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Single-longitudinal-mode multi-wavelength fiber laser with independent tuning of channel numbers and wavelength spacing

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Abstract We propose and experimentally demonstrate a multi-wavelength fiber ring laser under single-longitudinal-mode (SLM) operation with independent tuning of channel numbers and wavelength spacing. Since a programmable filter in the cavity is used as the multi-wavelength selection component, the channel numbers and wavelength spacing can be independently varied by setting the response of programmable filter. Due to the nonlinear polarization rotation arising in the semiconductor optical amplifier, stable multi-wavelength emission can be obtained. For two wavelengths lasing under SLM operation, the wavelength spacing over the operation range of 1,530–1,565 nm can be tuned from 0.46 to 20.54 nm with a resolution of 8 pm. In particular, the power and wavelength fluctuation of individual channel is $<$0.1 dB and 0.02 nm after 2-h monitoring.

1 Introduction

Multi-wavelength fiber ring lasers have attracted considerable interests and been widely investigated for their potential applications in dense wavelength-division multiplexing communication systems, optical instrument testing, fiber sensor systems, photonic THz generation and microwave photonics system [1–7]. To satisfy practical requirements, a multi-wavelength fiber laser is expected to offer the tunability of both channel numbers and wavelength spacing simultaneously. Several schemes based on various gain media, such as erbium-doped fiber amplifiers (EDFAs) or erbium-doped fiber (EDF) [8–13], semiconductor optical amplifiers (SOAs) [14–18], and Raman amplifiers [19–22] have been proposed. A multi-wavelength Raman fiber laser has been demonstrated with continuously tunable wavelength spacing from 0.3 to 0.6 nm and an independently adjustable channel number from 2 to 10 [23]. A flexibly tunable multi-wavelength fiber ring laser was proposed with continuously tunable wavelength spacing, by using a superimposed chirped-fiber Bragg grating as a multi-wavelength filter [24]. Both wavelength spacing and operation wavelength of multi-wavelength fiber ring laser can be tuned. Meanwhile, a SOA is used as the gain medium while a tunable polarization-diversity loop configuration-based comb filter is used as the wavelength spacing and wavelength-selective element to achieve tunable capability; multi-wavelength emission operation of up to 23 laser lines with 0.8 nm wavelength spacing was demonstrated [25]. However, no matter what sort of gain mechanism was chosen, all above-mentioned schemes may suffer multi-longitudinal-mode oscillation and have relatively large linewidth. Therefore, single-longitudinal-mode (SLM) multi-wavelength fiber laser with both channel numbers and wavelength spacing tuning is highly desired.

In this paper, we propose and experimentally demonstrate a SLM multi-wavelength fiber ring laser with independently adjustable both channel numbers and

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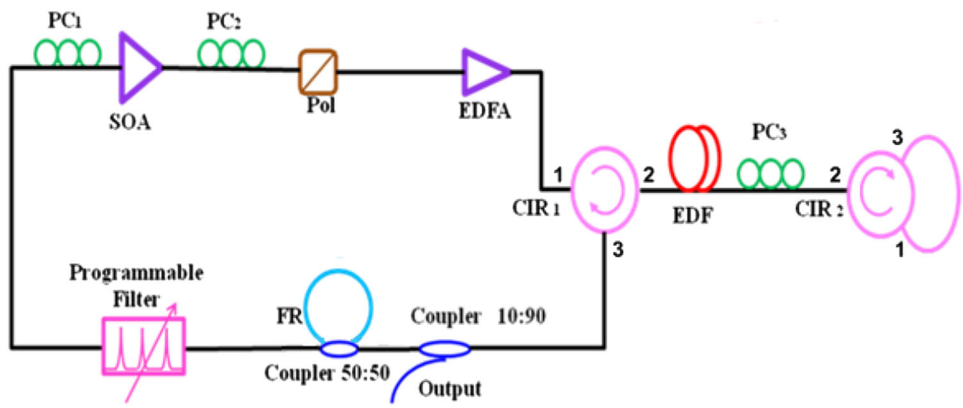

Fig. 1 Schematic scheme of SLM multi-wavelength fiber ring laser with independent tuning of channel numbers and wavelength spacing

wavelength spacing. Multi-wavelength selection is performed by a programmable filter whose response can be set arbitrarily. Stable multi-wavelength lasing under SLM operation is experimentally demonstrated with tunable channel number from 2 to 5 and wavelength spacing from 0.46 nm to 20.54 nm at room temperature.

2 Operation principle and experimental setup

The proposed multi-wavelength fiber ring laser is schematically shown in Fig. 1. The gain is provided by a SOA (SOA-NL-OEC-1550). Due to the property of inhomogeneous broadening, SOA can support simultaneous oscillation of many lasing wavelengths. Two polarization controllers (PCs) and a polarizer are employed to manage the state of polarization (SOP) within cavity. Supposing that the SOA is operated at the gain saturated area, the gain saturation of the TE mode differs from the gain saturation of the TM mode. Therefore, the refractive index change of the TE mode also differs from the refractive index change of the TM mode, leading to the nonlinear polarization rotation (NPR) effect. Therefore, the sandwich configuration with a combination of PC-SOA-PC-polarizer functions as an intensity-dependent element, in order to equalize the power of multi-wavelength emission and suppress the mode competition [18]. The multi-wavelength selection device of our proposed fiber laser is a programmable filter which is realized by waveshaper (Finisar 4000S). The waveshaper can realize multi-channel narrowband optical filters with arbitrary setting of both center wavelength and channel bandwidth, while the operation wavelength of waveshaper can cover the wavelength range of 1,530–1,565 nm with a wavelength resolution of 1 GHz. By setting response of the programmable filter, a comb filter with continuous tunability of wavelength spacing and channel numbers can be achieved. Since the insertion loss of the used waveshaper is 9.5 dB, an EDFA following the polarizer is used to provide sufficient gain and compensates the loss of laser cavity. The unidirectional traveling wave in the laser cavity is realized using circulator 1. However, the fiber ring lasers may suffer from densely spaced multiple-longitudinal modes, because the minimum passband bandwidth of waveshaper is 10 GHz which is relatively larger than the cavity mode spacing. To guarantee an SLM operation, a high-finesse fiber ring (FR) is inserted into the cavity for expanding the effective free spectrum range. Besides that, circulator 1, circulator 2, a piece of 3 m unpumped EDF, PC3 and fiber mirror are combined as a saturable absorber (SA). Lots of research results verify that if the EDF is not under pump, it can modulate the laser light intensity based on the standing-wave filtering effect and thus might behave as a SA [26]. Therefore, mode hopping between the resonant frequencies, which are dominated by the FR, can be eliminated efficiently. Thus, both channel numbers and wavelength spacing tunable multi-wavelength fiber laser with the SLM operation can be achieved finally.

3 Experimental results and discussions

In the experiment, the bias current of SOA is set to 240 mA in order to provide 21 dB small signal gain. The total cavity insertion loss is 23 dB; in order to compensate the whole cavity insertion loss, a hybrid amplification including SOA and EDFA is chosen to provide sufficient gain. The programmable filter is initially set with dual-passband response. We set the bandwidth of passband to be 10 GHz, which is minimum passband bandwidth of waveshaper. The passband of used waveshaper is defined as full width at half maximum (FWHM), namely 3 dB bandwidth. The center wavelength of right passband is set at 1,567 nm. The wavelength spacing between two passbands is tunable with a range from 0.46 to 20.54 nm. By adjusting the PCs, stable dual-wavelength lasing is observed. Figure 2 shows the output spectra of the proposed tunable multi-wavelength laser with respect to the wavelength spacing. The

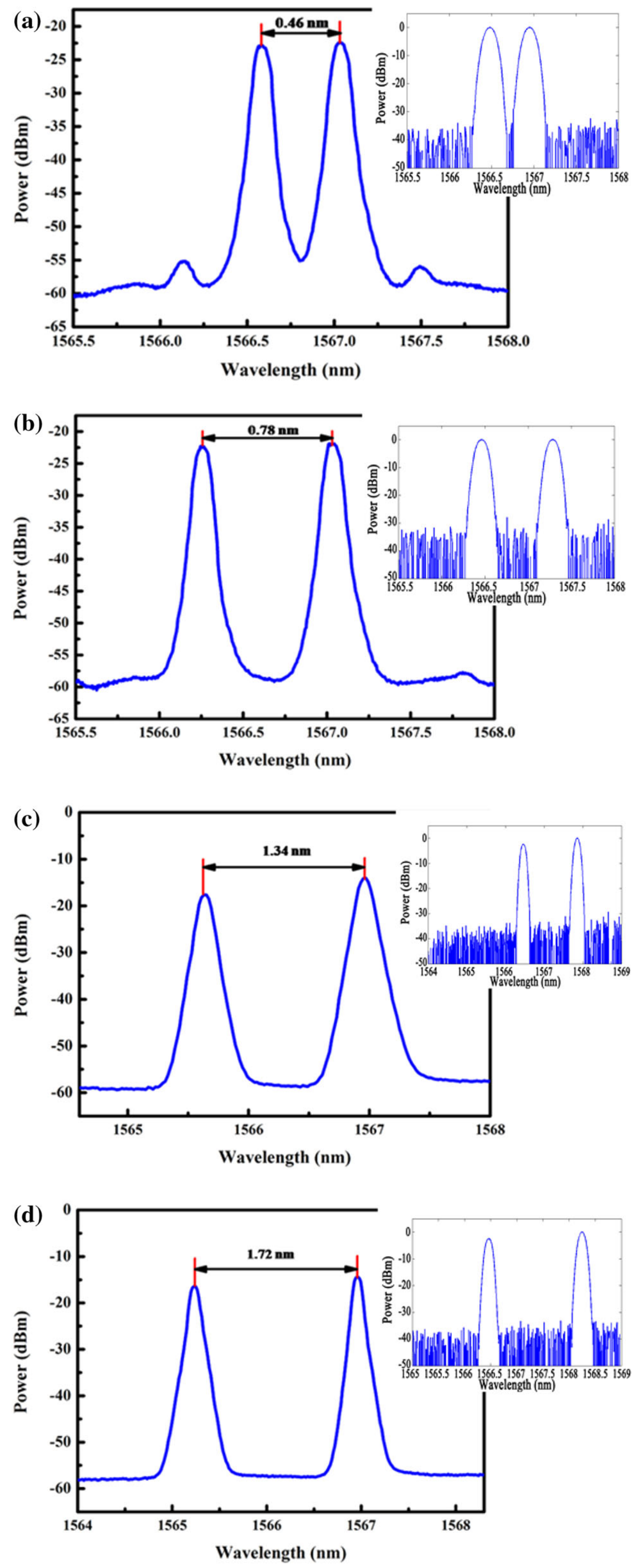

Fig. 2 Output spectra of the proposed multi-wavelength fiber ring laser with respect to the wavelength spacing, **a** 0.46 nm, **b** 0.78 nm, **c** 1.34 nm and **d** 1.72 nm. *Inset* **a**–**d**: the corresponding power transfer function of waveshaper

wavelength spacing between two emission wavelengths is determined by the programmable filter with stopband bandwidth of 50, 90, 150 and 200 GHz, respectively. Meanwhile, the power transfer function of individual programmable filter is shown at the insets of Fig. 2. The signal-to-spontaneous-noise ratio of two lasing lines is greater than 33 dB. When the wavelength spacing between two-wavelength laser is further reduced less than 0.46 nm, several four wave mixing components occur so that the carrier-to-noise ratio is greatly reduced. Due to the flat gain spectra of the SOA, wide wavelength spacing between two stimulated wavelengths is observed. The stopband bandwidth of the programmable filter has been set to be 1,500, 2,000, 2,300 and 2,500 GHz, respectively; the corresponding output spectra are shown in Fig. 3. The widest wavelength spacing between two wavelengths is 20.54 nm, due to the limited gain bandwidth of SOA. Thus, in our fiber ring laser scheme, the range of the tunable wavelength spacing between two stimulated wavelengths is found from 0.46 to 20.54 nm. The power difference between two laser channels is increased with the growth of wavelength spacing. The minimum power difference of 0.31 dB is realized at 0.46 nm wavelength spacing, while the maximum power difference of 1.89 dB is observed on the condition of 20.54 nm wavelength spacing. In our scheme, the number of stimulated wavelength is determined by the passband number of programmable filter setting. Fiber ring lasers of two, three and five wavelengths have been achieved with the number of passband set to be 2, 3 and 5, respectively. Due to the limited gain bandwidth of SOA and the wavelength-dependent insertion loss of waveshaper, the power difference among wavelength channels becomes worse with the growing number of lasing wavelength. On the condition of six-wavelength laser, the minimum power difference between arbitrary two wavelengths is larger than 10 dB. In Fig. 4, the power stability of two-wavelength lasing, three-wavelength lasing and five-wavelength lasing is monitored, respectively. During the power stability characterization, we filter out single wavelength of the proposed multi-wavelength fiber laser and measure the power variation using an optical power meter (Anritsu MA9331A optical sensor head plus MU931001A mainframe). The optical sensor head has a 3 dB bandwidth of 100 kHz, permitting us monitor the DC optical power precisely. Although the optical power meter enables measurement at a minimum interval of 1 ms due to the necessary time for recording and measuring function, an interval of 1 min is chosen for the purpose of clear presentation. The wavelength channel at 1,567.2 nm is chosen for the two-wavelength laser, three-wavelength laser and five-wavelength laser, respectively. We observe

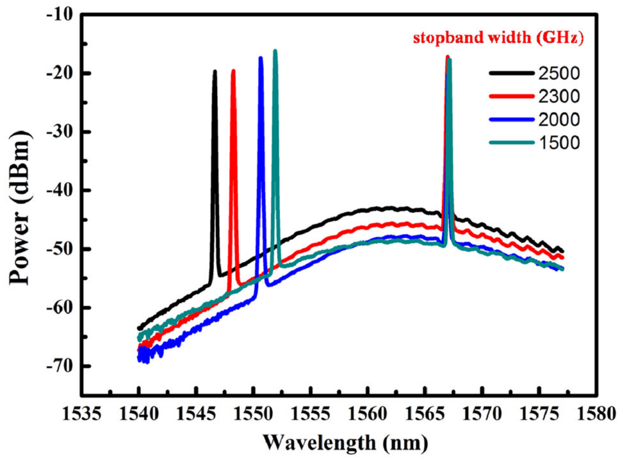

Fig. 3 Output spectra of the proposed multi-wavelength fiber laser with different wavelength spacing on the condition of two-wavelength lasing

that for the two-wavelength laser, the power fluctuation of designated channel is <0.1 dB after 2-h monitoring. For the three-wavelength laser, the value is less than 0.3 dB. For the five-wavelength laser, the corresponding value is smaller than 0.6 dB. The power stability of proposed multi-wavelength fiber laser is determined by the polarization and gain competition within the cavity. If the SOP is fixed, the power of individual wavelength channel can keep stable for a long time. Moreover, when the number of lasing channel is increased from 2 to 5, the NPR effect is weakened under a fixed SOA bias current. Consequently, the NPR effect cannot effectively suppress the gain competition among multi-wavelength lasing. The signal-to-spontaneous-noise ratio of the proposed fiber ring laser with different channel numbers is greater than 30 dB.

To verify the SLM operation, a 40 GHz photodetector (PD) and an electrical spectrum analyzer with 40 GHz operation frequency range are used for characterization. The programmable filter is set to have two 10 GHz passbands with 200 GHz stopband between them. A fiber Bragg grating (FBG)-based optical filter is employed to choose a specific wavelength channel from multi-wavelength fiber laser for the purpose of SLM characterization. The 3 dB bandwidth of optical filter, whose central wavelength is located at 1,567.2 nm, is 0.2 nm. Therefore, for the proposed multi-wavelength laser, the FBG-based optical filter with extinction ratio of 30 dB is unable to achieve SLM operation for a specific channel at 1,567.2 nm. Figure 5 shows electrical spectra of filtered channel from the proposed multi-wavelength fiber ring laser. When we remove the SA and high-finesse FR, we can observe lots of beating tones with equal frequency spacing, defined as the longitudinal mode spacing, within the PD bandwidth, as shown in Fig. 5a. Next, with the help of high-finesse FR inside the cavity, we can observe the

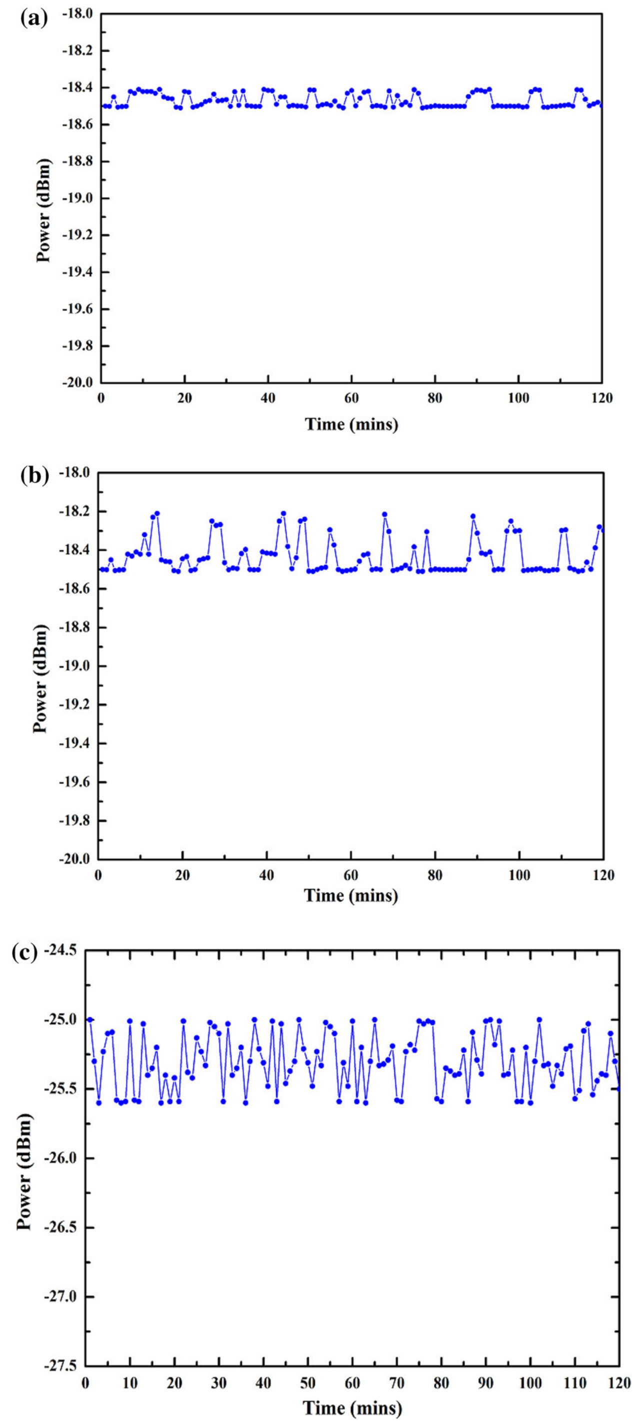

Fig. 4 Power fluctuation of specific wavelength channel filtered from the proposed multi-wavelength fiber ring laser at 1,567.2 nm. **a** two-wavelength lasing, **b** three-wavelength lasing and **c** five-wavelength lasing

beating tones are effectively suppressed, as shown in Fig. 5b. Moreover, the beat signals at the frequencies equal to the effective FSR of the FR and its harmonics are still observed. Therefore, we can estimate the effective FSR of the FR as 623 MHz, while the corresponding finesse is

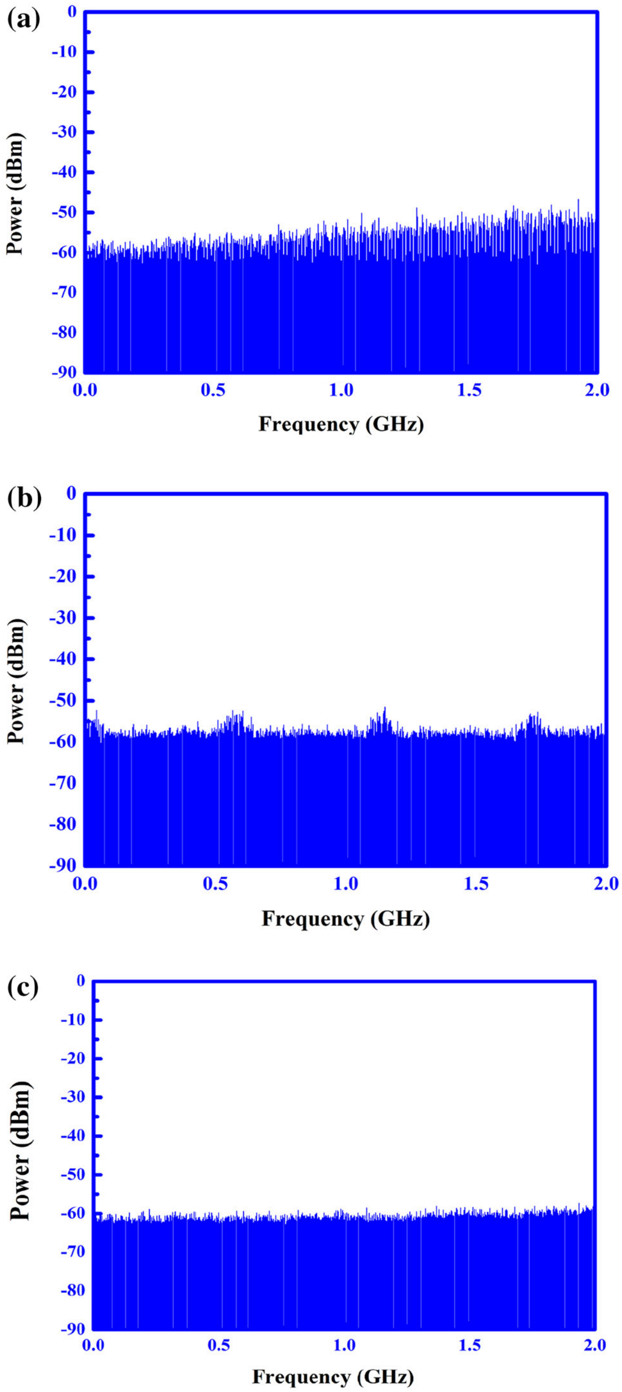

Fig. 5 Electrical spectra of specific wavelength channel filtered from the proposed multi-wavelength fiber ring laser, **a** without SA and high-finesse FR, **b** high-finesse FR employed without SA and **c** both high-finesse FR and SA are employed

around 20. Finally, the electronic spectrum, as shown in Fig. 5c, confirms the SLM operation when both a high-finesse FR and a SA are applied, because no beat signals can be observed at the whole scanning range of 2 GHz with a resolution of 10 kHz. To further investigate the

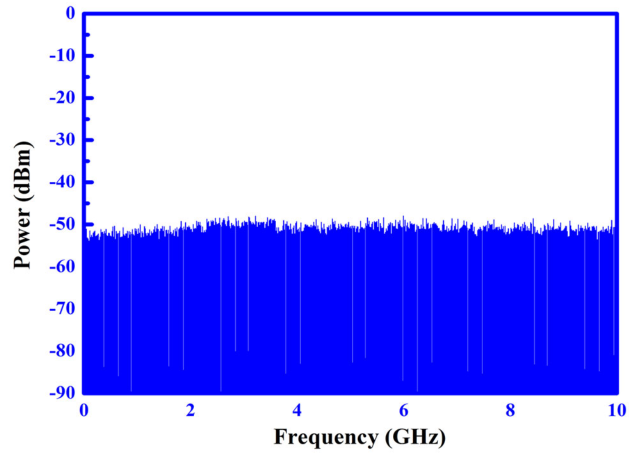

Fig. 6 Electrical spectrum of laser output using a high-finesse FR and a SA with a scanning range of 10 GHz

characteristics of electrical spectrum, the scanning frequency range is increased to 10 GHz with 50 kHz resolution. As shown in the Fig. 6, since only error floor is observed within the scanning frequency range which is larger than the longitudinal mode spacing, we can conclude that the filtered wavelength channel is under SLM operation. The linewidth of specific wavelength channel is defined in terms of the FWHM of the optical field power spectrum. Generally, delayed self-heterodyne measurement is implemented with Lorentzian fit to extract laser linewidth. The linewidth of the proposed fiber laser can be reduced from the several $\simeq$ MHz to sub $\simeq$ KHz. Therefore, the SLM operation in our proposed fiber laser is successfully verified.

4 Conclusion

We have proposed and experimentally demonstrated both channel numbers and wavelength spacing tunable multi-wavelength fiber ring laser under SLM operation. Compared with other schemes, both channel numbers and wavelength spacing can be flexibly and independently tuned. In particular, the proposed multi-wavelength laser is operated on the condition of SLM. The wavelength spacing over the operation range of 1,530–1,565 nm can be tuned from 0.46 to 20.54 nm with a resolution of 8 pm. In particular, the power and wavelength fluctuation of individual channel is less than 0.1 dB and 0.02 nm after 2-h monitoring. The proposed fiber ring laser scheme can be potentially used in photonic THz generation, high-resolution spectroscopy and optical fiber sensors.

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