Stable multi-wavelength erbium-doped fiber laser based on dispersion-shifted fiber and Sagnac loop filter

Ying Gao (高 莹), Daru Chen (陈达如), and Shiming Gao (高士明)

Centre for Optical and Electromagnetic Research, State Key Laboratory of Modern Optical Instrumentation,
Zhejiang University, Hangzhou 310058

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A multi-wavelength erbium-doped fiber laser (MEDFL) with simple line structure is experimentally demonstrated by using a Sagnac interferometer as a comb filter. It is shown that the multi-wavelength lasing is quite stable at room temperature due to the four-wave mixing (FWM) effect among different laser channels in the dispersion-shifted fiber cooperated in the laser cavity.

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Together with the blossoming development of wavelength-division-multiplexing (WDM) optical communication systems, multi-wavelength fiber lasers[1−6] have attracted much attention over the past decade, which also have potential applications in laser spectroscopy, optical fiber sensors, optical component testing, and spectroscopy. Several mechanisms have been successfully used to demonstrate multi-wavelength fiber lasers, such as erbium-doped fiber amplifier[1,2], fiber Raman amplifier[3,4], and semiconductor optical amplifier[5,6]. Multi-wavelength fiber lasers with EDFA have advantages of high saturated power, high conversion efficiency, low polarization dependent gain, and low threshold. However, the strong homogenous line broadening and cross-saturation gain of erbium-doped fiber (EDF) make the EDF lasers hardly stable at room temperature. Several effective methods have been reported to make the multi-wavelength EDF laser (MEDFL) stable at room temperature, such as cooling the EDF to 77 K with liquid nitrogen[7], or utilizing a frequency-shifted feedback technique in a laser cavity[8]. However, the setups of these designs are too complex.

Recently, stable and uniform MEDFL was developed by combining the nonlinear Brillouin gain and linear EDF gain[9]. But the wavelength spacing determined by the Brillouin shift was too small (~ 0.08 nm), and it employed the tunable distributed feed back laser to make the laser expensive. MEDFL can also be realized by incorporating a highly nonlinear fiber in a ring cavity[3,10,11] which utilized expensive special fiber as the flattened media. Compared with ring-structure lasers, the laser light oscillating in line-structure lasers goes through amplifier media twice per circulation and thus requires a low threshold pump. In this letter we propose and demonstrate a stable MEDFL with a simple line structure by incorporating a section of dispersion-shifted fiber (DSF) whose dispersion profile is low and flat around the operation wavelength. Therefore, four-wave mixing (FWM) effect will occur easily among these laser channels and their powers are dynamically balanced. The MEDFL gain is automatically flattened based on FWM mechanism[12]. In our experiments, stable 7-wavelength lasing is achieved at room temperature with the channel spacing of 0.85 nm.

The schematic configuration of the proposed MEDFL is shown in Fig. 1. The Sagnac loop filter (SLF) employed in the fiber laser consists of an 8.9-m-long polarization maintaining fiber (PMF) with a birefringence value of about 3.2×10^{-4}, a polarization controller (PC) and a 3-dB optical coupler (OC1). Theoretically, the wavelength spacing is determined by $\Delta\lambda = \lambda^2/(\Delta n \cdot L)$[6] where $\Delta\lambda$, λ, Δn, and L are the wavelength spacing, the operation wavelength, the fiber birefringence, and the effective fiber length, respectively. Then, the wavelength spacing can be determined by Δn and L when the laser operation wavelength is around 1570 nm. In our experiments, the wavelength spacing is calculated to be $\Delta\lambda = 0.865$ nm. Figure 2 shows the experimental transmission characteristic of the SLF. In this proposed structure SLF determines the lasing wavelength by its

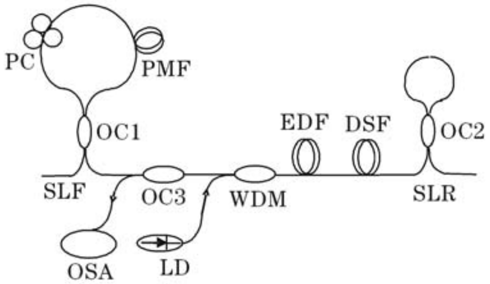

Fig. 1. Schematic configuration of the proposed MEDFL.

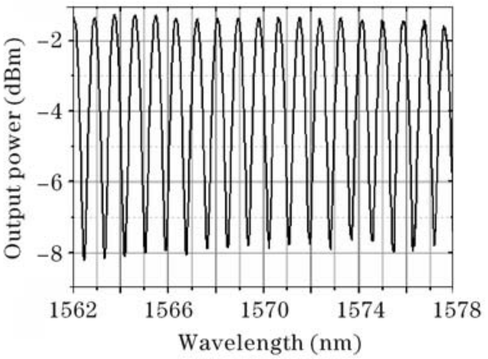

Fig. 2. Transmission characteristic of the SLF in the proposed MEDFL.

reflection characteristic. Therefore, the channel spacing of the multi-wavelength fiber laser should be the distance between the troughs (not the peaks) of the transmission spectrum. According to Fig. 2, the channel spacing is 0.864 nm, which agrees well with the calculated one. A section of DSF with the length of 2138 m is employed as the stabilization medium of the MEDFL. A 6.3-m-long EDF and a laser diode (LD, whose lasing wavelength and maximum output power are 1481.6 nm and 240 mW, respectively) compose the EDFA. A Sagnac loop reflector (SLR) and the SLF described above form the laser cavity. SLF is employed as the comb filter in this proposed fiber laser. The 2% arm of an OC3 serves as the output port of this fiber laser, which is connected to an optical spectrum analyzer (OSA).

The stabilization mechanism of multi-wavelength lasing is the FWM effect[11]. The lasing channel with higher power plays the role of the pump when traveling in DSF and the lasing channel with lower power can obtain energy and be amplified through FWM process. Thus the multi-wavelength lasing in MEDFL can be stabilized and equalized by the FWM mechanism. Since the nonlinear coefficient (γ) of DSF used here is fixed and only 1.5 times as large as that of the single mode fiber, there are three factors will strongly influence the magnitude of the FWM products[12]. The first factor is the channel spacing. When the channel spacing becomes smaller, the efficiency of the FWM increases dramatically. The second factor is the fiber dispersion. The efficiency of the FWM is inversely proportional to the fiber dispersion and the maximal efficiency should be achieved near the zero-dispersion wavelength. The third factor is intensity of the interacting wavelengths. The efficiency of the FWM is proportional to the intensity of the interacting light-waves, which means that the energy of lasing wavelength with higher intensity will probably be transferred to the lasing wavelength with lower intensity. In our experiments, the channel spacing is fixed at 0.864 nm, the DSF's zero-dispersion wavelength is about 1497 nm. As a result, the FWM progressing efficiency is only determined by the energy of the pumping wavelength. Then, it will dynamically balance the intensity of each lasing wavelength in the laser cavity and make the multi-wavelength stable at room temperature.

By carefully adjusting the PC in the SLF, one can obtain the optimal output spectrum. Multi-wavelength lasing is achieved when the pump LD is switched on to 240 mW. The output spectrum of the proposed MEDFL is shown in Fig. 3(a). The wavelength span, resolution, and sensitivity of the OSA (Agilent 86142B) are set to be 20 nm, 0.06 nm, and −65 dBm, respectively. There are 7 wavelengths oscillating in the MEDFL cavity. The wavelength spacing is 0.864 nm which agrees well with the SLF's channel spacing and the extinction ratio is over 30 dB. If the DSF is removed from this line structure, the output spectrum is shown in Fig. 3(b) after adjusting the PC in SLF. Comparing Figs. 3(a) and (b), one can see that DSF will dramatically stabilize and equalize the multi-wavelength lasing in the cavity and broaden the output bandwidth (from 3 lasing wavelengths to 7 lasing wavelengths with the same channel spacing) at room temperature.

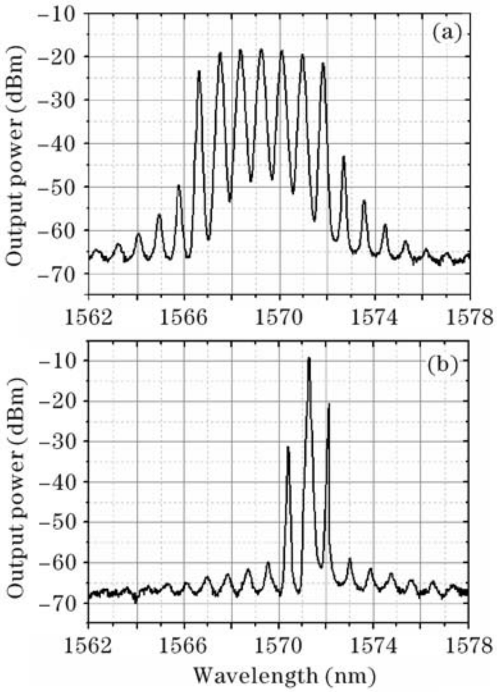

Fig. 3. Output spectra of the multi-wavelength fiber laser. (a) DSF is added in the laser structure; (b) DSF is removed from the laser structure.

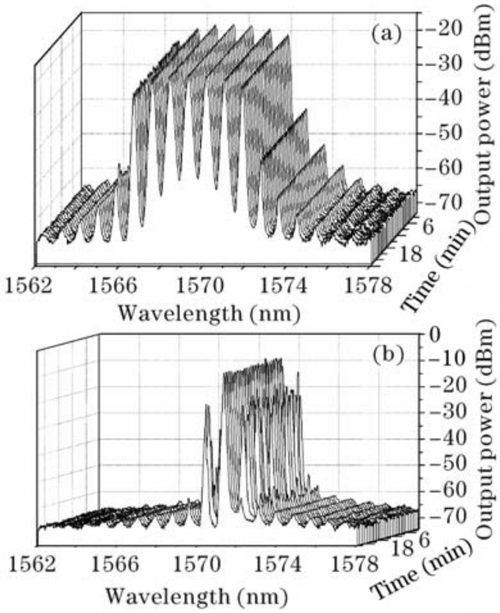

Fig. 4. Repeated scanning spectra per minute within 27 minutes for the output spectrum. (a) DSF is added in the laser structure; (b) DSF is removed from the laser structure.

The good stability of the proposed MEDFL is demonstrated in Fig. 4(a). The spectrums in 27 minutes (each per minute) at room temperature agree well with each other. The maximal fluctuation of each peak power is less than 0.37 dB and the minimum is only 0.09 dB within 27 minutes, which means that the proposed line-structure multi-wavelength fiber laser is quite stable at room temperature. Without the DSF as the FWM medium in this line structure, the repeated scanning spectrum per minute within 27 minutes is shown in Fig. 4(b). As we predicted, it is unstable at room temperature. Thus a section of DSF can improve the stability of the proposed multi-wavelength line-structure fiber laser at room temperature.

In conclusion, a stable MEDFL with a simple line structure by employing a section of DSF has been introduced in this letter. The homogenous line broadening effect of EDF which causes the instability has been depressed by the FWM effect. All components in the proposed fiber laser are fiber-compatible and no special fiber (e.g. photonic crystal fiber) or instrument is needed. The experimental results have shown that FWM effect can dramatically and automatically stabilize and equalize the intensities of different lasing wavelengths. However, the nonlinear coefficient and zero-dispersion wavelength of DSF have not been optimized in our experiment. For further improvement, we could use highly nonlinear DSF (of a short length) with zero-dispersion wavelength around 1570 nm to achieve stabler MEDFL.

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