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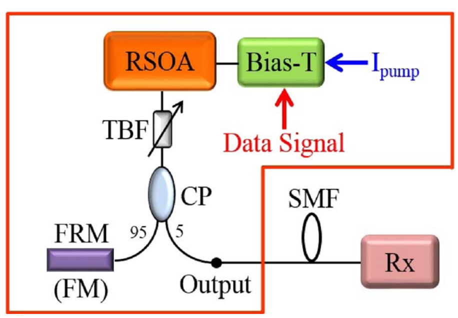


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# Stable and Wavelength-Tunable Self-Injected Reflective Semiconductor Optical Amplifier-Based Fiber Laser

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**Abstract:** In this investigation, we propose and demonstrate a stable and wavelength-tunable self-injected reflective semiconductor optical amplifier (RSOA)-based laser by using the Faraday rotator mirror (FRM) and the fiber mirror (FM) serving as a reflected element, respectively. Here, a 1.2-GHz RSOA can be enhanced to ~3 GHz by utilizing a self-injected mechanism. In the measurement, applying the optical orthogonal frequency-division multiplexing quadrature amplitude modulation (OFDM-QAM) with a bit-loading algorithm on the self-injected RSOA directly, the proposed laser can achieve a 3.5-Gb/s data rate in a 20-km single-mode-fiber transmission below a forward error correction (FEC) threshold. Moreover, the related output performance of the proposed RSOA-based laser is also discussed, whereas the FRM and the FM are utilized for comparisons.

**Index Terms:** Fiber lasers, fiber optics, communication optical.

## 1. Introduction

Stable and wavelength-tunable fiber laser sources have been widely used for different applications, such as the optical sensing, optical metrology, and optical wavelength division multiplexed (WDM) communication. Fundamentally, the wavelength-tunable lasers consisted of wavelength selecting components and optical gain media. Some optical devices and technologies were used to achieve wavelength selecting inside laser cavity [1]–[4] and various optical amplifiers [5]–[15] could be used in laser cavity to act as a gain media for wavelength lasing. And to achieve the laser cavity, either one needs some kind of reflector (mirror) to form a liner cavity [16] or one builds a fiber ring laser [17]. To achieve the higher modulation data rate in fiber laser scheme, the high spectral efficiency orthogonal frequency-division multiplexing quadrature amplitude modulation (OFDM-QAM) formats have been proposed and studied [18].

We propose a stable and wavelength-tunable self-injected RSOA-based laser utilizing a Faraday rotator mirror (FRM) serving as a reflected element inside a laser cavity. Hence, ~3 GHz bandwidth can be employed by the proposed RSOA laser due to self-injecting.

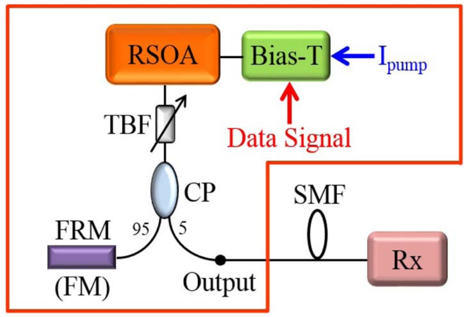


Fig. 1. Experimental setup of the proposed tunable self-injected RSOA-based laser.

Besides, the OFDM-QAM with bit-loading algorithms is applied on RSOA for data transmission. The measured performance of lasing wavelength and the output stabilities of proposed laser are also demonstrated and analyzed. We also use a conventional fiber mirror (FM) to replace the FRM for the comparison of optical output signal. When compared to the use of FM for serving as a reflector, using FRM not only can achieve 3.5 Gbit/s OFDM modulation rate within the forward error correction (FEC) requirement after 20 km fiber transmission but attains more stabilized output performance in terms of power variation as well.

However, the data rate in the experiment is limited by the modulation bandwidth of the RSOA. The typical modulation bandwidth of RSOA is 1–2 GHz. Higher modulation bandwidth can be achieved by optimizing the design of the RSOA [19]–[21]. However, all these increase the system complexity. In our experiment, we only deployed the self-injection RSOA-based scheme using spectral-efficient orthogonal frequency division multiplexing (OFDM) format with bit-loading; and the maximum data rate is around 3.5 Gb/s. By applying special design and other external equalization schemes, much higher data rates can be expected. Furthermore, both [22] and our proposed work depend on the self-injection. However, in [22], the injected wavelength should match with the longitudinal modes of FP-LD by proper selecting the wavelength of the fiber Bragg grating (FBG). Besides, higher injection power is required. In our scheme, wavelength matching is not needed; hence, the scheme may be simpler.

## 2. Experimental Setup and Discussion

Experimental setup of the proposed RSOA-based fiber laser by using the Faraday rotator mirror (FRM) or fiber mirror (FM) acting as a reflected element to achieve the self-injected mechanism is illustrated in Fig. 1.

The proposed fiber laser consists of a 1.2 GHz C-band RSOA, a C-band tunable band-pass filter (TBF), a $1 \times 2$ optical coupler (CP) with 95:5 spilt ratio, and a FRM / FM. In the experiment, the 1.2 GHz RSOA is operated at 70 mA bias current and provides 20 dB small signal gain with 10 dBm saturated output power. The polarization dependent gain of the RSOA is less than 3 dB. Here, the TBF (1528 $\sim$ 1563 nm) is used to perform tunable wavelength selection in the proposed fiber laser. The FRM / FM is connected to the 95% port of the $1 \times 2$ CP for serving as a reflected element. The 5% port of the $1 \times 2$ CP is the output of the proposed RSOA-based laser. The FRM could provide $90^\circ \pm 2^\circ$ rotational angle of polarization at 1550 $\pm$ 6 nm, and the FM could be operated at 1530 $\sim$ 1560 nm with 99% reflection.

The proposed RSOA laser can be directly modulated by utilizing the OFDM-QAM with bit-loading algorithm and the OFDM symbol is encoded offline by using MATLAB. A serial binary stream is transformed into multiple parallel streams. Then, each parallel binary stream is mapped into specific QAM symbols. Inverse fast Fourier transform (IFFT) operation with 512 IFFT size is performed on the QAM symbols to generate the digital OFDM symbols. 1/32 cyclic prefix (CP) is inserted in each OFDM symbol to mitigate the dispersion induced performance degradation. The encoded digital OFDM symbol is transferred into an arbitrary waveform generator (AWG) and transformed into analogue electrical signal through a digital-to-analogue converter (DAC).

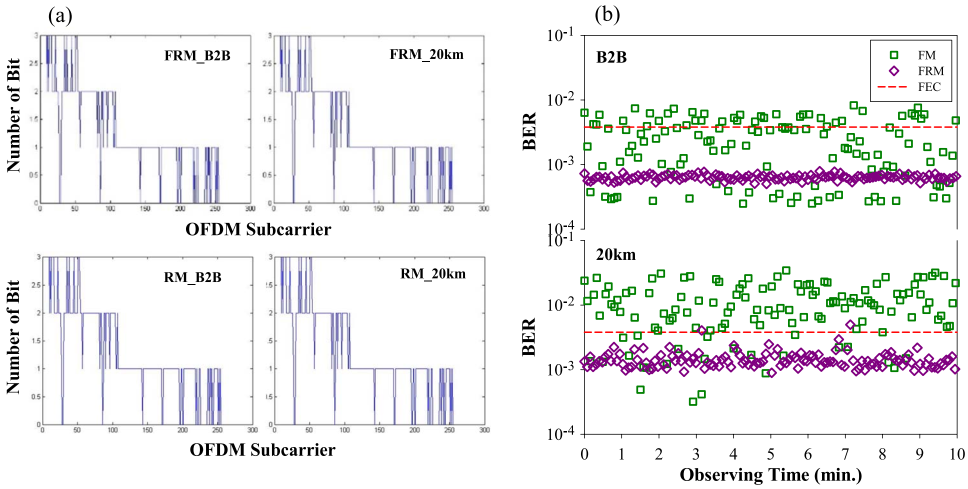


Fig. 2. (a) Bit allocations under different OFDM subcarriers. (b) Stability of BER measurement.

6 Gsample/s sampling rate and 8-bit DAC resolution is set for the AWG. At the receiver (Rx) side, the optical signal is directly detected by a pre-amplified 10 GHz PIN photodiode (PD) cascaded by a real-time oscilloscope with 20 Gsample/s rate for signal demodulation. The OFDM signal is decoded offline by reverse process of the encoder. The bit error rate (BER) of the signal is estimated by the QAM constellations distribution of each OFDM subcarrier.

First, in the experiment, the output wavelength of 1550.0 nm is selected in the proposed RSOA laser. Due to the self-injected operation in the proposed laser scheme, nearly 3 GHz modulation bandwidth can be employed. In order to investigate the maximum modulated rate, we use the 256 OFDM subcarriers occupying in the frequency of 0.0117 to 2.9883 GHz for the related signal to noise ratio (SNR) measurement. Hence, Fig. 2(a) and (b) show the bit allocations under different OFDM subcarriers in our proposed fiber laser scheme by using the FRM and FM, respectively, at the back-to-back (B2B) state and 20 km SMF transmission. In the experiment, the entire bit numbers are obtained between 0 and 3 whether at the B2B state or after 20 km SMF transmission, as shown in Fig. 2(a). As a result, the total data rate of proposed RSOA-based laser could be achieved at 3.5 Gbit/s by using OFDM-QAM with bit-loading method.

Then, to realize and investigate the output stability of the self-seeding RSOA laser, we perform the corresponding BER measurements when the output wavelength is set at 1550.0 nm. And we set the received power of $-14$ dBm at the receiver (Rx) side for ensuring the minimum BER measurement, while the FRM and FM are used respectively in the proposed RSOA laser scheme. Fig. 2(b) prevents the stability of BER measurement. In the B2B status, the average BERs are both obtained bellow the forward error correction (FEC) threshold ($\mathrm{BER} = 3.8 \times 10^{-3}$) for while the FRM and FM are utilized respectively. Here, the BER fluctuations intensely are observed between $8.3 \times 10^{-3}$ and $2.5 \times 10^{-4}$ and $7.9 \times 10^{-4}$ and $5.0 \times 10^{-4}$ when the FM and FRM are used, respectively However, in the 20 km fiber transmission, the average BER in the case of using FRM is below the FEC threshold and the BER oscillate slightly around $10^{-3}$. Besides, in the case of using FM, the BER fluctuation is change dramatically between $10^{-1}$ and $10^{-4}$. As a result, we could obtain the better the output performance of proposed RSOA laser, when the FRM is employed in proposed laser configuration.

Next, we also execute the BER performance of proposed self-seeding RSOA laser under different received power. As shown in Fig. 3(a), when the FM is used for acting as a reflector, the BER cannot achieve the FEC limit after 20 km fiber transmission. Even though the received power is set up to $-14$ dBm, the measured BER cannot be below the FEC threshold. And the power penalty is $\sim$2.6 dB after 20 km fiber transmission when the FRM is utilized. Besides, the signal performance also can be indicated by comparing the OFDM diagrams with bit-loading

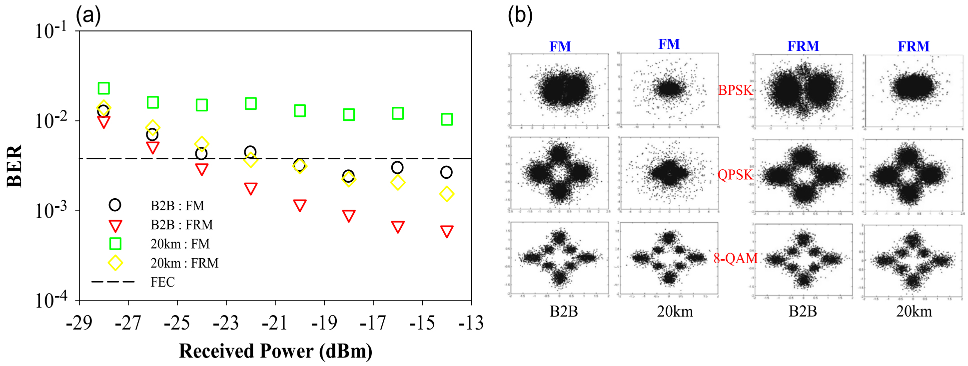


Fig. 3. (a) BER performance measurement at the 1550 nm. (b) Related OFDM constellation diagrams.

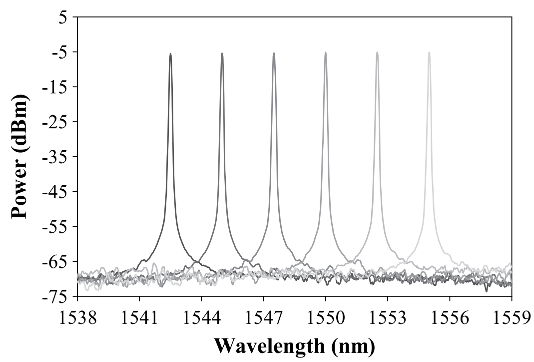


Fig. 4. Output spectrum of proposed RSOA-based laser at the different wavelength.

algorithm. Hence, the corresponding constellation diagrams are shown in Fig. 3(b) while the FM and FRM is employed respectively. The constellation diagrams are clearer and more concentrated by implementing a FRM-based reflector after 20 km fiber transmission especially.

Here, the FRM is a wavelength-dependent component and provides $90^\circ \pm 2^\circ$ rotational angle of polarization at the wavelength range of $1550 \pm 6$ nm. Thus, we would perform the output performance of the self-seeding RSOA laser using the FRM as a reflector for lasing wavelength. In the measurement, an optical spectrum analyzer (OSA) with a 0.1 nm resolution is employed to measure the wavelength spectrum. Fig. 4 shows the optical output spectra of proposed RSOA laser at the wavelengths of 1542.5, 1545.0, 1547.5, 1550.0, 1552.5, and 1555.0 nm respectively, with 2.5 nm tuning step. Here, the measured optical signal to noise ratio (OSNR) of each lasing wavelength could be larger than 60 dB and the amplified spontaneous emission (ASE) noise is distributed around $-68$ dBm, as seen in Fig. 4, and the maximum power variation of the six lasing wavelengths is 0.48 dB.

We also compute the BER fluctuation, defined as the standard deviation of sample BER normalizes the average BER value ($\phi$BER/BER), for the six wavelengths. The minimum and maximum BER fluctuations of 0.041 and 0.419 are observed at the wavelengths of 1547.5 nm and 1542.5 nm, respectively, as shown in Fig. 5(a). For the six lasing wavelengths, the corresponding power penalty is also investigated after 20 km fiber transmission. Hence, Fig. 5(b) illustrates the power penalty spectrum under the six lasing wavelengths. As illustrated in Fig. 5(b), the power penalty is larger at the edge of the wavelength range. In addition, the maximum and minimum power penalties are 8.77 dB and 0.01 dB at 1542.5 nm and 1552.5 nm, respectively. As mentioned above, the FRM is designed to rotate polarization at the wavelengths of $1550 \pm 6$ nm. Therefore, when the tuning wavelength exceeds the tuning range of 1542.5 to 1555.0 nm, the average BER would not achieve the FEC threshold after 20 km fiber transmission.

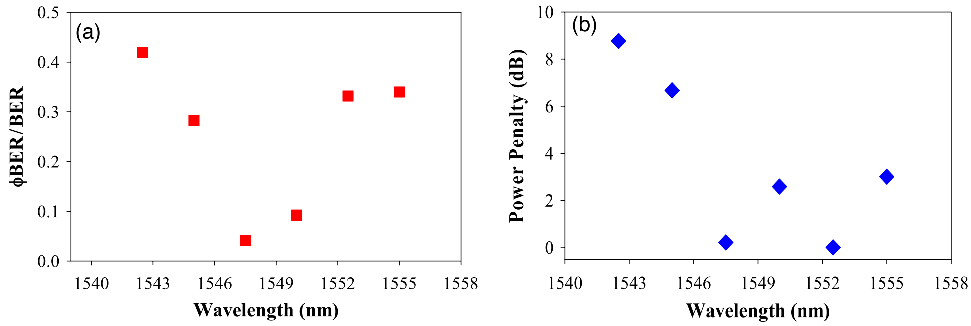


Fig. 5. (a) BER variation of proposed RSOA-based laser at the different wavelength. (b) Power penalty at the different wavelength.

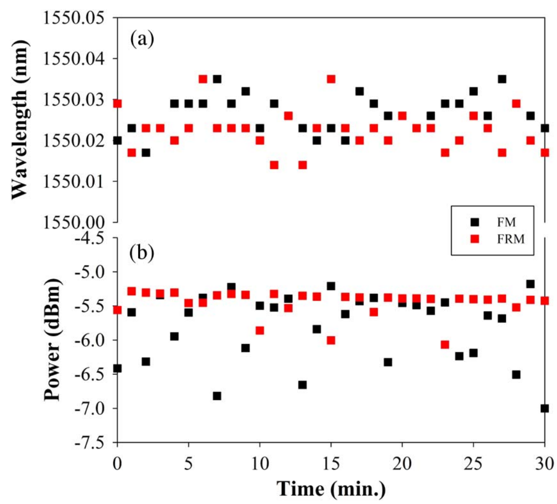


Fig. 6. Stability of proposed RSOA-based laser in terms of (a) wavelength and (b) power during 30 min. observing time.

Finally, we demonstrate the wavelength and power stabilities of the proposed self-injected RSOA laser using the FRM and FM to serve as a reflector, respectively, when the lasing wavelength is set at 1550 nm. We observe and record the wavelength and power variation of the laser source during 30 minutes observation time. Fig. 6(a) and (b) show the output stabilities of wavelength and power. We observed that the stability of output wavelength is similar. The wavelength variations of 0.021 and 0.018 nm are obtained, when the FRM or FM is used, respectively. However, the output power fluctuations are measured at 0.8 and 1.8 dB when the FRM and FM are utilized respectively under 30 minutes observing time. Therefore, whether the FRM or FM is used to serve a reflector in the proposed scheme, the wavelength variation could be ignored. The implementation of FRM in the proposed RSOA-based laser is advantageous to reduce power variation. To achieve better output performance and widely wavelength tuning, a broadly operation range of FRM could be utilized.

The proposed self-injected RSOA has a large numbers of longitudinal modes due to a relatively long cavity between the FRM and the RSOA. As discussed in [23], initially, the spectral width of the laser is determined by the tunable bandpass filter (TBF) bandwidth. After a few lasing, the laser field builds up and the mode competition leads to a spectral width narrowing. As also analyzed in [23], when the fiber cavity is short, the chromatic dispersion is insignificant and the RSOA with strong gain saturation can suppress the power fluctuation. When the fiber cavity is long, these modes interfere constructively and destructively creating strong power fluctuations that cannot be suppressed by the RSOA gain. Thus, this leads to increased spectral broadening, and the chromatic dispersion induced mode partition noise substantially increases the relative intensity noise (RIN) of the self-injected RSOA. We think that our proposed scheme is also limited by the mode partition noise. Furthermore, according to [24] and [25], the cavity loss decreased when the coupling ratio increased, whereas the transmission output power increased when the coupling ratio increased.

## 3. Conclusion

A stable and wavelength-tunable self-injected reflective RSOA-based laser scheme has been proposed by using the FRM and FM serving as a reflector, respectively. Here, the 1.2 GHz modulation bandwidth could be extended to 3 GHz by using proposed self-injected RSOA laser. Thus, 3.5 Gbit/s data rate could be achieved below the FEC threshold by utilizing OFDM-QAM with bit-loading algorithm in a 20 km fiber transmission. Related output performances of proposed RSOA-based laser are also analyzed and discussed. Compared with using FM for serving as a reflector, using FRM not only can achieve 3.5 Gbit/s data rate after 20 km fiber transmission but attains more stable output performance in terms of power variation as well.

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