD-ISO: polarization dependent isolator; PC: polarization controller. (b) Schematic diagram of the optical delay line.

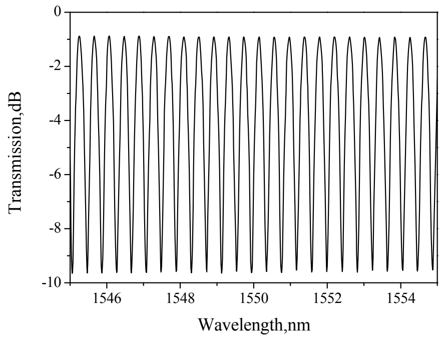

Figure 2: A typical measured transmission spectrum of the fiber Michelson interferometer.

$$\Delta\lambda = \lambda_m - \lambda_{m+1} = \frac{2n\Delta L}{m} - \frac{2n\Delta L}{m+1}$$

$$= \frac{2n\Delta L}{\frac{2n\Delta L}{\lambda_m} * \frac{2n\Delta L}{\lambda_{m+1}}} = \frac{\lambda_m \lambda_{m+1}}{2n\Delta L} \cong \frac{\lambda^2}{2n\Delta L} \qquad (1)$$

Where λ is the central wavelength, n is the refractive index of air which is near to 1 in our case; *ΔL* is the optical path difference introduced by the ODL. As the laser propagates through the ODL twice, there is a coefficient 2 in the formula. A typical measured transmission spectral of the Michelson interferometer using an ASE source is shown in Fig. 2. The value of the transmission peak is -0.9 dB which can be attributed to the loss of the two arms. The transmission spectrum of the Michelson interferometer indicates its great potential to be used as a multi-wavelength filter. The optical path difference of the two arms can be continuously adjusted by tuning the ODL. Therefore, we can realize wide range tuning of the wavelength spacing of multi-wavelength fiber laser by changing the ODL in the Michelson interferometer. The ruler of the ODL marks the position of the corner cube mirror in the ODL. The changing of the optical path introduced by the ODL can be calculated by the reading of the ruler of the ODL. In the measurement of the transmission spectra of the Michelson interferometer, it was found that when the ODL ruler reading is set to ~30 mm the transmission peak spacing become very wide. It means that in this case the optical path difference of the two arms is about zero. When changing the ODL ruler reading to a position that makes the two arms of the Michelson interferometer have the same length, the optical path difference is zero. Moving the ODL ruler reading away from 30 mm leads to the increasing of the optical path difference and the narrowing of the transmission peak spacing. So the ODL ruler reading 30 mm can be deemed as the zero point. As the ruler reading is the position of the corner cube mirror in the ODL, the optical path difference ΔL introduced by the ODL is twice of the difference between the ruler reading and the zero point.

3 RESULTS

In the experiments, wideband, flat and stable multi-wavelength laser can be obtained with correct setting of the polarization controllers and suitable pump power. Once the pump power reaches the threshold, the multi-wavelength output can be achieved by correct setting of polarization controllers.

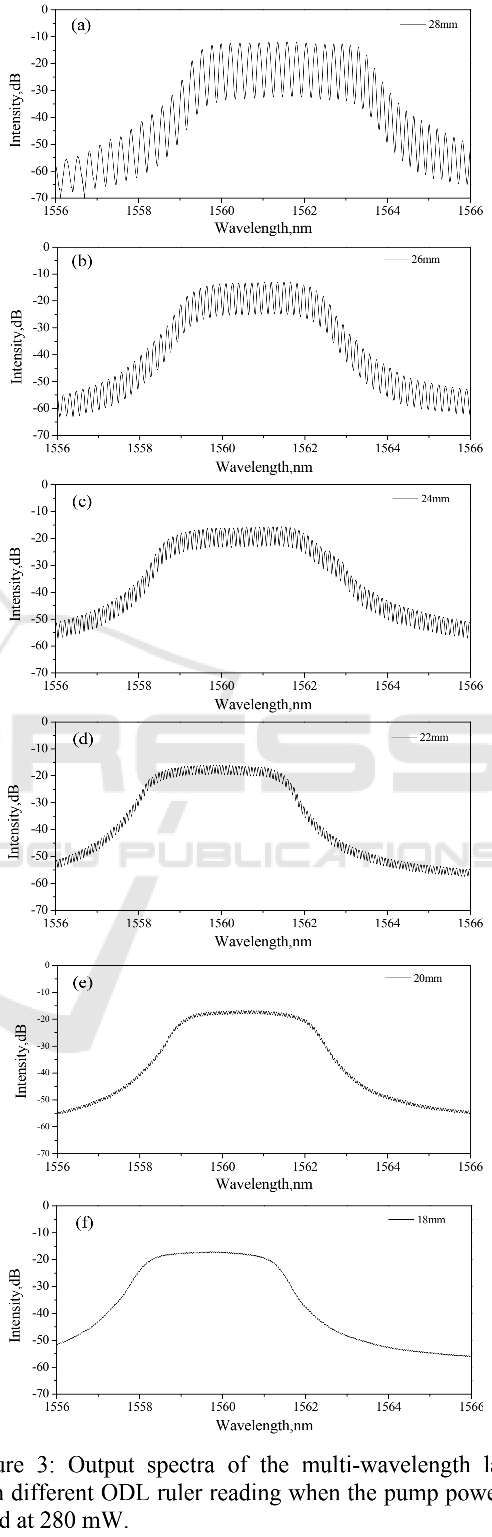

Figure 3: Output spectra of the multi-wavelength laser with different ODL ruler reading when the pump power is fixed at 280 mW.

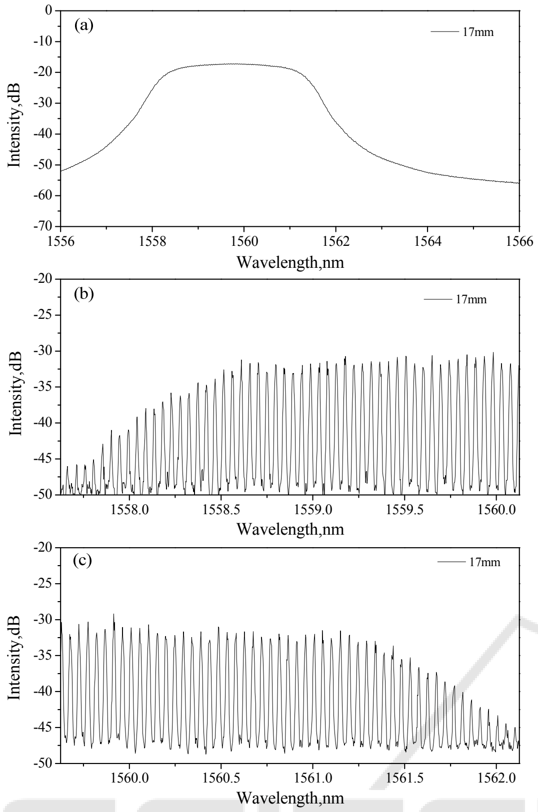

Figure 4: Output spectra of the multi-wavelength laser with ODL ruler reading of 17 mm. (a) Overall spectrum measured by the OSA. (b) and (c) Detailed spectra measured by the HRS.

As we mentioned above, the wavelength spacing of the multi-wavelength laser can be tuned continuously by adjusting the ODL according to formula (1). Figure 3 shows the output spectra of the multi-wavelength laser with different ODL ruler reading. For instance, as shown in Fig. 3(e), the multi-wavelength spacing is ~0.0607 nm. In this case, the ODL ruler reading is 20 mm, the optical path difference ΔL equal to 2*(30mm-20mm) =20mm. When the central wavelength of the laser is about 1560 nm and the optical path difference is 20 mm, from formula (1), the calculated wavelength spacing is ~0.061 nm. The experiment results are in good agreement with the theoretical values. As shown in Fig.3, with different ODL ruler reading, the wavelength spacing of the multi-wavelength laser is different. The larger the ODL ruler reading deviates from 30 mm, the narrower the wavelength spacing is. It can be found that the contrast of the multi-wavelength peaks to the background decreases with the narrowing of the wavelength spacing. We believe it is due to the limited resolution (0.05 nm) of the optical spectral analyzer (OSA, Yokogawa AQ6375B). When the ODL ruler reading is 18 mm, the measured output spectrum of the multi-wavelength laser is shown in Fig. 3(f). In this case, the output spectrum seems very flat and the spectral peaks of the multi-wavelength almost cannot be recognized. When the ODL ruler reading is 17 mm, the measured output spectrum is shown in Fig 4.(a) and the theoretical wavelength spacing calculated with formula (1) is ~0.047 nm. In order to obtain more information about the output spectrum, we used a high resolution spectrometer (HRS, Agilent 83453B) to measure the output of the multi-wavelength laser. The measured spectra are shown in Fig. 4(b) and Fig. 4(c). Obvious spectral peaks with wavelength spacing 0.0474 nm can be observed. About 60 wavelengths are obtained with 3 dB flatness. We believe that increasing the deviation of the ODL ruler reading of the ODL further, the wavelength spacing will become narrower and more wavelengths can be obtained. By tuning the ODL carefully, the wavelength spacing can be adjusted continuously and we can obtain multi-wavelength laser output with any wavelength spacing within the range. We believe that with proper ODL setting and pump power, it is feasible to realize multi-wavelength output with spacing of 0.8 nm which is standard in telecommunication. In the experiment, no obvious power and wavelength fluctuation were observed when all the fibers are fixed well on the optical table. On the other hand, as the NPR structure is sensitive to the polarization status, we found that the central wavelength of the laser would change if we bend the fibers in the laser.

4 CONCLUSION

A multi-wavelength fiber laser with tunable wavelength spacing is demonstrated. A Michelson interferometer consist of an optical delay line was used as a tunable multi-wavelength filter. A NPR structure with a long piece of dispersion shift fiber was used to the equalize multi-wavelength and suppress wavelength competition. Finally, a multi-wavelength ring fiber laser with flat spectra was obtained with continuously tunable wavelength spacing. The wavelength spacing can be tune continuously from 0.045 nm to 0.7 nm. More than 60 wavelengths within 3 dB flatness with spacing of 0.0474 nm can be achieved.

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