Multi-wavelength hybrid gain fiber ring laser based on Raman and erbium-doped fiber

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A stable and uniform multi-wavelength fiber laser based on the hybrid gain of a dispersion compensating fiber as the Raman gain medium and an erbium-doped fiber (EDF) is introduced. The gain competition effects in the fiber Raman amplification (FRA) and EDF amplification are analyzed and compared experimentally. The FRA gain mechanism can suppress the gain competition effectively and make the present multi-wavelength laser stable at room temperature. The hybrid gain medium can also increase the lasing bandwidth compared with a pure EDF laser, and improve the power conversion efficiency compared with a pure fiber Raman laser.

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Multi-wavelength fiber lasers have attracted much interest in recent years because of their potential applications in wavelength division multiplexing (WDM) systems, optical fiber sensors, optical component testing, and spectroscopy, and their various advantages, such as multi-wavelength operation, low cost, compact structure, and compatibility to fibers[1−3]. Multi-wavelength lasing has been achieved with various gain mechanisms including erbium-doped fiber (EDF) amplification (EDFA), semiconductor optical amplification (SOA)[1,2], and fiber Raman amplification (FRA)[3−5]. Multi-wavelength fiber lasers using EDFs have been investigated widely due to their advantages such as the high power conversion efficiency and lower threshold. However, it is an intrinsic disadvantage that an EDF has a strong homogenous line broadening and cross-saturation gain at room temperature[6]. In other words, the serious gain competition among different lasing wavelengths within the large homogenous line broadening region will make the multi-wavelength laser unstable at room temperature. FRA has the advantages of compatibility with fiber structure, higher saturation power giving higher output power of the fiber laser[7], and larger gain bandwidth (FRA also has a dominant inhomogeneous line broadening property at room temperature)[3,4]. Utilizing the complementary advantages of FRA and EDF lasers, we introduce in this letter a stable multi-wavelength fiber laser with good performance.

The schematic diagram of the experimental setup is shown in Fig. 1. A section of dispersion compensating fiber (DCF) with a length of about 4 km, which is originally used for compensating the dispersion of 20-km single-mode fiber (SMF) is employed as the Raman gain fiber. Three laser diodes (LD2, LD3, and LD4) are used as the Raman pumps, and their wavelengths (maximum output powers) are 1430 (185 mW), 1440 (183 mW), and 1467 nm (117 mW), respectively. A section of EDF with the erbium ions concentration of 1.35×10^{25} m^{-3} and length of 6.3 m and a laser diode (LD1) with the wavelength of 980 nm and maximum output power of 150 mW form the EDF part of amplification. An optical circulator which also makes the lasing operation anticlockwise and a Sagnac loop filter (SLF) form a resonant cavity. The 2% arm of an optical coupler (OC) is used as the output port. The SLF, which determines the lasing wavelengths, is composed of a section of polarization-maintaining fiber (PMF) with a birefringence of 3.2×10^{-4}, two polarization controllers (PCs), and a 3-dB optical coupler. The wavelength spacing is given by $\Delta\lambda = \lambda^2/(\Delta n \cdot L)$[8,9], where $\Delta\lambda$, Δn, L, and λ are the channel spacing, fiber birefringence, effective fiber length, and operational wavelength, respectively. In our experiment, $L = 15.2$ m and thus the calculated channel spacing of the SLF is 0.5 nm around the wavelength of 1560 nm.

The instability of multi-wavelength lasing is mainly due to the gain competition effect. First we experimentally study and compare the gain competition between two signal channels for the FRA and EDFA parts of the proposed fiber laser. The setups of the FRA and EDFA, which are forward pump structures, are shown in box (I) and box (II) of Fig. 1, respectively. For FRA, the wavelength λ_A (input power) of signal #A is fixed to 1555 nm (−5 dBm); the wavelength λ_B of signal #B can be tuned from 1525 to 1580 nm (−4.5 dBm), and the pump powers of LD2, LD3, and LD4 are 164, 163, and 111 mW, respectively. For EDFA, the wavelength λ_A (input

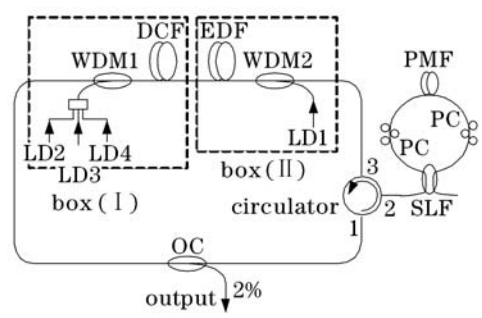

Fig. 1. Schematic diagram of the multi-wavelength fiber laser based on a loop structure of EDFA and FRA.

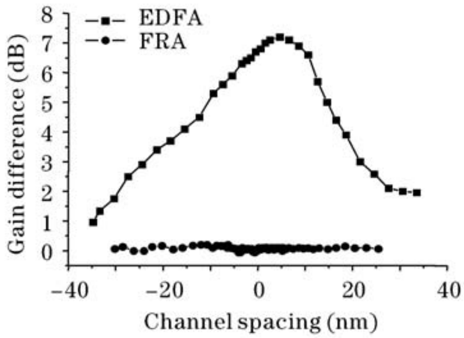

Fig. 2. Variation of the gain for signal #A influenced by signal #B at various channel spacings for RFA and EDFA.

power) of signal #A is fixed to 1555 nm (−7.5 dBm); the wavelength λ_B of signal #B can also be tuned from 1525 to 1580 nm (−5.8 dBm), and the pump power of LD1 is 35.2 mW. Figure 2 shows the measured gain difference for signal #A between the gains when signal #B is off and on in EDFA (the curve connected by squares) and in FRA (the curve connected by circles) as channel spacing $(\lambda_B - \lambda_A)$ varies. From it one can see that the gain competition effect is very strong in the EDFA even for two wavelengths separated by more than 20 nm, whereas it is hardly observed in the FRA even for two wavelengths separated by less than 0.1 nm. Therefore, we can expect stable multi-wavelength lasing of good performance by incorporating the FRA gain mechanism with small gain competition into the EDFA gain mechanism.

Next we demonstrate multi-wavelength lasing of the proposed hybrid gain fiber laser. By carefully adjusting the PCs in the SLF (see Fig. 1) and the four pump powers of the laser, we obtain the optimal output as shown in Fig. 3(a). The corresponding pump powers are listed in Table 1. The output spectrum is shown in Fig. 3(a), from which one can see that the maximum fluctuation of the output powers at these 6 wavelengths is less than 1.2 dB and the extinction ratio is over 42.3 dB. To show the good stability of the multi-wavelength lasing at room temperature, we show the repeated scanning spectrum per 0.5 minutes within 6 minutes in Fig. 3(b). The fluctuation of each peak power is less than 0.31 dB within 6 minutes (see Fig. 3(c)). Thus, the present multi-wavelength laser is uniform and very stable in power and wavelengths. The total measured output power is more than 0.35 dBm. Note that all the outputs in our experiments are measured by an optical spectrum analyzer (OSA) (Agilent 86142B), the resolution and sensitivity of the OSA used in the measurement are 0.06 nm and −50 dBm, respectively.

Besides the advantages to effectively suppress the gain competition as the result of the EDF's homogenous feature, to increase the lasing bandwidth and output power as compared with a pure EDF laser, and to improve the power conversion efficiency as compared with a pure fiber Raman laser, the proposed hybrid gain mechanism can also provide the flat gain by the optimization of the pump powers and enable the power uniformity of the multi-wavelength lasing. Additionally, due to the 1467-nm FRA pump (LD4) light can also act on the EDF and contribute some EDF gain, higher 1467-nm pump can improve the power conversion efficiency of the multi-wavelength laser with the present hybrid gains of the DCF and EDF.

Table 1. Wavelengths and Powers of the Four Pump LDs Injected into the Loop Cavity

	LD1	LD2	LD3	LD4
Wavelength (nm)	980	1430	1440	1467
Pump Power (mW)	95.4	183	181	116

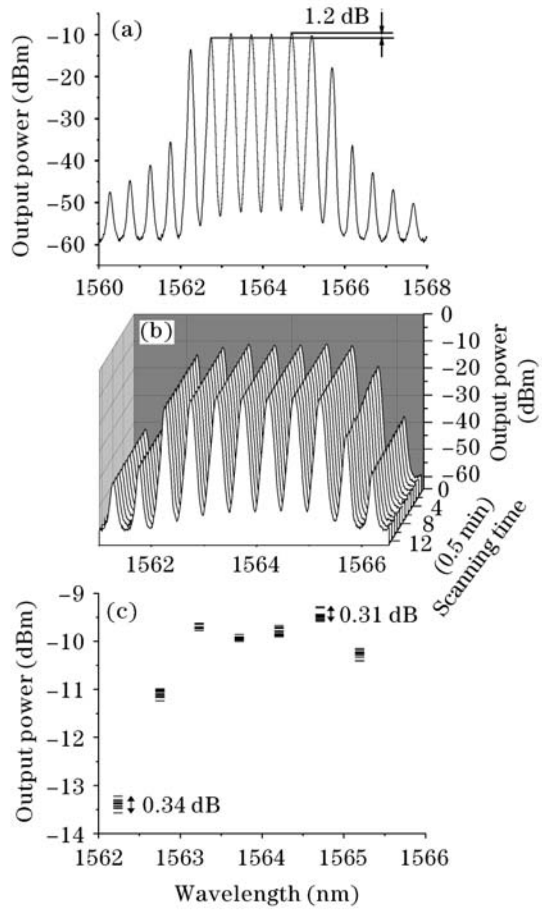

Fig. 3. Experimental results of the present multi-wavelength fiber laser. (a) Output spectrum; (b) repeated scanning spectrum every 0.5 minute; and (c) fluctuation of each peak power within 6 minutes.

In summary, a stable and uniform multi-wavelength fiber laser based on the hybrid gain of a Raman gain fiber and an EDF has been introduced. The gain competition which causes the instability of the multi-wavelength lasing has been analyzed and compared for the EDFA and FRA. By incorporating the FRA gain mechanism (small gain competition) into the EDFA gain mechanism (to obtain a large gain), we have obtained an effective hybrid gain mechanism for multi-wavelength lasing stable at room temperature. Together with a loop cavity structure and a PMF SLF, we have achieved stable and uniform 6-wavelength lasing, with the fluctuation of the peak powers less than 0.31 dB in 6 minutes, a power nonuniformity of less than 1.2 dB, extinction ratio of over 42.3 dB, and a total output power of 0.35 dBm.

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