Multi-wavelength erbium-doped fiber laser using four-wave mixing effect in doped fiber

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We demonstrate a multi-wavelength erbium-doped fiber laser (EDFL) using erbium gain and four-wave mixing (FWM) effect in a piece of erbium-doped fiber (EDF) with high erbium ion concentration. The EDF has a pump absorption rate of 24.6 dB/m at 979 nm and is bi-directionally pumped by 980-nm laser diodes. FWM effect redistributes the energy of different oscillating lines and causes multi-wavelength operation. The laser generates more than 22 lines of optical comb with a line spacing of approximately 0.10 nm at the 1569-nm region using only 1.5-m-long EDF.

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Multi-wavelength lasers are required for dense wavelength division multiplexing (DWDM) optical system, an enabling technology to fulfil the demand of bandwidth in the modern information age. Simultaneous multi-wavelength oscillations have been demonstrated using fiber grating sagnac loop[1], overlap fiber Bragg grating[2], multiple quantum-well waveguide[3], high birefringence fiber loop mirror[4], acousto-optic frequency shifter[5], elliptical core fiber[6], and semiconductor optical amplifier[7]. Another attractive method is to make use of nonlinear effects, such as stimulated Brillouin scattering and four-wave mixing (FWM), which occur in optical fibers. Multi-wavelength lasers with a high number of channels have been reported using Brillouin erbium fiber laser[8,9]. However, the spacing of this laser is fixed at 0.08 nm, which is too narrow for DWDM applications. To cope with the problem, FWM-based multi-wavelength fiber lasers are proposed[10,11]. FWM can occur when two or more frequencies of light propagate through a nonlinear medium, provided that the condition known as phase matching is satisfied. In the FWM process, light is generated at new frequencies through the conversion of optical power from the original signal wavelengths. In quantum-mechanical terms, FWM occurs when photons from one or more waves are annihilated and new photons are created. These new photons, although created at different frequencies, still conserve net energy and momentum[12].

Recently, a high erbium ion concentration erbium-doped fiber (EDF), IsoGain™ was commercially developed by FiberCore Co. Ltd. to provide the ultimate in cost-effectiveness for the EDF amplifier, with typical C-band gain-lengths of only a few meters[13]. This fiber is actually more suited to reducing the exceptionally long gain lengths required for effective L-band amplification. In this letter, to the best of our knowledge, a multi-wavelength EDF laser (EDFL) is demonstrated using IsoGain™ EDF assisted by FWM process in a ring cavity resonator for the first time. The bi-directionally pumped EDF acts as both linear and nonlinear gain media. The linear gain will generate erbium laser lines, which interact with each other in the same medium to generate a multi-wavelength comb with constant spacing.

The experimental setup of the proposed ring multi-wavelength laser is shown in Fig. 1. The setup consists of an IsoGain™ EDF with a numerical aperture of 0.24, a cut-off wavelength of 910 nm, an attenuation of 6.8 dB/km, and a pump absorption rate of 24.6 dB/m at 1,200 and 979 nm, respectively. This fiber has high alumina content to help in controlling the quenching effect. The EDF is bi-directionally pumped using a 980-nm laser diode. Wavelength division multiplexer (WDM) is used to combine the pump and laser wavelengths. Polarization controller (PC) is used to control the birefringence in the ring cavity so that the output laser generated can be controlled and optimized. Two optical isolators are used to ensure unidirectional operation of the laser. A 10-dB coupler is used to tap the output of the laser via 10% port (Fig. 1), which is then characterized by an optical spectrum analyzer (OSA) with a resolution of 0.015 nm.

Figure 2 shows the output spectrum of the multi-wavelength EDFL for different EDF lengths. The EDFL uses a single pump laser with 120-mW pump power. The operating wavelength of the multi-wavelength EDFL is determined by the 980-nm pumped EDF gain spectrum,

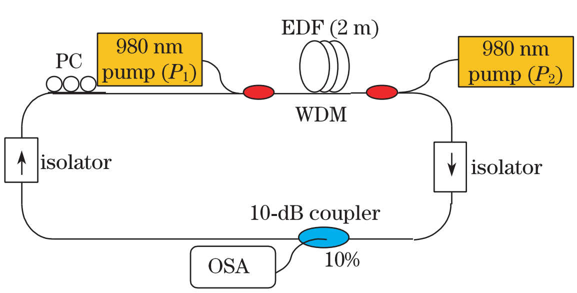

Fig. 1. Experimental setup for the proposed multi-wavelength EDFL.

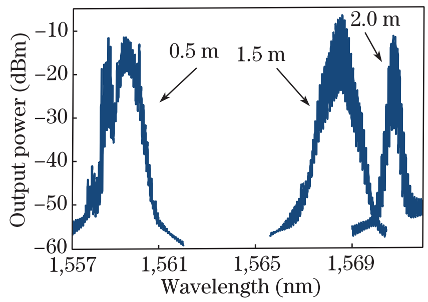

Fig. 2. Output spectra of the proposed multi-wavelength EDFL at various EDF lengths.

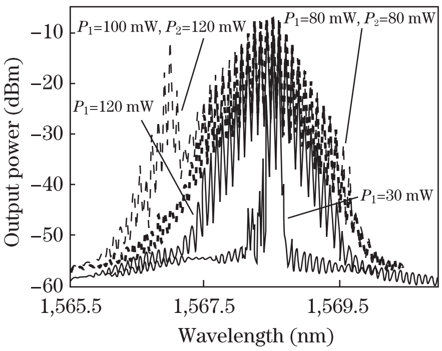

Fig. 3. Output spectra of the proposed multi-wavelength EDFL at different 980 nm pump powers.

which covers the C-band region from 1,530 to 1,570 nm, as well as the cavity loss. The EDF amplifier has a small signal gain of approximately 40 dB at the 1,570 nm region with a pump power of 120 mW. As shown in Fig. 2, a laser comb is observed in wavelength regions of 1,559–1,571 nm, depending on EDF length. The laser operates at this region due to the cavity loss, which is lower at the longer wavelength. The operating wavelength shifts to a longer wavelength as the EDF length increases. This is attributed to the EDF's gain spectrum, which moves to a longer wavelength as the EDF length increases. The 980-nm pumped EDF generates amplified spontaneous emission at C-band region, which oscillates in the linear cavity to generate at least two oscillating lines whose spacing is determined by the cavity length and the birefringence in the cavity. Multi-wavelength laser generation with constant spacing is assisted by the FWM process, which annihilates photons from these waves to create new photons at different frequencies. The FWM effect redistributes the energy of different oscillating lines and causes the multi-wavelength operation. A PC is used to control the polarization and the birefringence inside the cavity, which in turn controls the number of line generated, the channel spacing, and the peak power. From Fig. 2, the optimum EDF length is about 1.5 m, where the number of lines decreases as the EDF length is increased to 2 m. This is attributed to erbium gain, which is lower with a longer EDF length of 2 m due to insufficient 980 nm pump power. The gain spectrum then shifts to a longer wavelength.

Figure 3 shows the output spectra of the multi-wavelength EDFL for different 980 nm pump powers. The EDF length is fixed at 1.5 m in this experiment. As shown in Fig. 3, more than 22 lines are obtained with peak powers above –30 dBm when the pump powers are fixed at 100 and 120 mW for P_1 and P_2, respectively. At the single pump and minimum power of 30 mW, erbium gain is lower and only three strong oscillating lines are generated. The number of generated lines, as well as the peak power, is observed to increase as the pump power increases, which is attributed to the increment of the erbium gain with pump power. In this experiment, the strongest line has a peak power of approximately –7 dBm. The line spacing is measured to be around 0.10 nm, which is determined by the cavity length and the birefringence in the ring cavity. The number of lines is limited by the availability of the 980 nm pump power or erbium gain, fiber nonlinearity, and polarization filtering effect in the linear cavity resonator. The multi-wavelength output is observed to be stable at room temperature with only minor fluctuations observed coinciding with large temperature variances. The uniformity of the output spectrum can be improved using nonlinear polarization rotation effect as suggested in an earlier Ref. [14]. The operating wavelength of the proposed EDFL can be slightly tuned by changing the cavity loss and the polarization state of the oscillating light.

In conclusion, a stable multi-wavelength EDFL comb is achieved at room temperature using a short piece of IsoGain$^{\text{TM}}$ EDF fiber as both linear and nonlinear gain media. The EDF has a pump absorption rate of 24.6 dB/m at 979 nm and is bi-directionally pumped by 980-nm laser diodes. The multi-wavelength generation is due to oscillating EDFL lines, which interact with each other to create new photons at other frequencies via the FWM process. The generated laser comb has more than 22 lines with a constant spacing of approximately 0.10 nm.

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