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# Utilization of Reflective Semiconductor Optical Amplifier (RSOA) for Multiwavelength and Wavelength-Tunable Fiber Lasers

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Additional information is available at the end of the chapter

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## Abstract

In this chapter, there are three sections to demonstrate the reflective semiconductor optical amplifier (RSOA)-based fiber laser architectures for multiwavelength and wavelength-tunable operations. In the first section, we introduce an L-band multiwavelength laser by utilizing a C-band RSOA with a linear cavity, which is produced by a polarization controller (PC), an optical coupler (OCP), and a reflected fiber mirror (RFM). In the proposed RSOA laser scheme, two to seven wavelengths could be lased and created simultaneously in the L-band range, while the RSOA operates at various bias currents.

In the second section, we demonstrate a multiwavelength laser source by utilizing a C-band RSOA with dual-ring fiber cavity. In the measurement, the laser cavity is constructed by an RSOA, a 1×2 OCP, a 2×2 OCP, and a PC, respectively. Thus, 13–18 wavelengths around L-band could be produced simultaneously, as the bias current of C-band RSOA is driven at 30–70 mA.

**Keywords:** RSOA, SOA, Multiwavelength, Wavelength-tunable

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## 1. Introduction

Recently, the wavelength-tunable and multiwavelength fiber laser schemes are very essential for several optical applications, such as the wavelength-division-multiplexed (WDM) communication systems [1], optical testing and measurement [2], fiber optics sensor [3], and radio-frequency (RF) photonics [4]. Therefore, the different laser resonators for the multiwavelength lasing have been proposed and investigated, such as utilizing the dual Sagnac loop [5], fiber ring cavity [6], compound ring scheme [7], and Fox–Smith ring cavity [8].

To achieve wavelength lasing, several gain media approaches have been proposed and utilized, such as the erbium-doped fiber amplifier (EDFA) [9], semiconductor optical amplifiers (SOA) [5,10], reflective semiconductor optical amplifiers (RSOA) [11], Raman amplifier [12], and hybrid optical amplifier [13]. However, SOA would be a better option over EDFA due to the nature of inhomogeneous broadening. As a result, the past SOA-based lasers have been also proposed and investigated to generate multiwavelength output at room temperature [14, 15].

Generally, to accomplish a wavelength-tunable output with single longitudinal mode (SLM), the several wavelength selective elements (optical filters) and laser architectures have been used inside ring cavity. The proposed fiber lasers could be designed in linear or ring architectures [16, 17]. Besides, the fiber Fabry–Perot filter (FFPF), tunable bandpass filter (TBF), and fiber Bragg grating (FBG) could be utilized inside the fiber ring cavity to select different wavelength lasing. In fact, owing to the limited gain amplification of the amplifiers, the output power would drop rapidly on both sides of their operating bandwidth [16–18].

In this chapter, there are three sections to demonstrate the RSOA-based fiber laser architectures for multiwavelength and wavelength-tunable operations. In section 2, we propose an L-band multiwavelength laser by utilizing a C-band RSOA with a linear cavity, which is produced by a polarization controller (PC), an optical coupler (OCP), and a reflected fiber mirror (RFM). In the proposed RSOA laser scheme, two to seven wavelengths could be lased and created simultaneously in L-band range, while the bias-current of RSOA is operated at various bias currents.

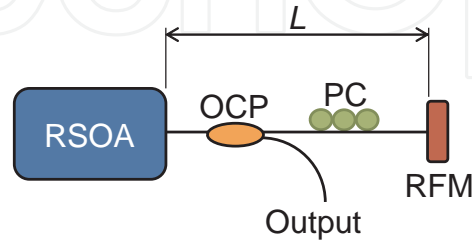
In section 3, we demonstrate a multiwavelength laser source by utilizing a C-band RSOA with dual-ring fiber cavity. In the measurement, the laser cavity is constructed by an RSOA, a 1×2 OCP, a 2×2 OCP, and a PC, respectively. Thus, 13–18 wavelengths around the L-band could be produced simultaneously, as the bias current of C-band RSOA is driven at 30–70 mA.

In section 4, we investigate the wavelength-tunable fiber ring laser architecture by using the RSOA and SOA. Here, the wavelength tuning range of 1538.03–1561.91 nm can be obtained. The measured output power and optical signal-to-noise ratios (OSNRs) of the proposed fiber laser are between –0.8 and –2.5 dBm and 59.1 and 61.0 dB/0.05 nm, respectively. The power and wavelength stabilities of the proposed laser are also studied. Besides, the proposed laser can be directly modulated at 2.5 Gbit/s quadrature phase shift keying-orthogonal frequency division multiplexing (QPSK-OFDM) signal. In addition, 20–50 km single-mode fiber (SMF) transmission distances are also achieved within the forward error correction (FEC) limit without dispersion compensation. We believe that it can be a cost-effective and promising candidate for next-generation wavelength-division multiplexed-passive optical network (WDM-PON).

## 2. Linear cavity for multiwavelength lasing

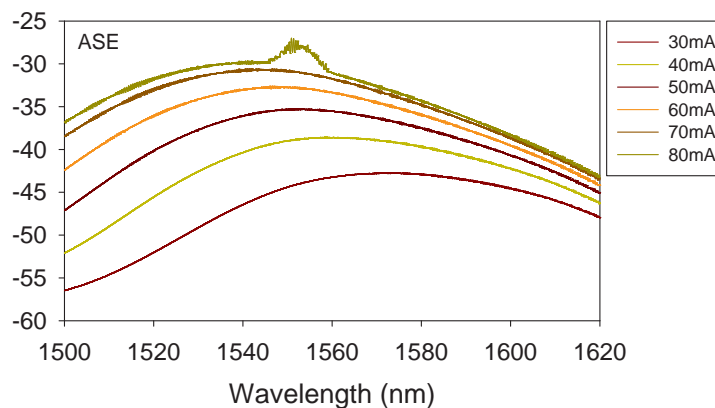
In the section, we present and demonstrate using the C-band RSOA with a linear fiber cavity to produce multiwavelength in the L-band range at room temperature [19]. Hence, two to

seven lasing wavelengths could be observed by adjusting the DC bias currents of the RSOA. Fig. 1 shows the experimental setup of the proposed multiwavelength fiber laser scheme. The laser is constructed by an RSOA, a PC, a 1×2 and 50:50 OCP, and an RFM with 95% reflection in C + L bands. In the experiment, the bias current range of RSOA (*produced by CIP*) is between 30 and 80 mA. In addition, the PC can be used to maintain the polarization state and obtain a maximum output power. Moreover, the output wavelength spectrum is observed by an optical spectrum analyzer (OSA) with a resolution of 0.01 nm.



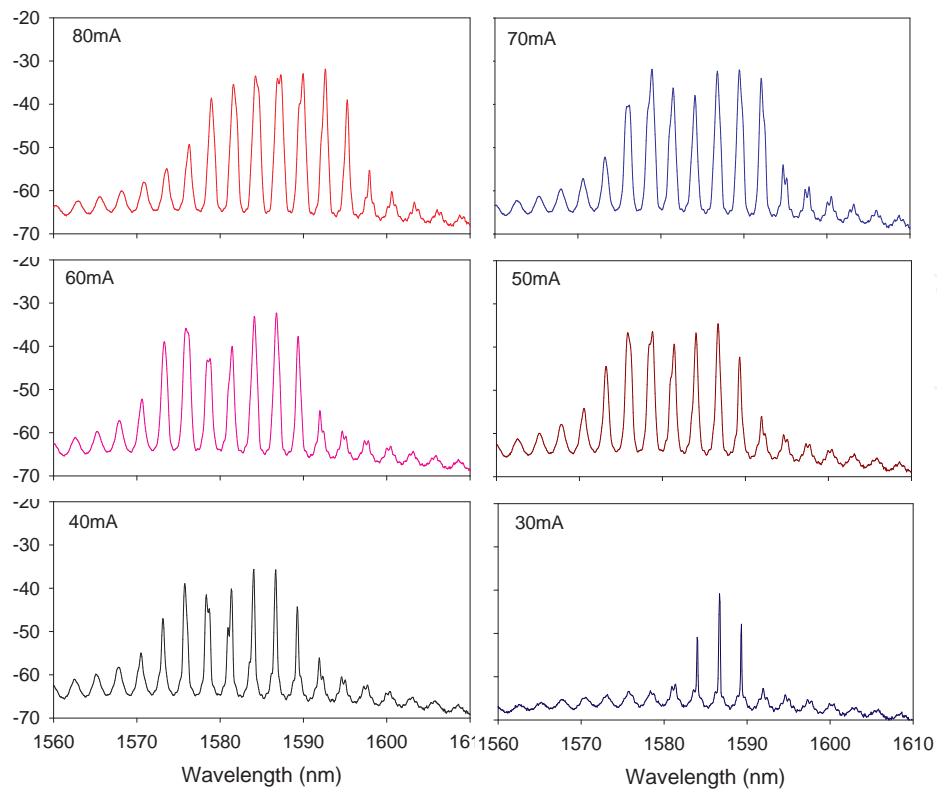
**Figure 1.** Experimental setup of the proposed fiber laser scheme in linear cavity scheme.

Hence, first we measure and observe the output amplified spontaneous emission (ASE) profile of RSOA in the bias currents of 30–80 mA. As illustrated in Fig. 2, when we increase the DC, the observed output power of the ASE also raises. And the center wavelength of the ASE would drift to shorter wavelength locations. In addition, the gain spectrum of the RSOA is observed at C-band in the entire operated currents.



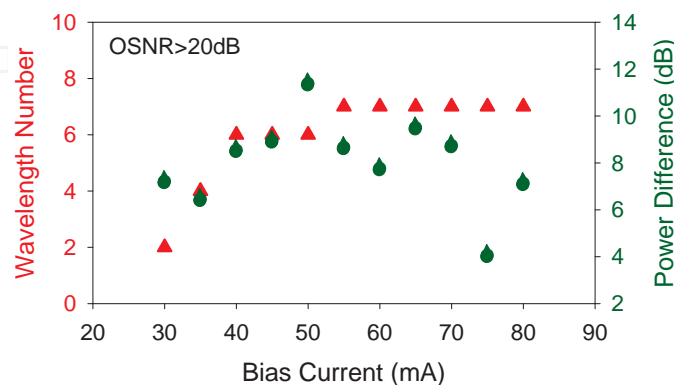
**Figure 2.** The output ASE spectra of RSOA at the operated currents of 30–80 mA.

In the proposed RSOA-based laser scheme, multiwavelength could be produced under the accurate polarization statement. Hence, Fig. 3 shows the observed output spectra of proposed multiwavelength RSOA laser at the bias currents of 30–80 mA. In the measurement, we obtain that seven wavelengths are generated simultaneously as the operated current of RSOA is larger than 40 mA. As a result, the threshold current of the laser is around 40 mA in the proposed laser scheme. While the operated currents are 80, 70, 60, 50, 40, and 30 mA, respectively, the



**Figure 3.** Output spectra of proposed fiber laser at the bias currents of 30–80 mA.

lasing wavelengths are also observed at 1592.62, 1578.88, 1586.74, 1586.68, 1586.68, and 1586.68 nm. Previous researches presented that in high input power, the SOA would show a peak gain drift toward longer wavelength range [20]. Thus, the proposed multiwavelength RSOA lasers are produced in the L-band window rather than the C-band in the lasing condition under a high feedback power. As shown in Fig. 3, the mode spacing of proposed laser is nearly 2.7 nm at various bias currents. Furthermore, when we increase the bias current of RSOA gradually, the lasing multiwavelength also drifts to longer wavelength range, as seen in Fig. 3.



**Figure 4.** The number of lasing wavelength in the proposed laser, when the OSNR is larger than 20 dB.

Fig. 4 presents the number of lasing multiwavelength and the peak power difference among these wavelengths as the OSNR is larger than 20 dB. When lasing wavelengths larger than six are required, the bias current must be larger than 40 mA. Here, Fig. 4 displays the power variation ( $\Delta P$ ) of lasing multiwavelength at the different operated currents. The maximum and minimum power differences of 11.3 and 3.9 dB are observed, respectively, under the current of 50 and 75 mA. Besides, as seen in Fig. 5, we also execute the output power of proposed RSOA laser under a bias current range of 25–80 mA. According to the measured result, the observed output powers are between 0.001 and 0.223 mW.

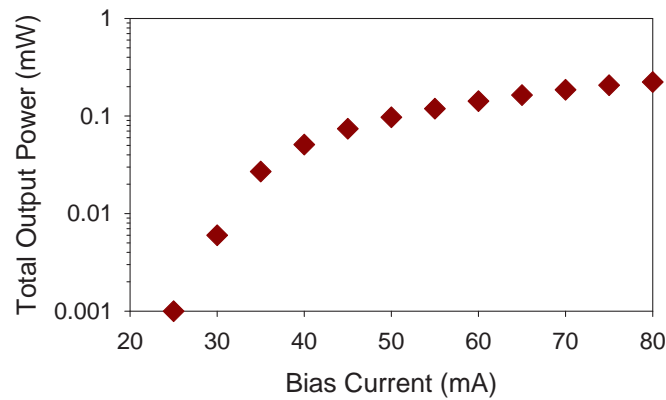


Figure 5. Total output power of proposed fiber laser at the bias currents of 25–80 mA.

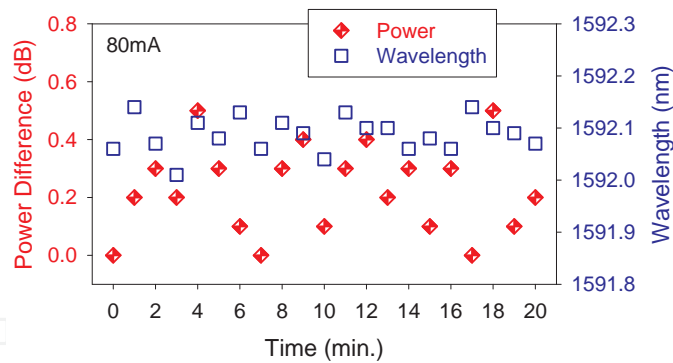
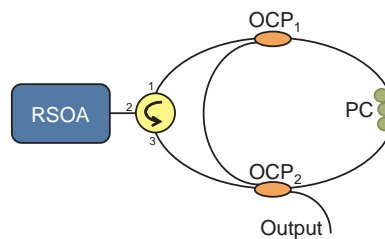


Figure 6. Wavelength and power variations of the proposed multiwavelength fiber laser in an observing time of 20 minutes.

Finally, the output stability testing of proposed multiwavelength RSOA laser is made to execute the output performance of power and wavelength. In this experiment, the RSOA is operated at 80 mA current. Besides, we select one of the lasing lightwaves at 1592.06 nm initially for measurement. Here, the observation time is set at 20 minutes. As seen in Fig. 6, the output power and wavelength variations are measured at  $\pm 0.25$  dB and  $\pm 0.065$  nm, respectively. Hence, the results present that the proposed multiwavelength RSOA laser has the excellent optical output stabilities for future system application. In addition, under 2 hours observing time, the measured output stabilities of the proposed laser are still maintained.

### 3. Dual-ring cavity for multiwavelength lasing

In this section, we introduce and demonstrate the multiwavelength fiber laser source by employing a C-band RSOA with a dual-ring fiber cavity [21]. Thus, experimental setup of the proposed multiwavelength RSOA-based laser scheme with a dual-ring cavity design is shown in Fig. 7. The proposed laser is composed of a C-band RSOA, a PC, a 1×2 OCP, a 2×2 OCP, and an optical circulator (OC). Here, two OCPs could create a dual-ring cavity of proposed fiber laser scheme. The OC is used to generate a counterclockwise direction. The PC, which is placed in the ring cavity, is used to maintain the polarization state and obtain a maximum output power.

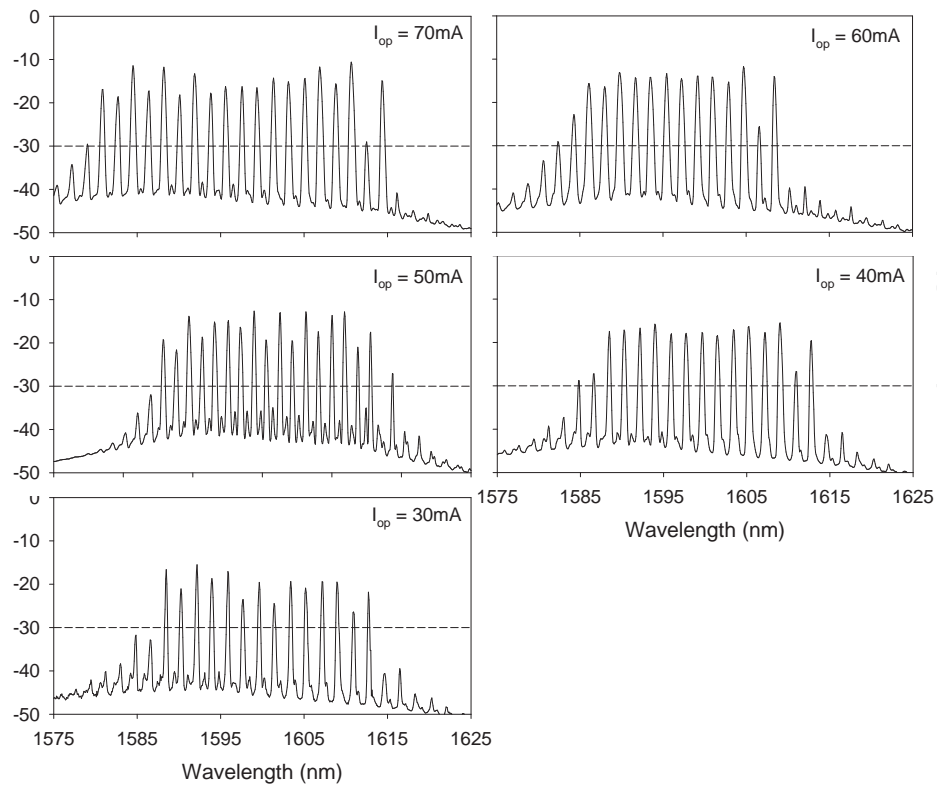


**Figure 7.** Experimental setup of the proposed RSOA-based fiber ring laser.

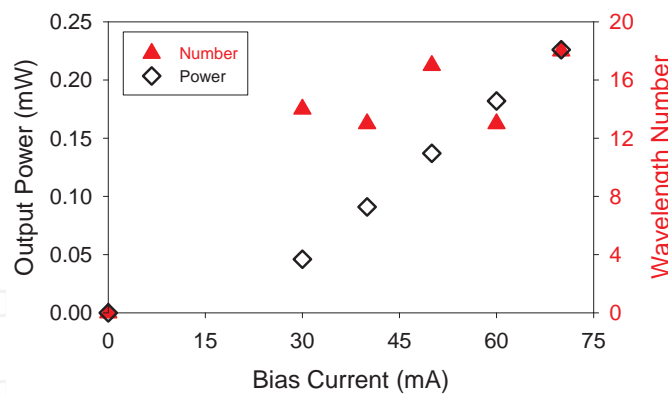
In the proposed RSOA-based dual-ring scheme laser, the generated multiwavelength would be obtained under a proper polarization tuning. Here, Fig. 8 displays the observed output spectra of proposed RSOA laser in the bias current range of 30–70 mA. As seen in Fig. 8, when the OSNR of each wavelength is larger than 20 dB and the bias current of RSOA is 30 mA, the proposed RSOA-based laser can emit ~14 wavelengths simultaneously. The multiwavelength output range could be observed at the wavelengths of 1588.48–1612.71 nm. Besides, if the bias current of RSOA is less than 30 mA, the proposed laser cannot generate any wavelength. Thus, the threshold current of the proposed fiber laser is around 30 mA. As illustrated in Fig. 8, while the bias current of RSOA is 40, 50, 60, and 70 mA, respectively, the output wavelength range of proposed RSOA laser is observed at 1588.48–1612.71 nm, 1580.74–1613.70 nm, 1584.22–1608.37 nm, and 1580.81–1614.34 nm.

In this study, the maximum peak powers of the output wavelengths are obtained at 1592.18, 1593.95, 1593.81, 1604.68, and 1610.65 nm, while the bias currents of RSOA are 30, 40, 50, 60, and 70 mA, respectively. Previous studies presented that under high input power, the SOA would show a peak gain drift toward longer wavelength range [20]. Thus, the proposed multiwavelength RSOA-lasers are produced in the L-band window rather than the C-band in the lasing condition under a high feedback power. Moreover, if the bias current of RSOA increases gradually, the output multiwavelength also drifts to a longer wavelength range. Moreover, the measured mode spacing is nearly 1.9 nm in the proposed fiber laser at different operating current ranges.

Then, Fig. 9 presents the number of lasing wavelengths under the OSNR of >20 dB. In this measurement, when the various bias currents of 30–70 mA are used, 13–18 multiwavelengths



**Figure 8.** Output spectra of proposed multiwavelength laser under the bias currents of 30–70 mA.

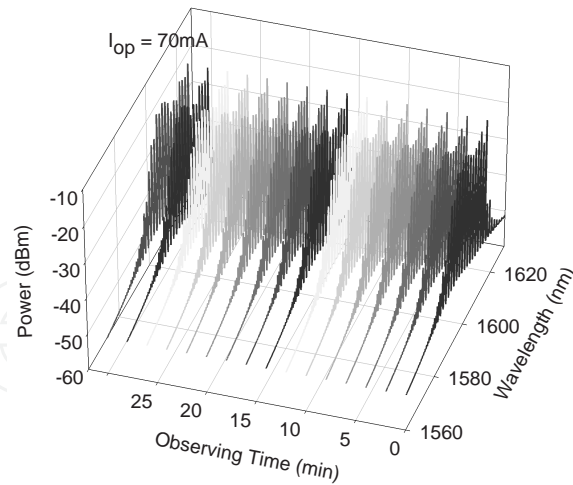


**Figure 9.** Measured number of lasing wavelengths and total output power of the proposed laser under different bias currents.

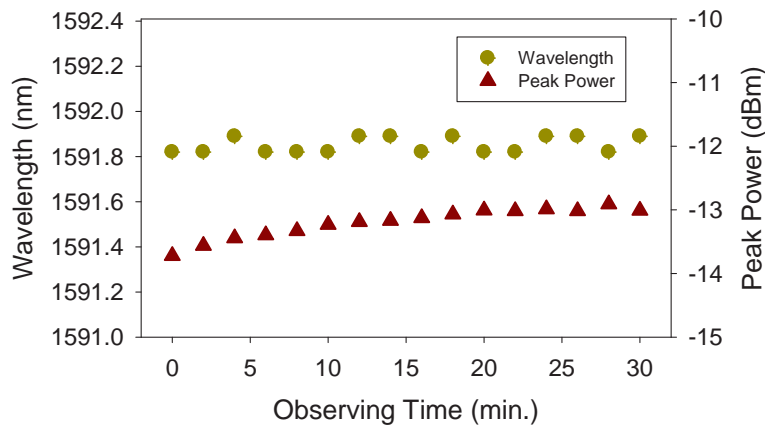
could be also measured. Besides, we also execute the output power of proposed RSOA-based laser under the bias current range of 30–70 mA as shown in Fig. 9. In addition, the output powers are observed at the range of 0.046–0.226 mW.

To verify the performance of output power and output wavelength, a short-term stability test of proposed multiwavelength laser is executed. In the measurement, the RSOA is set at 70 mA.





**Figure 10.** Output spectra of proposed RSOA-based laser under an observation of 30 minutes.



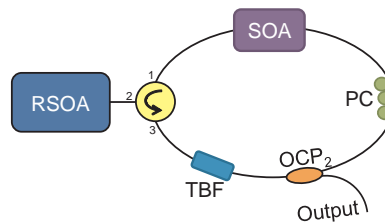
**Figure 11.** Output wavelength and the power fluctuations of the proposed fiber laser in an observing time of 30 minutes.

Then, Fig. 10 shows the output stability of proposed RSOA-based laser under an observation time of 30 minutes. Initially, one of lasing wavelength is chosen at 1591.82 nm with peak power  $-13.9$  dBm for stability measurement. As illustrated in Fig. 11, the output power and wavelength fluctuations of 0.4 dB and 0.07 nm are completed, respectively, in an observing time of 30 minutes. As a result, experimental results show that the proposed fiber laser has excellent output stabilities. In addition, after 2-hour observing measurement, the measured output stabilities of the proposed laser are still maintained.

#### 4. Wavelength-tunable laser in single mode

In the final section, a stable and continuous wavelength-tuning ring laser scheme using a C-band RSOA and a C-band SOA in the wavelength-tuning range of 1538.03–1561.91 nm is proposed and demonstrated for serving as the upstream transmitter (Tx) of colorless optical

network unit (ONU) [22]. Here, Fig. 12 presents the experimental setup of the proposed wavelength-tunable fiber ring laser scheme. The fiber laser consists of a C-band SOA, a C-band RSOA, a three-port optical circulator (OC), a 1×2 OCP, a PC, and a C-band tunable bandpass filter (TBF). The SOA is commercially available (*GIP, OAU116BB128001A*). Its gain is around 9 dB. The SOA is fixed at 120 mA pumping current and the bias current of RSOA is operated at 50, 60, 70, and 80 mA, respectively, in the experiment. The TBF is utilized inside a ring cavity for wavelength selection. The 3-dB bandwidth, tuning range, and insertion loss of TBF are 0.4 nm, 30 nm (1530–1560 nm), and ~6 dB, respectively. The PC is employed to vary the polarization status for maintaining the maximum output power. As seen in Fig. 12, a ring laser cavity is formed in which the gain media are the SOA and RSOA. Moreover, the TBF selects the desired wavelength within the gain bandwidth of the SOA. Then the signal will launch into the RSOA, which is modulated directly by data; hence, the optical signal can be modulated. Then, the modulated optical signal is observed at the output port of the laser via an OCP. The cavity length of the laser is estimated to be ~34.5 m.

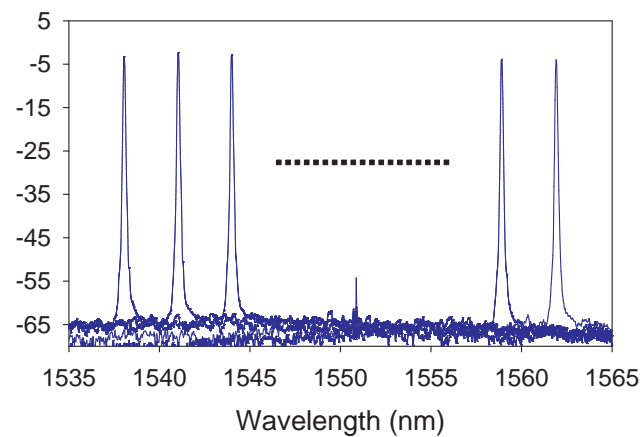


**Figure 12.** Experimental setup of proposed stable wavelength-tunable fiber ring laser.

Fig. 13 shows the output spectra of proposed fiber ring laser in the wavelength range of 1538.03–1561.91 nm, since the bias currents of the SOA and RSOA are 120 and 80 mA, respectively. The tunability of the fiber laser is continuous, and the wavelength tuning is performed by using the TBF. The measured peak power of lasing wavelength is between –3.9 and –2.8 dBm in this wavelength range. The observed background noise of lasing wavelength is below –61 dBm. As a result of cascading the SOA and RSOA inside the fiber cavity, the effective gain bandwidth range is enhanced and the output power of lasing wavelength in both sides of the spectrum could not drop rapidly, as shown in Fig. 13. However, other previous schemes would have a rapid drop of output power in both sides of the spectrum [23].

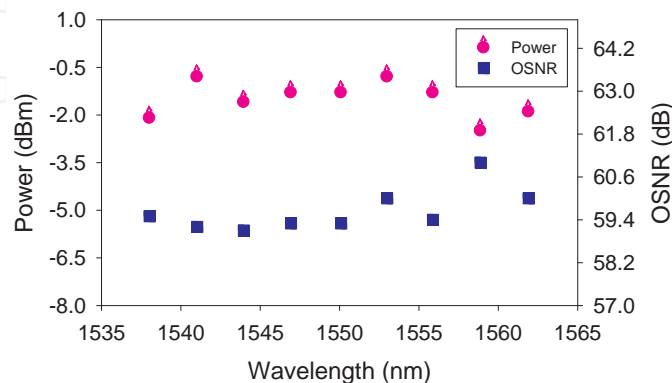
Fig. 14 displays the measured output power and OSNR in the lasing wavelengths from 1538.03 to 1561.91 nm. As seen in Fig. 14, the measured minimum and maximum output powers are –2.5 and –0.8 dBm at 1559.88 and 1541.03 nm, respectively. The maximum power difference ( $\Delta P$ ) is 1.7 dB in the lasing wavelength range. Moreover, the observed OSNR could be larger than 59.1 dB in this wavelength range. The maximum difference of OSNR measured is 1.9 dB, as illustrated in Fig. 14. Furthermore, utilizing the technique described in ref. [24], the relative intensity noise (RIN) of the proposed laser is –79.5 dB/Hz.

In the measurement, a 2.5-Gbit/s quadrature phase shift keying-orthogonal frequency division multiplexing (QPSK-OFDM) modulation format is applied on the RSOA of the ring laser for



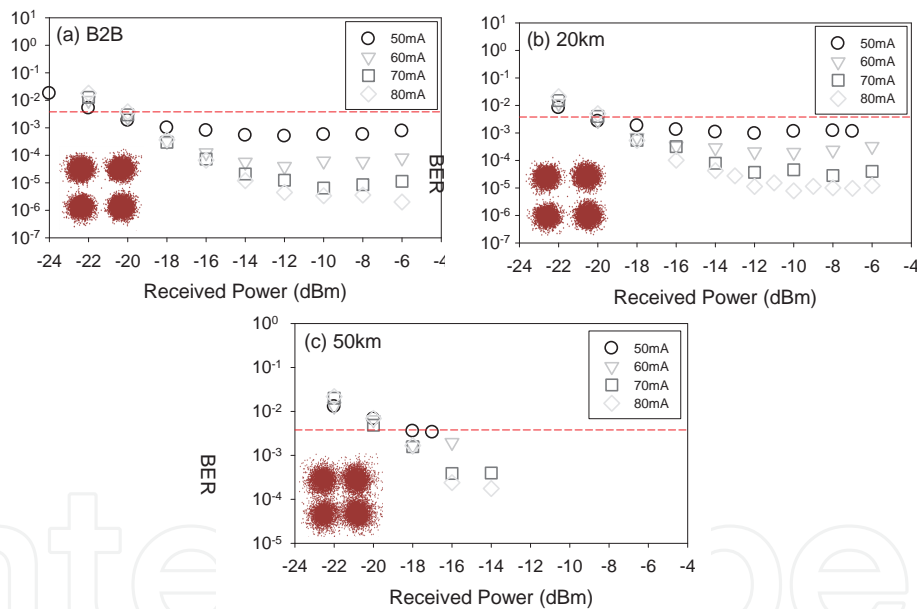
**Figure 13.** Output wavelength spectra of proposed fiber ring laser in the wavelength range of 1538.03–1561.91 nm, when the bias currents of SOA and RSOA are 120 and 80 mA.

direct signal modulation. Besides, the RSOA is designed to have a direct modulation bandwidth of  $\sim 1$  GHz. The QPSK-OFDM signal and the DC are combined and applied to the RSOA via a bias tee (BT). Here, the electrical OFDM baseband upstream signal could be created by using an arbitrary waveform generator (AWG) and the Matlab<sup>®</sup> program. The OFDM transmitter (Tx) signal consists of the serial-to-parallel conversion, QPSK symbol encoding, inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analog conversion (DAC) for signal processing. Here, the 63 subcarriers of QPSK-OFDM format occupy  $\sim 1.25$  GHz modulation bandwidth with a fast-Fourier transform (FFT) size of 128 and cyclic prefix of  $1/32$ . Therefore, a 2.5-Gbit/s total data rate is obtained. Then, the lasing wavelength signal would be detected directly via a 9-GHz PIN receiver (Rx), and the received OFDM signal can be taken by a real-time sampling oscilloscope for signal decoding. In order to demodulate the vector signal, the use of the off-line DSP program is required. And the demodulation processing covers the synchronization, FFT, zero forcing equalization, and QPSK symbol decoding. Therefore, the bit error rate (BER) is obtained from the observed signal-to-noise ratio (SNR).



**Figure 14.** Measured output power and optical signal-to-noise ratio (OSNR) in the lasing wavelengths of 1538.03–1561.91 nm.

For the next experiment, the bias current of SOA is fixed at 120 mA, while the RSOA is operated at the DC bias current of 50, 60, 70, and 80 mA, respectively. The lasing wavelength is selected at 1553.0 nm for performance testing. Figs. 15(a) to 15(c) show the BER performances of proposed laser at the back-to-back (B2B) status and after 20 and 50 km fiber transmissions, respectively, when the RSOA is operated at 50, 60, 70, and 80 mA. And the insets of Figs. 15(a) to 15(c) are corresponding constellations at the BER of  $3.8 \times 10^{-3}$  (the FEC threshold) under the B2B and after 20 and 50 km SMF transmissions, respectively, when the SOA and RSOA are 120 and 80 mA. As seen in Figs. 15(a) to 15(b), the optical power penalties are 0.5 and 3.3 dB (RSOA@50mA); 0.6 and 1.8 dB (RSOA@60mA); 0.3 and 1.2 dB (RSOA@70mA); and 0.2 and 1 dB (RSOA@80mA), respectively, after 20 and 50 km SMF transmissions at FEC threshold. Moreover, the optical sensitivities of received powers are also observed in Fig. 15, at the B2B and after 20 and 50 km fiber transmissions, respectively, when the RSOA is operated at 50, 60, 70, and 80 mA and SOA is fixed at 120 mA. At the B2B status and after 20 km fiber transmission, by increasing the bias current of RSOA gradually, the received powers are also increased, as seen in Fig. 15. However, when the bias current of RSOA is increased after 50-km fiber transmission, the optical received sensitivities could be enhanced. That means that the received power and penalty can be improved after 50-km fiber transmission, when the bias current of RSOA is increased to 80 mA.



**Figure 15.** BER performances of proposed laser (a) at the B2B and (b) after 20- and (c) 50-km fiber transmissions, respectively, when the RSOA is operated at 50, 60, 70, and 80 mA. And the insets are corresponding constellations at the FEC threshold.

## 5. Conclusion

In conclusion, we have introduced three RSOA-based fiber laser architectures for multiwavelength and wavelength-tunable operations in three different laser architectures. In the first section, we have demonstrated an L-band multiwavelength laser by utilizing a C-band RSOA

with a linear cavity, which is produced by a PC, an OCP, and an RFM. In the proposed RSOA laser scheme, two to seven wavelengths could be lased and created simultaneously in the L-band range, while the RSOA operates at various bias currents.

In the second section, we have proposed a multiwavelength laser source by utilizing a C-band RSOA with dual-ring fiber cavity. In the measurement, the laser cavity was constructed by an RSOA, a 1×2 OCP, a 2×2 OCP, and a PC, respectively. Thus, 13–18 wavelengths around L-band could be produced simultaneously, as the bias current of C-band RSOA was driven at 30–70 mA.

In the final section, we have investigated the wavelength-tunable fiber ring laser architecture by using the RSOA and SOA. Here, the wavelength tuning range of 1538.03–1561.91 nm could be obtained. The measured output power and OSNRs of the proposed fiber laser were between –0.8 and –2.5 dBm and 59.1 and 61.0 dB/0.05 nm, respectively. The power and wavelength stabilities of the proposed laser were also studied. Besides, the proposed laser could be directly modulated at 2.5 Gbit/s QPSK-OFDM signal. And 20–50-km SMF transmission distances were also achieved within the FEC limit without dispersion compensation. We believe that it can be a cost-effective and promising candidate for next-generation WDM-PON.

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