Channel-spacing-tunable multi-wavelength fiber ring laser with hybrid Raman and Erbium-doped fiber gains

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Abstract: A multi-wavelength fiber ring laser of tunable channel spacing is proposed by employing an optical variable delay line (OVDL) in a Mach-Zehnder interferometer. Stable lasing is achieved at room temperature with the hybrid gains of a single mode fiber (as the Raman gain medium) and an Erbium-doped fiber (EDF) in a ring structure. The channel spacing of the present multi-wavelength fiber ring laser can be continuously tuned by adjusting the computer-controlled OVDL.

OCIS codes: (140.3510) Lasers, fiber; (140.3500) Lasers, Erbium; (140.3550) Lasers, Raman; (140.3600) Lasers, tunable.

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1. Introduction

Multi-wavelength fiber lasers have attracted much attention due to their potential applications in e.g. WDM systems, optical fiber sensors, optical component testing, and spectroscopy [1-5]. Multi-wavelength lasing has been achieved with various gain mechanisms including Erbium-doped fiber amplification (EDFA) [6-7], fiber Raman amplification (FRA) [8-9] and semiconductor optical amplification (SOA) [10]. Multi-wavelength Erbium-doped fiber lasers (MEDFLs) have been investigated widely due to their advantages such as the high power conversion efficiency and low threshold. However, as an intrinsic disadvantage a standard MEDFL is not stable at room temperature due to the strong homogenous line broadening and cross-saturation gain of an Erbium-doped fiber (EDF) [11]. Several effective methods have been reported to make an MEDFL stable at room temperature [12-17]. We have recently developed a method to achieve a stable and uniform MEDFL by incorporating a dispersion compensating fiber (as the Raman gain medium) [17]. However, this multi-wavelength fiber laser has a cavity of line structure, and its channel-spacing is fixed to 0.5 nm (determined by the length and the birefringence of the polarization-maintaining fiber in the fiber laser) which can not be tuned.

Tunability of the channel spacing is very useful for the above-mentioned applications of multi-wavelength fiber lasers (particularly in some reconfigurable or upgradable optical communication systems). In this paper we propose a multi-wavelength fiber ring laser with continously tunable channel spacing. To keep the advantages of both EDFL (with high power conversion efficiency) and fiber Raman laser (with large lasing bandwidth), hybrid Raman and EDF gains are utilized in the lasing cavity of ring structure (see Fig. 1). A Mach-Zehnder interferometer (MZI) with a large channel-spacing tuning range (e.g., from 0.1 nm to 100 nm, which can not be achieved by simply applying a stronger tension on one fiber arm) is achieved by using an optical variable delay line (OVDL), and is employed here as a comb filter with tunable channel spacing. The channel spacing of the MEDFL can be coutinuously tuned, and stable multi-wavelength lasings at room temperature with the standard ITU (International Telecommunication Union) channel spacing of 25 GHz (0.2 nm), 50 GHz (0.4 nm) and 100 GHz (0.8 nm) are demonstrated.

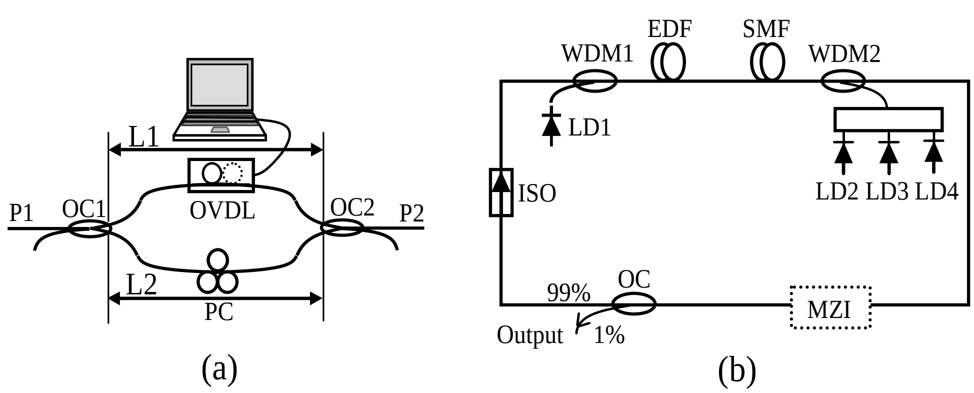

Fig. 1. Schematic configurations of the tunable Mach-Zehnder interferometer (a) and the channel-spacing tunable multi-wavelength fiber laser of ring structure (b). OC: optical coupler; OVDL: optical variable delay line; PC: polarization controller; ISO: isolator; WDM: wavelength division multiplexer; LD: laser diode; SMF: single mode fiber; EDF: Erbium-doped fiber.

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2. Experimental setup, results and analysis

Figure 1(a) shows the schematic configuration of the MZI used in the proposed fiber ring laser. The MZI consists of two 3-dB couplers (OC1 and OC2), a polarization controller (PC) and an OVDL. The OVDL (which is controlled by a computer) is a commercial product (MDL-002, General Photonics Corporation) with an optical delay accuracy of 3 μm, an optical delay range of 168 mm and an insertion loss of ~1 dB. Considering the insertion loss of the OVDL, the transfer matrix of the MZI can be written as

$$M_{MZ} = M_{2\times 2}(\theta_2)\begin{pmatrix} \gamma \cdot \exp(i\phi) & 0 \\ 0 & 1 \end{pmatrix} M_{2\times 2}(\theta_1)\,, \tag{1}$$

where

$$M_{2\times 2}(\theta) = \begin{pmatrix} \cos(\theta) & i\sin(\theta) \\ i\sin(\theta) & \cos(\theta) \end{pmatrix} \tag{2}$$

is the transfer matrix of the optical coupler and

$$\phi = \beta_0 (L_1 - L_2) = \beta_0 \Delta L \tag{3}$$

is the phase difference between the two arms of the MZI. β_0, ΔL and γ are the propagation constant, the path difference of the two arms of the MZI and the transmission coefficient of the OVDL, respectively. Assuming the two 3-dB optical couplers [i.e., $\theta_1 = \theta_2 = \pi/4$ in Eq. (1)] are polarization-independent and the power is launched into port P1, the intensity transmission at port P2 is

$$T = \frac{1}{4}(1 + \gamma^2 - 2\gamma\cos(\phi))\,. \tag{4}$$

From Eq. (3) and (4) one sees that the transmission spectrum of the MZI has equal frequency-spacing ($\Delta\nu = c/n\Delta L$, where c and n is the speed of light in vacuum and the effective index of the medium) in the frequency domain, which indicates the MZI can be used as a

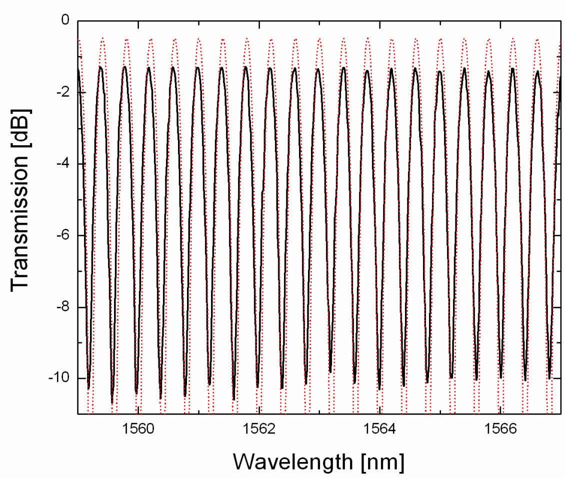

Fig. 2. Theoretical (red short dotted line) and experimental (black solid line) transmission characteristics of the MZI used in the proposed fiber laser.

comb filter. The corresponding wavelength spacing between the transimission peaks can be calculated by $\Delta\lambda = \lambda^2 / n\Delta L$ (where λ is the central wavelength). For example, if the central wavelength is 1563 nm and the wavelength spacing is 0.4 nm (50 GHz), the optical path difference of the two MZI arms introduced by the OVDL should be $n\Delta L = 6.1074$ mm [the calculated transmission spectrum is shown as the red short dotted line in Fig. 2]. The measured transmission spectrum of the MZI [shown as the black solid line in Fig. 2] agrees well with the calculated one and the measured insertion loss is less than 1.3 dB. The wavelength spacing of the MZI comb filter can be tuned in a large range (e.g. from 0.1 nm to 100 nm by changing ΔL from 24 mm to 0.024 mm). This indicates that the OVDL has sufficient accuracy and range for the proposed fiber ring laser if the MZI is carefully designed.

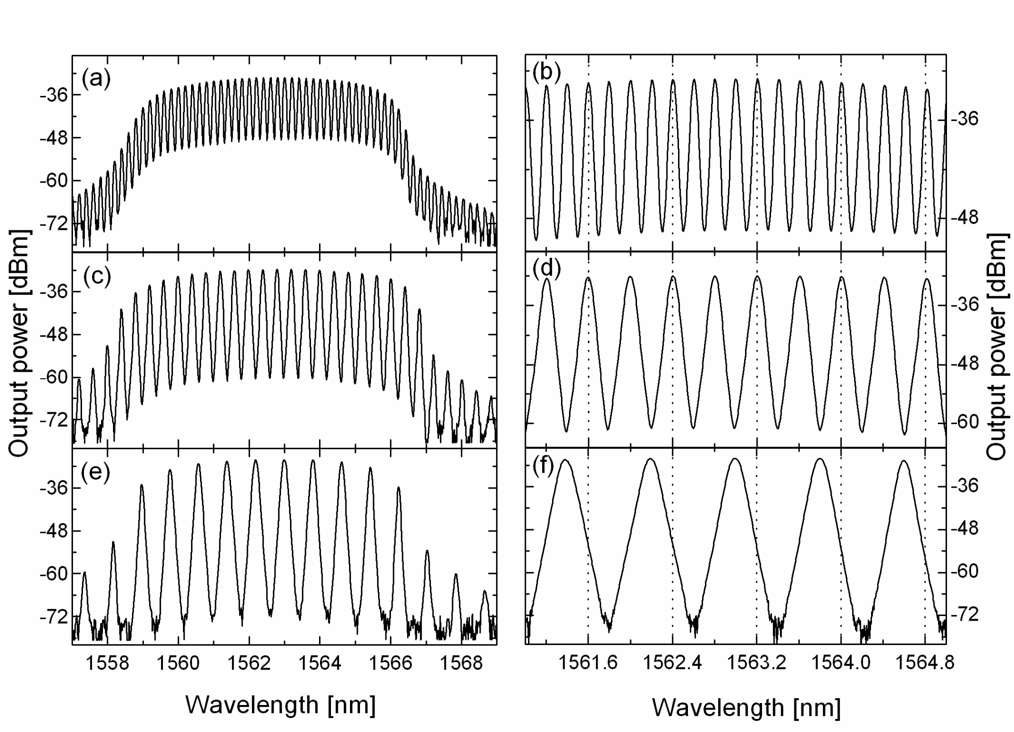

Fig. 3. Output spectra of the proposed multi-wavelength fiber ring laser when the channel spacing is tuned to 25 GHz (0.2 nm) [(a) and (b)], 50 GHz (0.4 nm) [(c) and (d)] or 100 GHz (0.8 nm) [(e) and (f)].

The experimental setup of the proposed multi-wavelength fiber ring laser is shown in Fig. 1(b). A section of single mode fiber (SMF) with a length of about 25 km 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 nm (185 mW), 1440 nm (183 mW), and 1467 nm (117 mW), respectively. A section of EDF with a length of 4 m and a laser diode (LD1, whose wavelength and maximum output power are 980 nm and 140 mW, respectively) form the part of EDF amplification. The 1% arm of an optical coupler (OC) is used as the output port. An optical isolator (ISO) ensures a clockwise ring cavity. The MZI is employed as the comb filter in the proposed fiber ring laser.

In our experiments, in order to achieve a flat gain in a wide wavelength region centred around 1563 nm, the powers of pumps LD1, LD2, LD3 and LD4 are set to 130 mW, 165 mW, 146 mW and 64 mW, respectively. By carefully tuning the OVDL (through the controlling computer) and adjusting the PC, stable multi-wavelength lasing is achieved. Figure 3 shows the output spectra of our multi-wavelength fiber ring laser when the channel spacing is tuned to 25 GHz (0.2 nm) [(a) and (b)], 50 GHz (0.4 nm) [(c) and (d)] or 100 GHz (0.8 nm) [(e) and (f)] (compatible with the ITU grid) (Note that we do not give 0.1 nm-spacing lasing because the resolution of our optical spectrum analyzer (OSA) (Agilent 86142B) is only 0.06 nm). The wavelength span of the OSA is set to 12 nm for Fig. 3 (a), (c) and (e) and 4 nm (different value) for Fig. 3 (b), (d) and (f). The resolution and sensitivity of the OSA used in the measurement are 0.06 nm and -65 dBm, respectively. One can see from Fig. 3 (a), (c) and (e) that the peak points of the lasing wavelengths in each sub figure form a similar envelope curve while the total number of the lasing wavelegths decreases when the wavelength spacing increases. For example, one sees from Fig. 3(c) and (d) that 17-wavelength lasing with a wavelegth spacing of 0.4 nm can be achieved when the maximum fluctuation of the output powers at these wavelengths is required to be less than 3 dB. The FWHM (full-width at half maximum) and the extinction ratio of each lasing channel are about 0.06 nm and 18.5 dB, respectively.

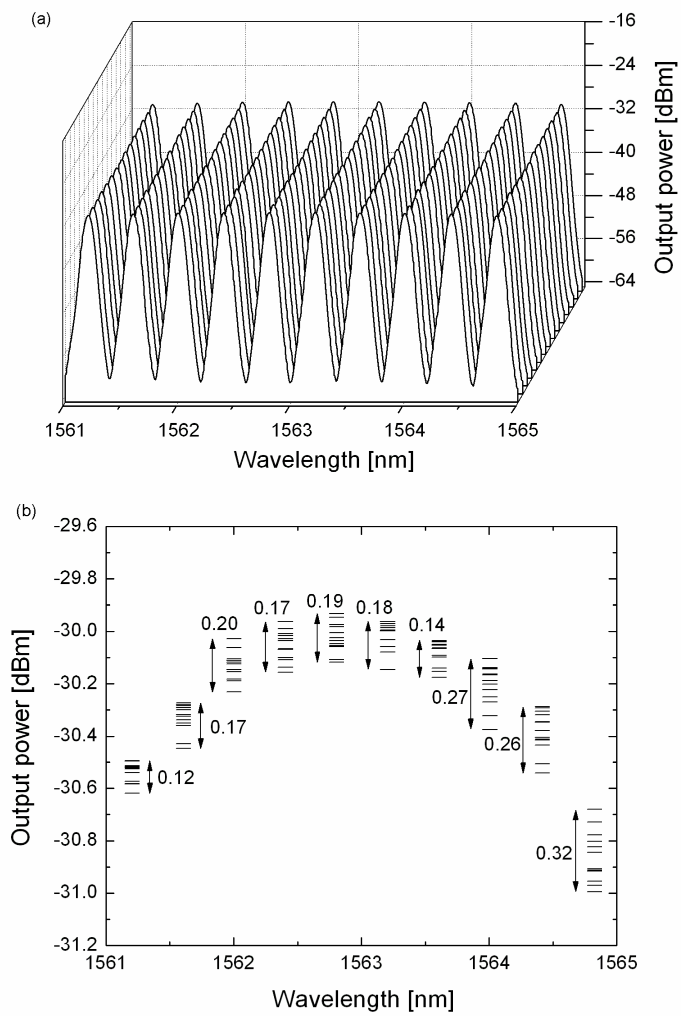

Fig. 4. Repeated scanning spectrum (a) per minute and peak power fluctuation (b) within 15 minutes for the main 10 lasing channels of the proposed fiber ring laser when the channel spacing is 50 GHz (0.4 nm).

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The good stability of the porposed multi-wavelength laser is also demonstrated. Figure 4 (a) shows the repeated scanning spectrum per minute within 15 minutes for the main 10 lasing channels of the proposed fiber ring laser when the channel spacing is 50 GHz (0.4 nm). The maximal fluctuation of each peak power is less than 0.32 dB within 15 minutes (shown in Fig. 4 (b)), which shows the proposed multi-wavelength fiber ring laser is quite stable at room temperature.

3. Discussion and conclusion

A stable multi-wavelength fiber ring laser of hybrid gain and tunable channel spacing has been demonstrated in this paper. The stable multi-wavelength fiber lasers based on Raman and EDF gains increase the lasing bandwidth (as compared with a pure EDF laser) and the power conversion efficiency (as compared with a pure fiber Raman laser). No special fibers (e.g., photonic crystal fibers) are needed in the proposed fiber lasers. Besides the untunibility, another disadvantage of the previously proposed line-structure fiber laser [17] (with the fixed channel spacing of 0.5 nm) is that it has two outputs (two 2% arms of the optical coupler) but only one output is used. The channel spacing of the present multi-wavelength fiber ring laser can be tuned continuously by adjusting the computer-controlled OVDL in one MZI arm (with a polarization controller in the other arm). The MZI has a large filtering range (unlike fiber gratings) and flexible tunability. Multi-wavelength lasing with standard ITU channel spacing of 25 GHz (0.2 nm), 50 GHz (0.4 nm) and 100 GHz (0.8 nm) has been demonstrated. For example, 17-wavelength lasing with a wavelegth spacing of 0.4 nm has been achieved with the maximum fluctuation of the output powers at these wavelengths being less than 3 dB. The maximal fluctuation of each peak power for 10 main lasing channels is less than 0.32 dB within 15 minutes, which indicates our multi-wavelength fiber ring laser is quite stable at room temperature.

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