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Tunable single-frequency fiber laser based on the spectral narrowing effect in a nonlinear semiconductor optical amplifier

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Abstract: A wavelength-tunable single-frequency fiber laser based on the spectral narrowing effect in a nonlinear semiconductor optical amplifier (NL-SOA) is proposed and experimentally demonstrated. The single-frequency operation is achieved based on the spectral narrowing effect resulted from the inverse four-wave mixing in a NL-SOA. By incorporating the NL-SOA in the fiber laser cavity, single-frequency lasing is achieved. The lasing frequency can be tuned by tuning the center wavelength of a tunable filter (TF) incorporated in the laser cavity. The proposed wavelength-tunable single-frequency fiber laser is experimentally evaluated. Stable single-frequency oscillation with a side-mode suppression ratio (SMSR) as high as 55 dB and a spectral linewidth of less than 10.1 kHz over a wavelength tuning range of as wide as 48 nm is demonstrated.

OCIS codes: (140.3510) Lasers, fiber; (060.4370) Nonlinear optics, fibers;(140.3570) Lasers, single-mode; (140.3600) Lasers, tunable.

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1. Introduction

Single-frequency fiber lasers with advantageous features such as high optical power, high optical coherence, low noise and compact structure have been extensively investigated and have found numerous applications such as in fiber sensing, optical communications, microwave generation, and high-resolution spectroscopy [1–5]. To date, different techniques have been reported to achieve single-frequency oscillation in fiber lasers, including the utilization of an optical resonator with a short cavity such as a distributed Bragg reflector (DBR) and a distributed feedback (DFB) resonator [6–9], the insertion of a sub-ring to form a compound cavity to increase the longitudinal-mode spacing [10–12], the incorporation of a segment of un-pumped doped fiber serving as an auto-tracking ultra-narrow-band filter [13–15], and the utilization of the narrow gain profile due to the stimulated Brillouin scattering in an optical fiber [16,17]. Other approaches by use of a two-dimensional (2-D) material such as Graphene, molybdenum disulfide (MoS_2), or topological insulator (TI) as a saturable absorber [18–20], FP-LD injection locking [21,22] have also been reported. However, most of the techniques have difficulty in achieving wide wavelength tuning [6–9], and some approaches have poor stability [10–15, 18–20].

The use of a semiconductor optical amplifier (SOA) to achieve single-frequency lasing has also been reported. In [21,22], injection locking of Fabry-Pérot laser diode (FP-LD) was used to introduce spectrum narrowing effect. In [23], a fiber ring laser using an SOA was proposed. The single frequency operation was realized using a composite cavity, to make the cavity to have a much greater free spectral range. In [24], a single-frequency fiber ring laser was proposed with the single-frequency operation realized based on the high pass filtering effect of the SOA. Since no analysis on the high pass filtering on the mode selection was provided, it is not clear if such effect exists in all SOAs or only in the SOA used for the

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experiment reported in [24]. Recently, Turitsyn et al. reported a new nonlinear self-action effect, self-parametric amplification (SPA), which manifests itself optical spectrum narrowing in a normal dispersion fiber [25]. The spectrum narrowing is resulted from the inverse four-wave mixing (FWM), resembling an effective parametric amplification of the central part of the spectrum by energy transfer from the spectral tails. The physical mechanism underlying the spectral narrowing was explained qualitatively through numerical modeling and the spectrum of an optical field containing multiple longitudinal modes in a normal dispersion fiber could be narrowed and the number of longitudinal modes could be reduced. The demonstration reported in [25] was based on a normal dispersion fiber, if used in a fiber ring laser to achieve single frequency lasing, the loop length could be very long, which may make lasing operation unstable.

In this paper, we propose to use an NL-SOA to demonstrate spectrum narrowing and its application in a fiber ring laser to achieve single-frequency lasing. In our study, we find that the spectrum narrowing effect due to inverse FWM also exists in an NL-SOA and the incorporation of an NL-SOA in a fiber ring laser cavity would lead to the reduction in the number of longitudinal modes, which would lead to single-frequency lasing. In fact, the number of a multi-longitudinal-mode (MLM) light wave would reduce from multiple to a single longitudinal mode after the MLM light wave is recalculating in the ring cavity multiple times. This is the key point that the use of an NL-SOA in a ring cavity can achieve stable single-frequency lasing. In addition, the wavelength of the light wave generated by the ring laser can be easily tuned. In the proposed single-frequency ring laser, a tunable filter (TF) is incorporated in the laser cavity. By tuning the center wavelength of the TF, the lasing wavelength is tuned. An experiment is performed. The results show stable single-frequency oscillation with a side-mode suppression ratio (SMSR) as high as 55 dB and a spectral linewidth of less than 10.1 kHz over a wavelength tuning range of as wide as 48 nm is achieved. The proposed single-frequency fiber laser has the advantages of simple configuration, good stability and wide wavelength tunable range.

2. Operation principle

Figure 1 shows the schematic configuration of the proposed wavelength-tunable single-frequency fiber laser. It has a ring structure consisting of a TF, an NL-SOA, an 80:20 optical coupler, a conventional SOA, two optical isolators (ISOs), and two polarization controllers (PCs). The center wavelength of the TF can be tuned from 1530 nm to 1610 nm with a 3-dB bandwidth of about 0.2 nm. The SOAs provide the required optical gain, which having a gain of about 23 dB. The ISOs in the cavity are used to ensure unidirectional operation. The two PCs are connected before the NL-SOA and the conventional SOA for optimum gain performance. The 20% output from the optical coupler is further divided into two parts by a 50:50 optical coupler, with one sent to an optical spectrum analyzer (OSA) with a resolution of 0.02 nm to monitor the optical spectrum and the other sent to a photo-detector (PD) followed by an electronic spectrum analyzer (ESA) to monitor the electrical spectrum.

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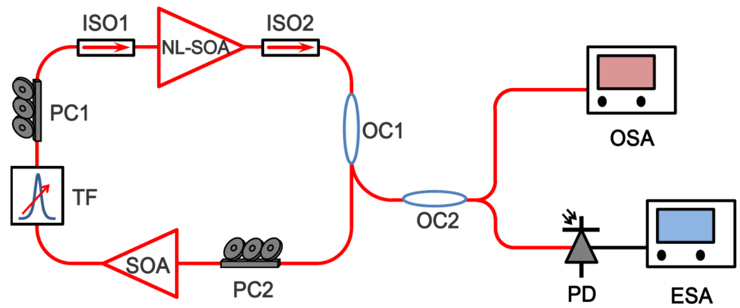

Fig. 1. The schematic configuration of the proposed wavelength-tunable single-frequency fiber laser.

The key component in the proposed fiber ring laser is the NL-SOA, which is used to ensure single-frequency lasing. Similar to the spectrum narrowing effect in a normal dispersion fiber, an MLM light wave will have a narrower linewidth with fewer longitudinal modes after passing through an NL-SOA. Figure 2(a) shows the optical spectra of an MLM light wave at the input and output of the NL-SOA. As can be seen from Fig. 2(a) the light wave at the output of the NL-SOA has not only a higher optical power due to amplification, but also a narrower linewidth. To see more clearly the spectrum narrowing effect, the corresponding radio frequency (RF) spectra of the MLM light wave before and after the NL-SOA are measured and shown in Fig. 2(b). The RF spectra actually represent the envelopes of the beat signals between the longitudinal modes. Based on the RF spectra we can estimate the linewidths of the light waves before and after the NL-SOA. It can be clearly seen from Fig. 2 that the number of longitudinal modes and the linewidth of the MLM light wave after the NL-SOA are both decreased. When the NL-SOA is incorporated in the ring cavity, the spectrum narrowing effect would happen and the number of longitudinal modes would reduce to one after the light wave recirculating in the ring cavity multiple times. Therefore, single-frequency operation would be achieved. In addition, the spectrum narrowing effect exists in the NL-SOA for a wide wavelength range, which can be used to achieve wavelength tuning. In our study, the lasing wavelength is tuned by tuning the center wavelength of the TF in the cavity.

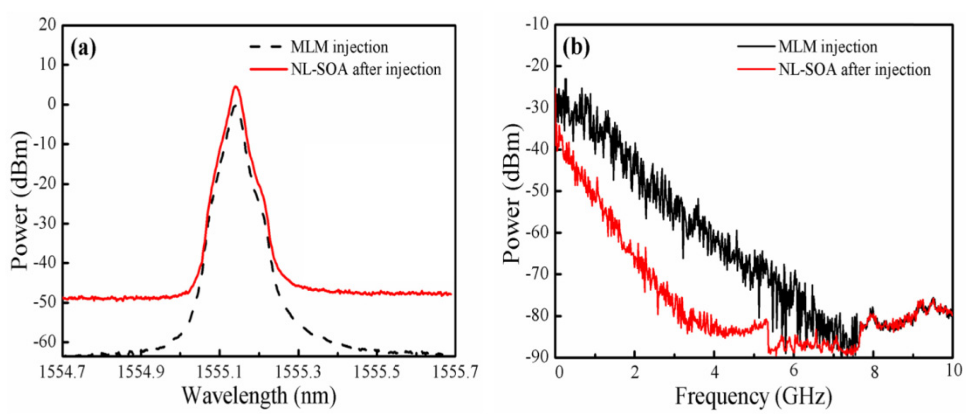

Fig. 2. (a) Optical spectra and (b) RF spectra of the MLM light waves before (the black line) and after (the red line) the NL-SOA.

Similar to the spectral narrowing effect in a normal dispersion fiber which is due to the inverse four-wave mixing, the spectral narrowing effect in an NL-SOA is also resulted from the inverse four-wave mixing, which resembles an effective self-parametric amplification, to transfer the optical energy from the spectral tails to the central part. Note that the inverse FWM or self-parametric amplification (SPA) only occurs in a normal dispersion optical fiber provided that the dispersion length becomes comparable with the nonlinear length [25]. While for an SOA, it can provide normal dispersion at certain wavelength range and the high nonlinear coefficient would also satisfy the second condition [26,27]. Therefore, an NL-SOA can effectively introduce nonlinear spectrum compression similar to a normal dispersion optical fiber, but with a much smaller size.

To confirm that an NL-SOA can indeed provide normal dispersion, we first measure the dispersion of an NL-SOA, which is done by using the chromatic-dispersion analysis method based on K-K transformation of the gain spectrum [27]. In the measurement, an NL-SOA from CIP Corporation (Model SOA-NL-OEC-1550) is used. The dispersion curves of the NL-SOA at different input optical power levels and under different driven currents are, respectively, shown in Figs. 3(a) and 3(b).

Figure 3(a) shows the dispersion curves measured under different drive currents for an input signal with a power of 5 dBm. Figure 3(b) shows the dispersion curves at different input signal power levels under a drive current of 100 mA. As can be seen from Fig. 3(a) the NL-SOA can provide the normal dispersion for a wavelength range from 1541 nm to 1595 nm. Due to the limited wavelength range of the measurement instrument, the dispersion for a wavelength longer than 1595 nm is not measured. The dispersion of the NL-SOA varies with the changes of the input signal power and the drive current. It is also related to the polarization state of the input signal. Therefore, we expect that the zero-dispersion wavelength of the NL-SOA could be shorter than 1540 nm and the NL-SOA can provide normal dispersion at a wavelength range covering the C and L bands.

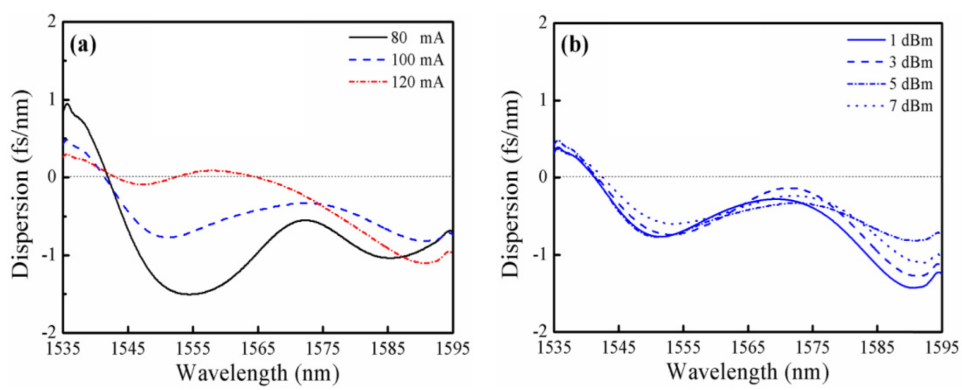

Fig. 3. The dispersion curves of the NL-SOA (a) under different drive currents for an input signal power of 5 dBm; (b) under different input signal power levels for a drive current of 100 mA.

3. Results

An experiment is performed based on the configuration shown in Fig. 1. First, we evaluate the operation of the fiber ring laser to be single frequency, which is done by allowing the laser to have a stable operation and then measuring the RF spectrum using the ESA. The fiber ring laser has an estimated cavity length of about 26 m, corresponding to a free spectrum range (FSR) of about 8 MHz. Figure 4(a) shows the spectrum of the lasing wavelength, a high SMSR is observed. Figure 4(b) shows the RF spectrum when the lasing wavelength is at 1550.36 nm, no beat note is observed up to 200 MHz. Since the longitudinal mode spacing, which is identical to the FSR, is about 8 MHz, the measurement confirms that the fiber ring laser is indeed operating in single-frequency mode.

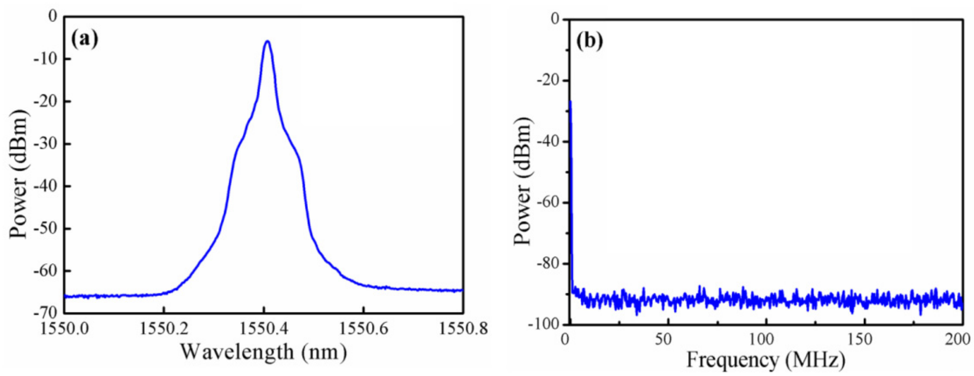

Fig. 4. (a) The spectrum of the lasing output. (b) The RF spectrum monitored by the ESA.

Then, we evaluate the wavelength tuning ability. In the experiment, the wavelength tuning is done by tuning the center wavelength of the TF. Figure 5(a) shows the wavelength tuning with a tunable range from 1530.87 to 1565.22 nm. Again, a high SMSR is maintained during the wavelength tuning. Figure 5(b) gives a zoom-in view of six wavelengths tuned from 1550.06 to 1550.57 nm. To ensure that singe frequency operation is maintained during wavelength tuning, for each wavelength, we also measure the RF spectrum. For all the wavelengths, no beat note is observed, which confirms that single frequency operation is always maintained when the wavelength is tuned.

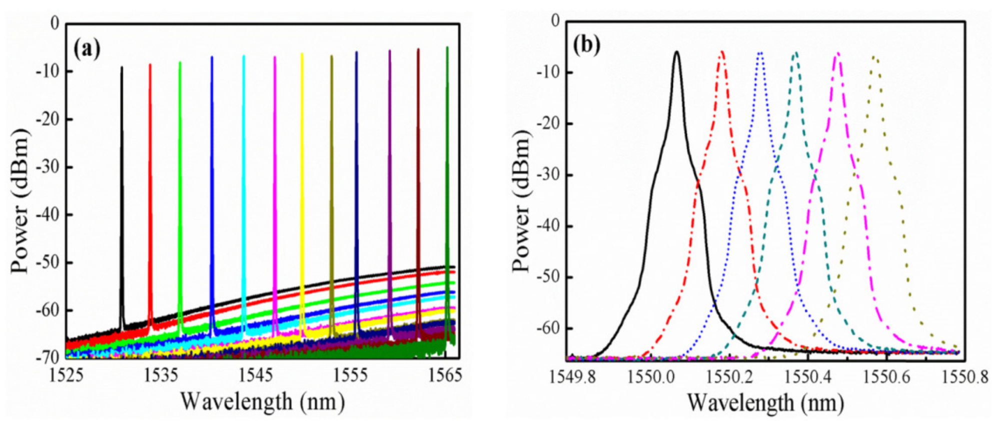

Fig. 5. (a) The spectra to show the wavelength tuning from 1530.87 to 1565.22 nm; (b) A zoom-in view of the spectra for six wavelengths tunable from 1550.06 to 1550.57 nm covering a tunable range of about 0.5nm.

The linewidth of the light wave generated by the fiber ring laser is also measured, which is done by using the self-heterodyne method [28], in which an acoustic optic modulator (AOM) and a length of single-mode fiber (SMF) are employed. The AOM has a maximum frequency shift of 210 MHz (Model EFB0612HHA, BRIMROSE) and the SMF has a length of 25 km, which is long enough to provide the required time delay. A typical delayed self-heterodyne RF spectrum (the black line) and the corresponding Lorentz curve fitting (the red line) are shown in Fig. 6(a). Assuming that the spectrum of the light wave is Lorentzian-shaped, the full width at half maximum (FWHM) of the light wave is estimated to be about 9.5 kHz, calculated from the −10 dB bandwidth of 57 kHz.

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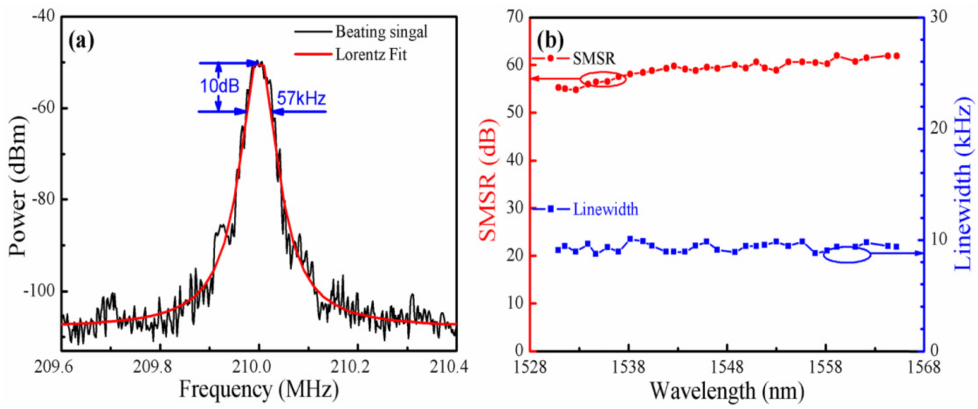

Fig. 6. (a) The RF spectrum measured by using the delayed self-heterodyne method; (b) The linewidth and SMSR versus the tuning wavelength.

Figure 6(b) shows the measured linewidth and SMSR versus lasing wavelength during the wavelength tuning process. It can be seen that the linewidth is maintained almost constant and narrower than 10.1 kHz, and the SMSR is also maintained constant and larger than 55 dB in the whole wavelength tuning range.

By slightly increasing the drive current to the NL-SOA, the tunable wavelength range is extended to cover longer wavelengths. Figure 7 shows the wavelength tuning with a tunable range from 1550.67 to 1598.78 nm covering a tunable range of 48 nm. It is expected that by adjusting the gain spectrum of the NL-SOA, the tuning wavelength of the proposed fiber ring laser can cover the C and L bands.

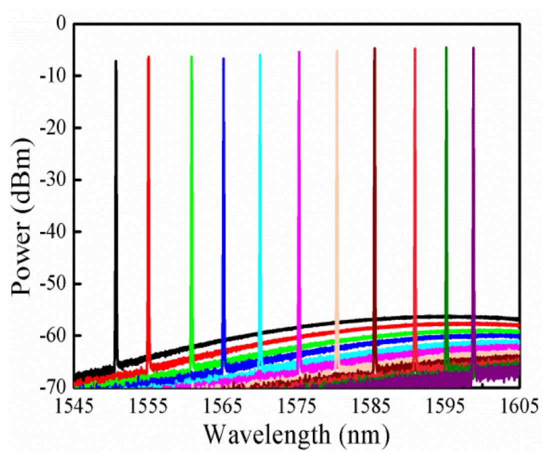

Fig. 7. Wavelength tuning from 1550.67 to 1598.78 nm.

As a comparison, we also measure the RF spectrum at the output of the fiber laser without incorporating the NL-SOA in the laser cavity. As can be seen in Fig. 8, beat notes at about 8.3 MHz and its multiples are observed, which confirms that without an NL-SOA in the laser cavity, the fiber laser is operating in the multi-longitudinal mode. Thus, the effectiveness of the use of NL-SOA to achieve single-mode operation is verified.

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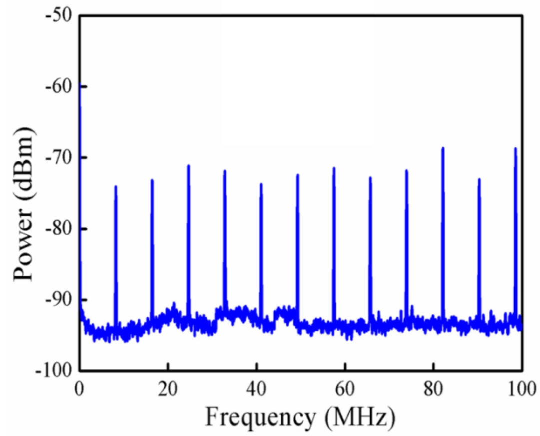

Fig. 8. Beat notes observed by measuring the RF spectrum at the output of the laser without an NL-SOA in the laser cavity.

To study if the dispersion of the conventional SOA has an impact on the performance of the fiber ring laser for single frequency operation, we also measured the dispersion of the conventional SOA. Figure 9(a) shows the dispersion measurements under different injection currents for an input optical signal with an optical power of 5 dBm. Figure 9(b) shows the dispersion measurements at different input signal power levels for a fixed injection current of 100 mA. As can be seen from Fig. 9(a), the conventional SOA can provide a normal dispersion for a wavelength from 1535 to 1590 nm. The total dispersion of the conventional SOA and the NL-SOA is kept normal to ensure inverse FWM, and spectral narrowing can take place to guarantee a single frequency operation at a wavelength shorter than 1540 nm, as shown in Fig. 5, although the dispersion of the NL-SOA becomes anomalous at that wavelength.

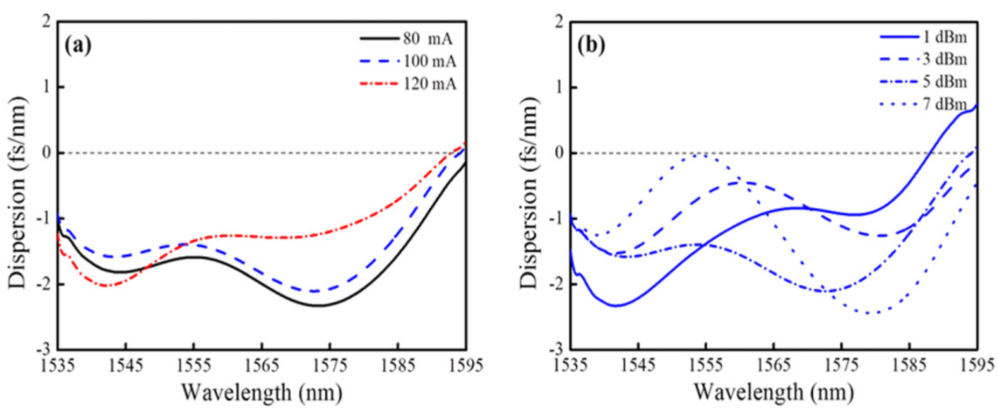

Fig. 9. The dispersion curves of the conventional SOA (a) under different drive currents for an input signal power of 5 dBm; (b) under different input signal power levels for a drive current of 100 mA.

Although the conventional SOA can provide normal dispersion, experimentally we could not achieve single frequency operation when using only the conventional SOA in the cavity. This could be explained from the inverse FWM effect as discussed in [25]. As stated in [25], spectral narrowing occurs when the dispersion length becomes comparable with the nonlinear length. A conventional SOA may not be able to provide the required dispersion to introduce the needed spectrum narrowing, to ensure single frequency lasing. While for an NL-SOA, the dispersion can be easily controlled to satisfy the spectrum narrowing condition, to enable a single-frequency operation.

The stability of the proposed fiber ring laser is also studied. To do so, we allow the laser to operate in a room environment for about an hour, no obvious change in the amplitude and wavelength of the lasing output is observed. A good wavelength repeatability is also observed when we tune the drive current. In the experiment, the accuracy of the lasing wavelength can be accurately controlled by precisely controlling the drive current.

4. Discussion and conclusion

A normal dispersion optical fiber could be used to ensure single-frequency operation of a fiber ring laser due to the spectrum narrowing effect in a normal dispersion. However, a normal dispersion optical fiber has a much longer length, and the use of a long normal dispersion optical fiber would make the laser have a poor stability. In addition, a normal dispersion optical fiber will not generate gain but loss, thus an additional gain medium with a high gain should be needed. Thus, an NL-SOA is a better choice to implement a single-frequency fiber ring laser with better performance.

In summary, we studied the spectrum narrowing effect in an NL-SOA, and proposed to implement a fiber ring laser by incorporating an NL-SOA to achieve single-frequency lasing. Compared with a normal dispersion optical fiber, an NL-SOA has a smaller size, and can act as a gain medium as well as nonlinear element to introduce nonlinear spectral narrowing effect to achieve single frequency operation. The spectrum narrowing effect of an NL-SOA was verified experimentally. The use of the NL-SOA in a fiber ring laser to achieve single frequency lasing was then demonstrated. The results showed stable single-frequency oscillation with a side-mode suppression ratio (SMSR) as high as 55 dB and a spectral linewidth of less than 10.1 kHz over a wavelength tuning range of as wide as 48 nm was achieved.

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