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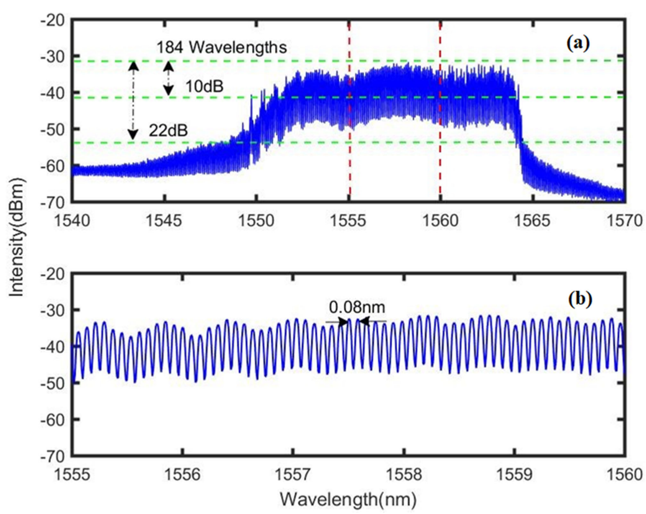

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Multi-Wavelength SOA Fiber Laser With Ultra-Narrow Wavelength Spacing Based on NPR Effect

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Abstract: A multi-wavelength semiconductor optical amplifier (SOA) fiber laser with ultra-narrow wavelength spacing is experimentally demonstrated in this paper. The SOA is used as the primary gain medium due to its inhomogeneous broadening and nonlinear polarization rotation (NPR) effect that allows to achieve stable multi-wavelength output with ultra-narrow wavelength spacing. The combination of PC (polarization controller)-SOA-PC-polarizer and nonlinear optical loop mirror (NOLM) serve as the intensity equalizer for inducing IDL to suppress mode competition effect furtherly, while the NOLM mainly achieves power equalization and improve SMSR in this laser. The Lyot-Sagnac loop mirror is designed to realize different channel spacing, when the length of PMF is 71 m, stable multi-wavelength output has been achieved at room temperature. The number of lasing lines is up to 184 with wavelength spacing of 0.08 nm within 10 dB bandwidth from 1549.75 nm to 1664.25 nm, and all peaks experience some minor power fluctuation, and the maximum value is about 5 dB. The side mode suppression ratio (SMSR) is about up to 22 dB. Moreover, the maximum value of optical signal-to-noise ratios (OSNR) is 10.7 dB.

Index Terms: Multi-wavelength fiber laser (MWFL), ultra-narrow wavelength spacing, nonlinear polarization rotation (NPR) effect, intensity-dependent loss (IDL).

1. Introduction

Multi-Wavelength fiber lasers (MWFLs) have the advantages of generating multiple lasing wavelengths simultaneously from a single fiber laser, good beam quality, low insertion loss, and compact structure. Therefore, they are widely used as light sources in optical communications, optical sensing, optical detection technology, and so on [1]–[3]. Furthermore, multi-wavelength lasers also play an important role in realizing millimeter-wave over fiber systems in addressing the demand for 5G wireless links in the near future [4].

Various gain mechanisms have been used in multi-wavelength fiber laser. Optical fibers doped with rare-earth elements such as erbium or ytterbium are widely used as primary gain medium in the development of multi-wavelength fiber lasers. The rare-earth-doped fibers with generated

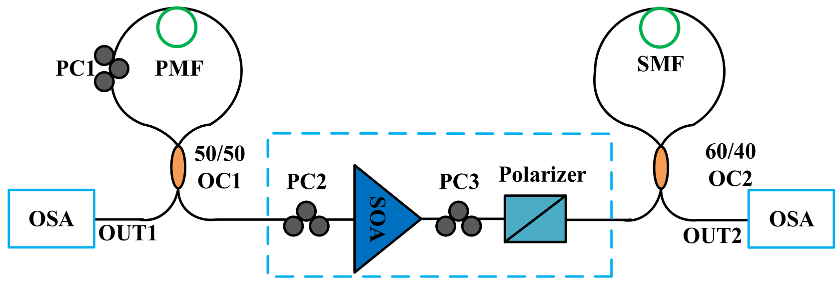


Fig. 1. Experimental diagram of multiwavelength SOA fiber laser based on NPR effect of SOA.

outputs can provide high gain, wide bandwidth, and low noise figure. However, due to the homogeneous line broadening of the rare-earth-doped fibers, this results in strong mode competition effect which is difficult to achieve stable multi-wavelength lasing output at room temperature [5]. Many approaches have been proposed to suppress model competition effect of EDFL, such as cooling EDF by utilizing liquid-nitrogen[6], utilizing four-wave mixing effect by using highly-nonlinear fiber [7], adding a frequency shifter or phase modulator[8], using an NOLM [9], taking advantage of the NPR effect[10] and so on. However, all these approaches with rare-earth-doped as gain medium could not generate large number of lasing modes. Compared with the rare-earth-doped fibers, SOA is inhomogeneous gain medium [11]–[12], stable multi-wavelength lasing output can be achieved when the wavelength spacing is greater than the homogeneous broadening linewidth, multi-wavelength fiber lasers based on SOA with different structures have been experimentally investigated [13]–[14]. SOAs can also be applied in the optical switching and wavelength conversion, which are highly useful characteristics for MWFLs.

In this paper, a stable multi-wavelength SOA fiber laser with ultra-narrow wavelength spacing is demonstrated. Unlike previous designs, the system does not need any expensive devices, such as isolator, circulator or high-power pumps, and thus simpler structure can realize large number of lasing lines output. A Lyot-Sagnac loop mirror serves as the comb filter, the combination of PC-SOA-PC-Polarizer is used to suppress mode competition effect within homogenous broadening linewidth, and an NOLM also serve as the intensity equalizer for inducing IDL to suppress mode competition effect furtherly, while it mainly achieves power equalization and improve SMSR in this laser. The proposed laser provides large number of lasing lines and stability at room temperature, making it suitable for use as source for DWDM systems.

2. Experimental Setup and Principle

The experimental setup of the multi-wavelength SOA fiber laser based on NPR effect proposed in this work is illustrated in Fig. 1. The setup is designed as a linear cavity with dual-output port. It consists of three components: the left part is a Lyot-Sagnac loop mirror, it serves as the comb filter, which is constructed by a PC (PC1), a 50/50 coupler (50/50 OC1) and a 71 m long PMF with birefringence of 4.012×10^{-4}. The middle part is the combination consisting of two PCs (PC2, PC3), an SOA and a polarizer, which serves as power equalization. The right part is a NOLM consisting of a 60/40 coupler (60/40 OC2) and a 600m long single-mode fiber (SMF), it also serves as the intensity equalizer to achieve power equalization and suppress mode competition effect. Two AQ6370 optical spectrum analyzers (OSA) with a resolution of 0.02 nm are used to monitor the output spectrum of the laser. The SOA is placed between the two loop mirrors, as the current flows through the SOA, the generated amplified spontaneous emission (ASE) spectrum propagates in both directions, longitudinal mode selectivity is realized by two loop mirrors and the NPR effect of SOA, the tunability of channel spacing is decided by the Lyot filter.

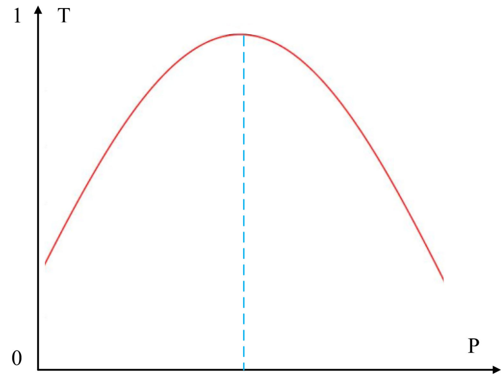


Fig. 2. Intensity-dependent transmission curve based on NPR effect of SOA.

2.1 NPR Effect SOA

The combination of PC2-SOA-PC3-polarizer, marked as blue dashed frame, it can produce a non-linear relationship between transmission and input light intensity and has the function of intensity equalizer as well as NPR in [15], [16]. The NPR effect is one of the most important non-linear effects of SOA, which can change the polarization of input light (output light usually be elliptically polarized light), mode competition within homogenous broadening lines was alleviated by the NPR effect. The phase difference and the orientation of the two PCs determine the intensity-dependent switch of the combination of PC2-SOA-PC3-Polarizer. And the polarization of the output light is related to the intensity of the input light. Polarizers can turn elliptically polarized light into linearly polarized light, and the PC can adjust light polarization state.

Intensity-dependent transmission curve based on NPR effect of SOA is simulated shown as Fig 2: at the left region of curve, the transmission goes up with the increase of light intensity and in this case the combination of PC-SOA-PC-Polarizer can be used to achieve passive mode-locking [15]. At the right region of curve, the transmission decreases with the increasing of light intensity, therefore, the combination of PC-SOA-PC-Polarizer can serve as a polarization rotation intensity equalizer [17], [18]. In our work, by adjusting the injection current of SOA, the combination worked as an intensity equalizer induces intensity-dependent loss (IDL) to suppress mode competition effect within homogenous broadening linewidth. Thus, stable multi-wavelength output with ultra-narrow wavelength spacing can be achieved.

The NOLM in the proposed laser also serves as the intensity equalizer to achieve power equalization and suppress mode competition effect [19]. Both the NOLM and the combination of PC-SOA-PC-Polarizer can work as intensity equalizer for inducing IDL to suppress model competition effects. But the NOLM is mainly used to achieve power equalization and improve SMSR in this laser, which will be verified in our experiment research.

2.2 Longitudinal Mode Selectively

The Lyot-Sagnac loop mirror is served as a multi-wavelength selection device [20]. The input light is divided into two same beams after passing 50/50 OC1. One beam is transmitted in the clockwise direction along the Sagnac loop mirror, and another beam is transmitted counterclockwise. Due to the birefringence of PMF, phase difference is produced between two beams in the loop. Finally, the two beams occur constructive interference at the 50/50 OC1 to produce a comb spectrum. The different wavelength spacing can be obtained by changing the length of PMF based on the formula of the wavelength interval,

$$\Delta\lambda = \lambda^2 / \Delta n L \tag{1}$$

where Δn and L represent the birefringence and length of the PMF.

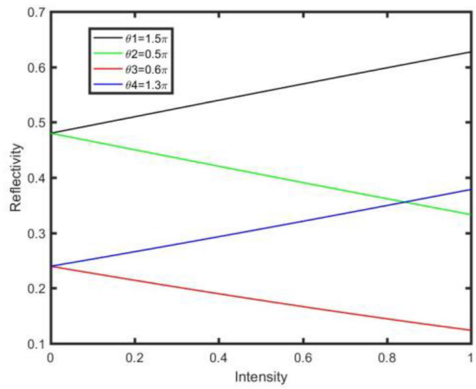


Fig. 3. Intensity-dependent reflectivity curve of NOLM for different θ.

According to Jones matrix theory, the reflectivity of NOLM is determined as [21]:

$$R\ (\lambda) = 2\alpha\,(1-\alpha)\left\{1 + cos\left[\theta + \frac{2\pi n_2\,(1-2\alpha)\,IL}{\lambda}\right]\right\} \tag{2}$$

where α is coupling ratio of the coupler, θ is the additional phase difference induced by PCs, n_2 is the nonlinear coefficient of SMF, L is the loop length, I is the intensity of the input light, λ is the operating wavelength. Here, $\alpha = 0.4$, $n_2 = 2.6 \times 10^{-20} m^2/W$, $L = 600\,\text{m}$, $\lambda = 1550\,\text{nm}$. Intensity-dependent reflectivity curve of NOLM for different θ is illustrated in Fig. 3. The reflectivity increases as light intensity increases, when θ are 1.5π or 1.3π. The reflectivity decreases as light intensity increases, when θ are 0.5π or 0.6π. Therefore, the NOLM can serve as the power equalizer to achieve power equalization and improve SMSR, and it also can suppress mode competition effect furtherly to improve stability.

3. Results and Discussions

In the experiment, the drive current of SOA is increased to 214 mA, all PCs are properly adjusted to achieve the optimum lasing output based on the simulation results shown in Fig. 3, stable multi-wavelength output with ultra-narrow wavelength spacing and large wavelength number is achieved and illustrated in Fig. 4(a). It is shown that the number of lasing lines is up to 184 within 10 dB bandwidth from 1549.75 nm to 1664.25 nm. The SMSR is used to define the amplitude difference between the main mode and largest side mode in units of decibels. As shown in the Fig. 4(a), the SMSR is up to 22 dB. But, due to the high noise figure of SOA, the value of OSNR is less than 10.7 dB.

Further analyzing the performance of output lasing lines, we enlarge the red dashed frame wavelength range from 1555 nm to 1560 nm and show in Fig. 4(b), it gives a separation of 0.08 nm between the lasing lines, and the peak power is about −28.5 dBm, and the experimental results are consistent with simulation. However, it is evident from the Fig. 4(b) that the output spectrum emerges envelope, it is because of the combination of SOA, PC1, PMF and PC2, which constructs a Lyot filter based on non-linear effect of SOA. Note that during the after-mentioned experiment, the SOA driving current is fixed at 214 mA, we investigate the system performance under the same PC angels and three different PMF lengths.

In order to verify the phenomenon of emerging envelope, the PMF and PC1 are removed and repeat the experiment, the output spectrum is illustrated in Fig. 5., Fig. 5 shows that few lasing lines can be generated and the lines power is smaller. The PMF is placed in the left loop for longitudinal mode selection, and the main purpose of the Lyot-Sagnac is to produce a sinusoidal wavelength-dependent filter transmission function. Therefore, the reason of emerging envelope is the Lyot filter consisting of SOA and PCs.

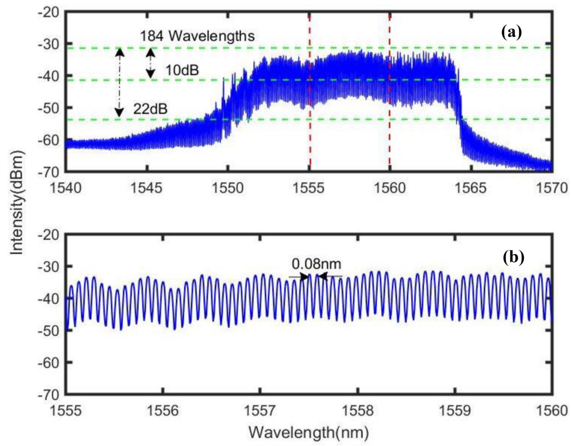


Fig. 4. (a) Stable multi-wavelength output spectrum with ultra-narrow wavelength spacing. (b) Enlarging red dashed frame from 1555 nm to 1560 nm in (a).

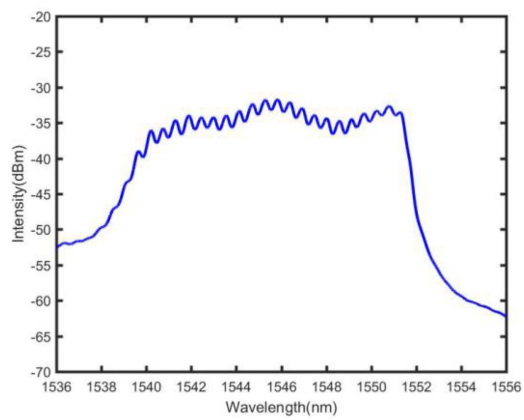


Fig. 5. Comb spectrum of Lyot filter consisting of SOA and PCs.

Then the effect of the polarization rotation intensity equalizer (PC2-SOA-PC3-Polarizer) is investigated. The polarizer is removed and then we repeat the experiment, the output spectrum is illustrated in Fig. 6. Stable multi-wavelength output with ultra-narrow wavelength spacing cannot be achieved by adjusting PCs arbitrarily. Therefore, though both the NOLM and the combination of PC-SOA-PC-Polarizer can server as intensity equalizer for inducing IDL to suppress mode competition effects within homogenous broadening linewidth of SOA, only NOLM as intensity equalizer for inducing IDL is hard to achieve it in this laser. So, the combination of PC-SOA-PC-Polarizer is the key component to suppress mode competition effects within homogenous broadening linewidth in this experiment.

Lastly, the effect of NOLM is also be verified by removing the SMF and the right part only serves as a reflection mirror. It is shown that the power equalization and stability of multi-wavelength output are destroyed in Fig. 7. This means that the polarization-rotation induced inhomogeneous loss effect is not strong enough to compensate for the mode competition among many lines at shorter or longer wavelengths. Therefore, NOLM serves as the intensity equalizer for inducing IDL to suppress mode competition effect furtherly, but the NOLM mainly achieves power equalization and improve SMSR in this laser.

The stability of multi-wavelength fiber laser has also been measured. The output light spectrum is scanned repeatedly from 1554 nm to 1558 nm for 60 minutes at time interval of 5 mins shown

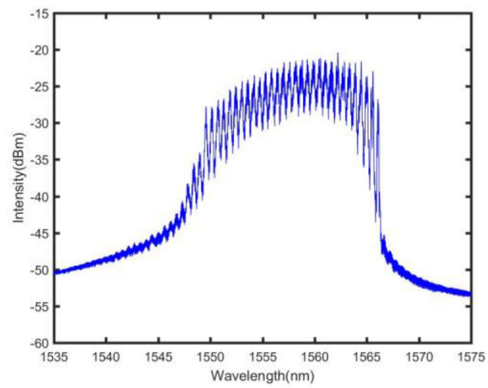


Fig. 6. Multi-wavelength output spectrum without ultra-narrow wavelength spacing when the Polarizer is removed

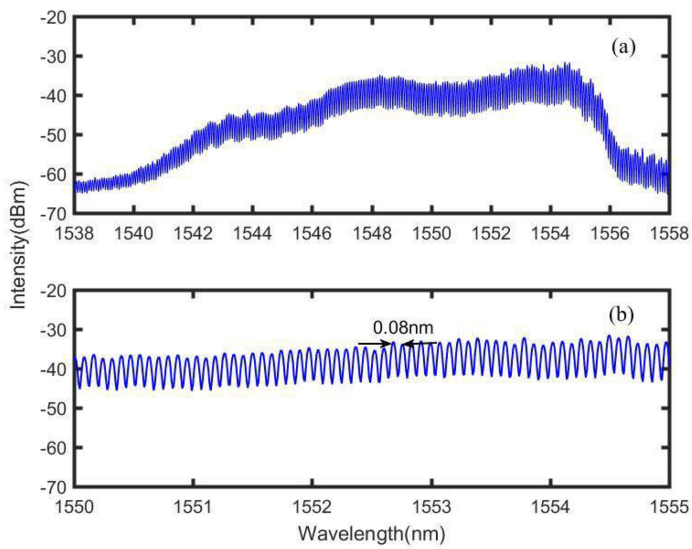
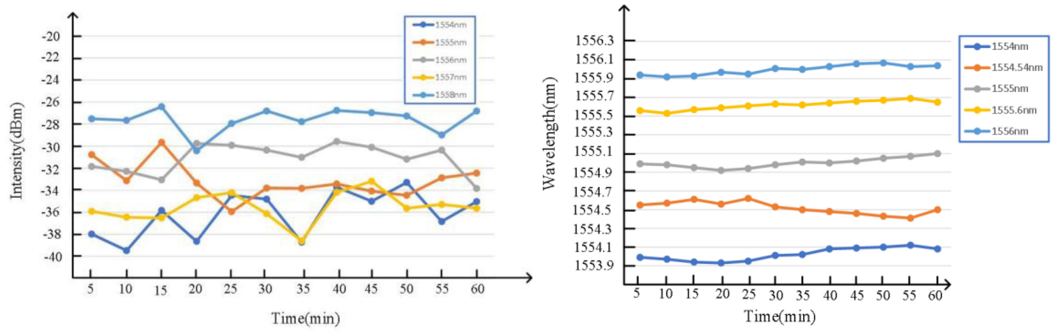


Fig. 7. The output spectrum of the proposed laser without SMF in the cavity

in Fig. 8 (a) and Fig. 8(b). Fig. 8(a) shows the maximum power fluctuations of 5 dB for wavelength of 1555 nm, and Fig. 8(b) shows the maximum wavelength fluctuations of 0.1 nm. We believe that the power fluctuation is caused by crosstalk, nonlinear impairment, waveform distortion, temperature variation, and optical power reflection, small temperature variations in the experimental environment, which is directly affect the state of polarization of the transmit signals and hence the output of the proposed laser. However, no wavelength drifting can be observed, indicating that the wavelength slicing mechanism is stable. Further optimization would be researched in order to achieve a higher stability to allow for its use in sensing or WDM sources.

The number of lasing lines and the wavelength spacing also depend on the length of PMF and the fiber birefringence, we can regulate the feedback power to the SOA by varying the PMF length of the left loop mirror and hence exploit the gain compression for wavelength tunability. By changing the length of PMF to 7.3 m and 13.5 m, stable multi-wavelength output with wavelength spacing of 0.63 nm and 0.33 nm is achieved respectively. Fig. 9 shows the number of lasing lines is 21 within 10 dB bandwidth. Fig. 10 shows the number of lasing lines is 40 within 10 dB bandwidth. The multi-wavelength output is stable and power equalization.



(a) (b)

Fig. 8. Power (a) and wavelength (b) stability measurement for five wavelength oscillation

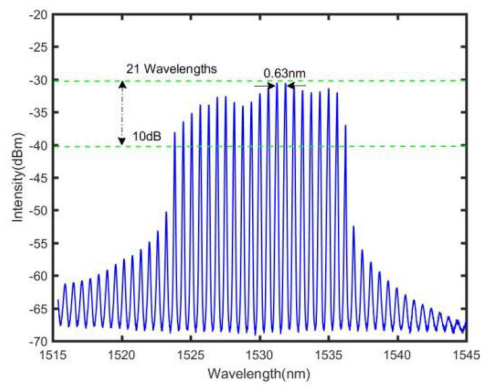


Fig. 9. Multi-wavelength output with wavelength spacing of 0.63 nm using the 7.3 m long PMF.

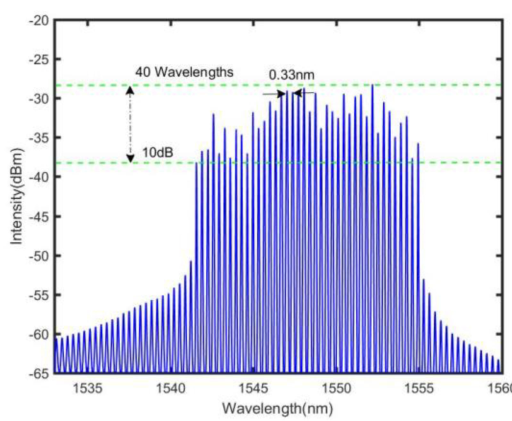


Fig. 10. Multi-wavelength output with wavelength spacing of 0.33 nm using the 13.5 m long PMF.

4. Conclusion

In conclusion, a multi-wavelength SOA fiber laser with ultra-narrow wavelength spacing based on NPR effect is proposed and demonstrated. It is a linear cavity dual-output port fiber laser, which has the advantage of low threshold current. The Lyot-Sagnac loop mirror is inserted into the left of the linear cavity serving as a comb filter and the wavelength spacing is controlled by the length of PMF. Due to the NPR effect of SOA, the combination (PC2-SOA-PC3-Polarizer) in middle part induce IDL to suppress mode competition effect within homogenous broadening linewidth. The NOLM is inserted into the right of the linear cavity serving as the power equalizer to achieve power equality and improve SMSR, and it also can suppress mode competition effect furtherly to improve stability. When the length of the PMF is 71 m, the number of lasing lines is up to 184 with wavelength spacing of 0.08 nm within 10 dB bandwidth, and the multi-wavelength output has no obvious power fluctuation. The side mode suppression ratio (SMSR) is about up to 22 dB. But, due to the high noise figure of SOA, the value of OSNR is less than 10.7 dB. Finally, the wavelength spacing of 0.63 nm and 0.33 nm are obtained by changing the length of PMF to 7.3 m and 13.5 m. We believe that, with the further optimization, the proposed laser can realize more channels output and has great potential applications in modern fiber communication.

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