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Tunable multiwavelength fiber laser based on bidirectional SOA in conjunction with Sagnac loop mirror interferometer

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ABSTRACT

A tunable multiwavelength fiber laser (MWFL) based on bidirectional semiconductor optical amplifier (SOA) in conjunction with a Sagnac loop mirror (SLM) interferometer is proposed. The best multiwavelength spectrum from this setup produces 164 lasing lines within 3 dB uniformity. The main study is to investigate the multiwavelength laser performance by varying the polarization state (PS) at two different locations of polarization controller (PC). Manipulation of a quarter-wave plate (QWP) of PC1 causes PS change before entering polarization-maintaining fiber (PMF) thus affecting the multiwavelength flatness and wavelength bandwidth. Meanwhile, manipulation of QWP of PC2 varied the output power of polarization beam splitter (PBS) and tuned the multiwavelength spectrum with almost similar performance. The multiwavelength tunability, extinction ratio (ER) difference and lasing lines difference is five nm, 2.4 dB and 48 when the QWP angle is adjusted from 0° until 70°, respectively. Lower SOA current reduced the multiwavelength flatness and number of lines. The laser output was found stable at a maximum of 0.31 dB power deviation during the 100 min of stability test.

Introduction

Multiwavelength fiber laser had been a significant attraction to researchers and industry due to its potential application in optical communications, dense wavelength division multiplexing system and optical fiber sensor. The best performance in MWFL should have stable and flat lasing lines, large numbers of channels, high ER and high laser output. The laser structure for MWFL is comparatively inexpensive and simple as compared to cascaded laser diodes. Erbium-doped fiber amplifier (EDFA) is typically used in the MWFL structure due to its high output power, lower wavelength shifting, and high gain saturation [1]. However, a homogeneous line broadening in the EDFA contributes to high mode competition, where a flat and stable multiwavelength spectrum is unachievable. SOA is a gain medium with low mode competition characteristic; thus, a stable and flat multiwavelength laser is achievable [2–7]. High mode competition from EDFA can be reduced from a mechanism of intensity-dependent transmission (IDT) [2], intensity-dependent loss (IDL) [6,7] or four-wave mixing [8] as they can act as an intensity equalizer to alleviate the mode competition in a laser cavity.

Recent work of MWFL based on comb filters were demonstrated by incorporating parallel-structured Lyot filter [9], seven-core-based Mach–Zehnder interferometer (MZI) [10], a combination of MZI and SLM interferometer [11], novel hybrid structure optical fiber filter [12], MZI by sandwiching a section of highly germanium-doped fiber between two sections of single-mode fiber [13], polarization-maintaining sampled fiber Bragg grating [14], four-mode fiber-based Sagnac loop [15], cascaded structure of SMF-TMF-SMF filter and Lyot filter [16]. Many researches demonstrated a multiwavelength tunability based on in-line comb filter in twin-core photonic crystal fiber [17] and also employing PM-TDF [18]. Multiwavelength tunability based on nonlinear polarization rotation (NPR) effect using SOA [19] and EDFA [20] were demonstrated previously. However, they did not investigate the multiwavelength laser performance at the adjustment of two different PCs and differences of lasing lines and ER due to PS adjustment were not detailed out. In this paper, a tunable MWFL based on bidirectional SOA is demonstrated and investigated. The best performance of MWFL produces 164 lasing lines within 3 dB uniformity, with ER of 11 dB. The QWP adjustment at PC1 changes flatness and bandwidth, while the change of QWP at PC2 has tuned the multiwavelength spectrum with varied lasing lines and ER.

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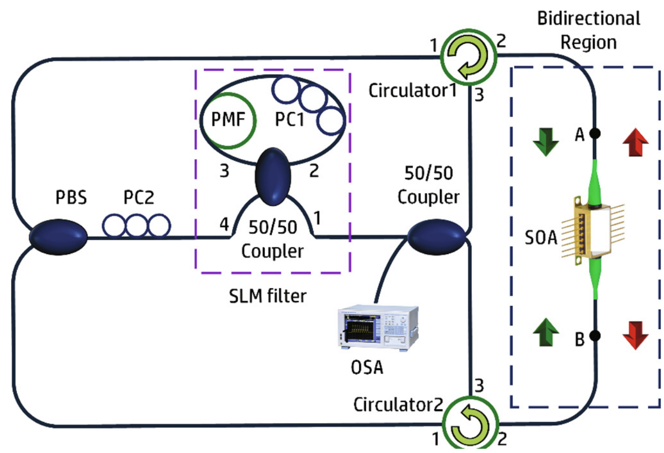

Fig. 1. The experimental setup of the bidirectional SOA in conjunction with the SLM interferometer.

Experimental setup

Fig. 1 depicts the experimental structure of the MWFL based on bidirectional SOA and SLM interferometer. The SOA acting as the gain medium and is manufactured by Alphion (SAS26p). The SOA has a polarization-dependent gain which is similar to the nonlinearity in a single-mode fiber to reduce mode competition [21]. Two circulators work to route the light from the PBS outputs to the bidirectional region of SOA. The two lights propagate in the opposite direction within the SOA and exit from port 3 of Circulator 1 and Circulator 2. The light routed to Port 2 of each circulator in the opposite direction, clockwise and counterclockwise. The circulators ensure the light is unidirectional except in the bidirectional region. Then, the light goes out through Port 3 of circulators before being combined at the output coupler. PMF is a birefringence device that is used as the medium of double refraction of light depending on the input of PS. The PMF is combined with PC1 and 50/50 coupler to form an SLM interferometer. PC1 and PC2 are used to control the light before entering PMF and PBS, respectively, so that the optimum performance of MWFL can be achieved. PBS has dual functions; firstly, to work as a polarizer when it is combined with PC2. Secondly, PBS is engaged to split the light into two and routed to the circulators. The PBS polarized the input light into horizontal and vertical depending on PS input, adjusted by PC2. The intensity of each PBS output will affect the intensity at point A and B. Meanwhile, a 50/50 output coupler is used to tap out the laser from the cavity, while the remaining light continues lasing via its throughput port. The laser spectrum is observed using an optical spectrum analyzer (OSA) with a constant resolution of 0.02 nm. The variation of PMF length and output coupler was not investigated, so they were fixed to 53.2 m and 50/50, respectively.

Principle of operation

First, the light enters into the 50/50 coupler from Port 1 before being split equally via Port 2 and 3. These two counterpropagating beams recombine in the loop, with PMF causes the light travels at both fast and slow axis to create a phase difference. Hence, when the light passes through the PMF, there is an angle deflection, and there is another angle deflection when the light passes through the PC1 [22]. After traveling through a fiber loop in the opposite direction, the two beams interfere in the coupler, making construction interference that defines the multiwavelength generation. If PC1 is not adjusted correctly, the light that goes into the fast and the slow axis has different PS and amplitude, thus affecting the multiwavelength performance.

An NPR effect has two mechanisms; IDL and IDT, which is changeable due to PS. The IDL works in a region where lower transmission is achieved by decreasing intensity, whereas for IDT, the higher transmission is subjected to intensity increment [2]. The IDL means intensity and loss are dependent on each other. The wavelength separation ($\Delta\lambda$) formula is given by $\Delta\lambda = \lambda^2/\Delta nL$, where it depends on the PMF length (L), birefringence value of the PMF (Δn), and operating wavelength (λ). In our experiment, the values of Δn and λ is fixed at 4.5×10^{-4} and 1550 nm, correspondingly. The B value maintains even the PMF is spooled due to the property of polarization-maintaining from the dual stress rod within the PMF.

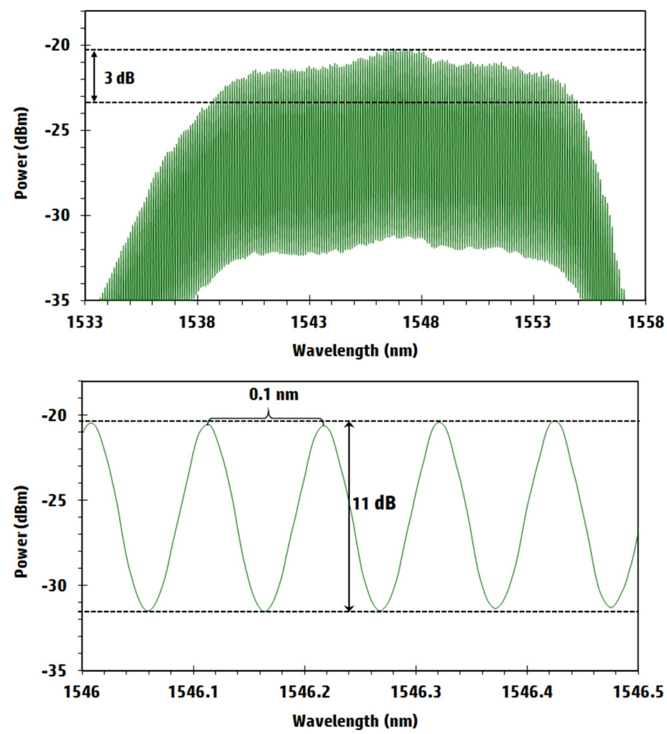

Fig. 2. (a) The 164 lasing lines within 3 dB bandwidth based on the bidirectional SOA and SLM interferometer at a maximum bias current of 575 mA. (b) Zoom in version according to the dashed lines of (a) to view the 0.1 nm line spacing.

Results and discussions

This MWFL structure is based on bidirectional SOA which offers a full utilization of SOA laser outputs to increase the intensity of the multiwavelength spectrum. The combination of PCs, SOA and PBS induce an IDL mechanism, which acts as the flatness element in flattening the multiwavelength spectrum. In the working mechanism of IDL, the IDL strength is increased with the insertion of polarizer in the setup. Fig. 2(a) shows the best multiwavelength spectrum at Maximum SOA current of 575 mA that generates 164 lasing lines within 3 dB uniformity with an average ER of 11 dB. The wavelength bandwidth and the center wavelength is at 16.4 nm and 1546 nm, respectively. The multiwavelength spectrum is flat with broad gain bandwidth thanks to the property of spectral reshaping by the bidirectional amplification process in SOA as well as complete counter propagation in the bidirectional region. High peak power of −20 dBm is due to the bidirectional SOA. Our previous work had only achieved a lower peak power of −28 dBm due to the propagation of unidirectional SOA in adherence to similar components and settings [7]. Fig. 2(b) is the magnified view at 2 nm wavelength span for better lasing lines measurement to display the channel spacing, which measured at 0.1 nm corresponding to the use of 53.2 m of PMF length. The channel spacing is consistent at 0.1 nm from 1538 nm to 1554 nm due to polarization-maintaining behaviour in the PMF.

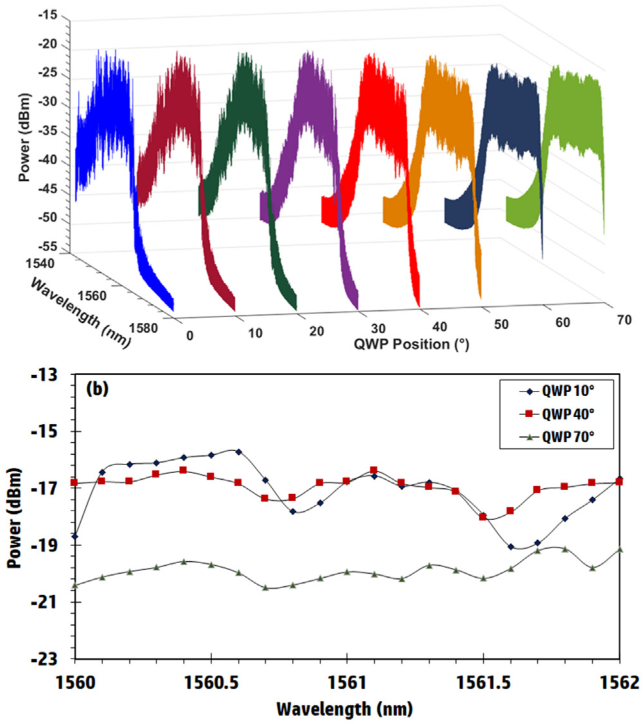

Fig. 3. (a) The evolution of multiwavelength lasing performance at the adjustment of the QWP angle of PC1. (b) The peak power of lasing lines within the wavelength range from 1560 nm until 1562 nm for the QWP angle position of 10°, 40° and 70°.

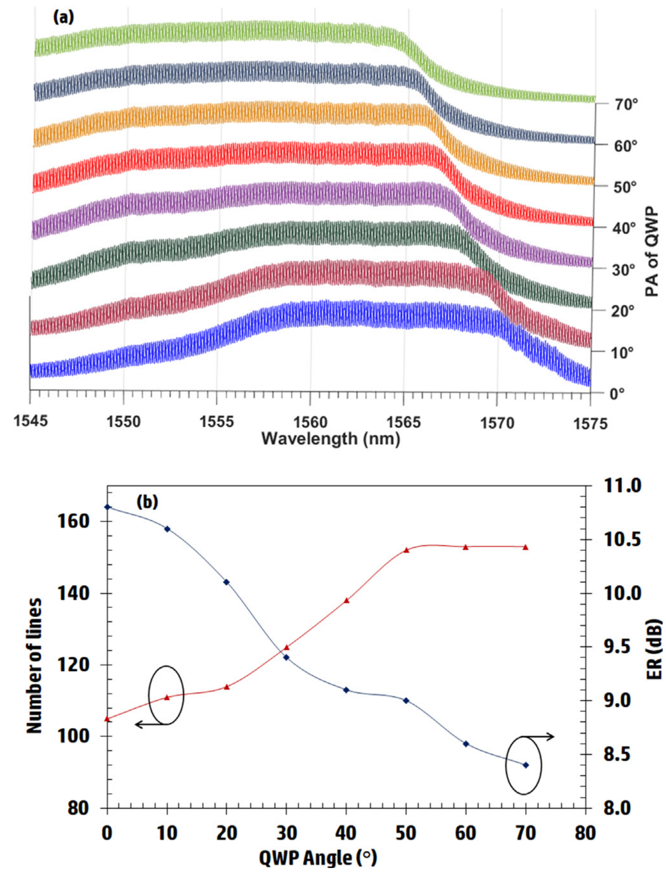

Fig. 4. (a) The tunability of the multiwavelength spectrum when the QWP of PC2 is altered. (b) The number of lasing lines and ER at the adjustment of QWP angle of PC2.

Further observation is multiwavelength laser performance when QWP of PC1 is rotated. The QWP of PC1 used to change the PS of the incoming light entering PMF either linear PS, circular PS or elliptical PS. Therefore, the QWP adjustment can improve the performance of the multiwavelength spectrum. Fig. 3(a) depicts the spectrum evolution from the worst multiwavelength flatness and wavelength bandwidth until the best multiwavelength spectrum when the QWP angle of PC1 is rotated from 0° until 70°. We can see from Fig. 3(a) the evolution of multiwavelength flatness and coverage of wavelength bandwidth due to the alteration of the QWP angle. Fig. 3(b) depicts the peak power of each lasing lines from 1560 nm until 1562 nm at three different QWP settings to observe the flatness behaviour as well as to measure the flatness value. The flatness value at QWP position of 10°, 40° and 70° is determined at 3.35 dB, 1.67 dB and 1.37 dB, respectively. The flatness values show the improvement of multiwavelength spectrum with the increment of QWP angle. The peak power at QWP of 70° is around −20 dBm due to a stronger IDL mechanism that leads to equal lasing lines but at reduced peak power. Meanwhile, based on the same SOA current, the coverage of wavelength bandwidth is widened with further QWP setting. The wavelength coverage within 3 dB bandwidth is observed at 1.5 nm and 4.5 nm when the QWP angle is set to 10° and 40°, correspondingly, while the best wavelength bandwidth is at 70° which measured at 17.6 nm. From the observation, the adjustment of QWP has affected the flatness and bandwidth of the multiwavelength spectrum. The best flatness and wavelength bandwidth can be achieved by adjsuting the QWP angle to linear PS so that an optimum constructive interference occurs, which in this case is at a QWP angle of 70°.

In the next investigation, another QWP of PC2 is altered at fixed SOA current to observe any change on the multiwavelength spectrum. Noted that, when the QWP of PC2 is changed, the PBS outputs will have different intensity due to PS change of either circular, elliptical or linear PS. Fig. 4(a) depicts the multiwavelength spectrum that tuned to the left with almost maintained multiwavelength flatness with QWP's angle alteration. Five nm multiwavelength tunability is observed when the QWP angle is changed from 0° to 70°. The multiwavelength tunability is due to the polarization-dependent gain of the SOA as well as the polarization-dependent transmission induced by the NPR effect in the SOA [19]. Fig. 4(b) depicts the change of lasing lines and ER at the adjustment of the QWP angle of PC2. From the figure, it shows that the ER is almost maintained even with QWP change with only 2.4 dB ER difference in between the QWP angle from 0° until 70°. Meanwhile, the lasing lines are increased with QWP angle increment, with only 48 lasing lines difference. From our observation, the change of QWP angle had tuned the multiwavelength spectrum with maintained flatness, but a slight variation on the number of lasing lines and ER. The multiwavelength tunability is due to unequal power at point A and B due to the different PBS output powers when the QWP angle of PC2 is rotated.

Fig. 5 depicts the multiwavelength performance at lower SOA current to figure out the intensity effect. The figure shows the multiwavelength spectrum when the SOA current is decreased to 375 mA and 175 mA, which affecting to lower lasing lines (within 3 dB uniformity) of 141 and 66, respectively. From our observation, the lower intensity in the cavity will not significantly drop the lasing lines due to the bidirectional SOA. Lower SOA current provides narrower wavelength bandwidth and lower lasing lines as the loss is higher than the gain at the vanished lasing lines.

Ultimately, the power stability of the best multiwavelength spectrum based on the bidirectional SOA is checked within 100 min. Fig. 6 shows the power stability of the best multiwavelength spectrum, according to Fig. 6. The laser stability is tested at two different wavelength span of 1546 nm to 1547 nm and 1547 nm to 1548 nm. From the figure, there is no significant fluctuation of the spectral line observed during the stability test, as the maximum power deviation is only 0.31 dB.

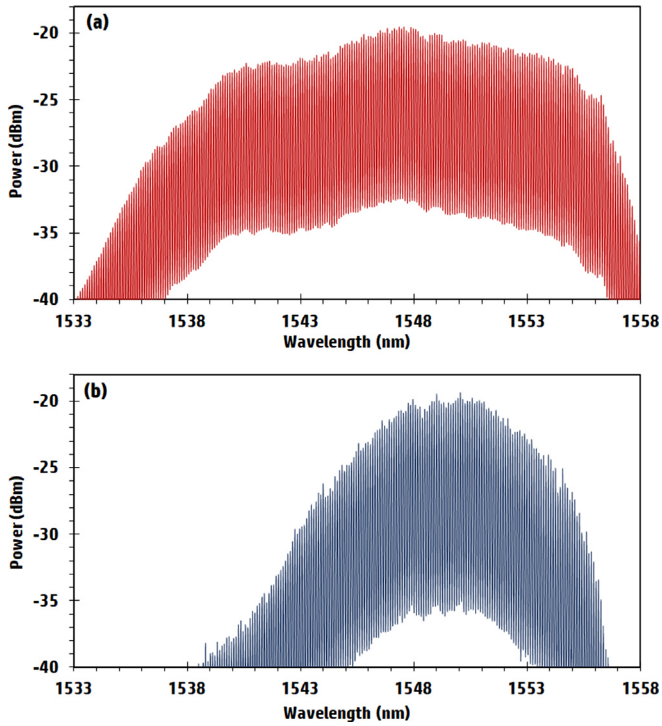

Fig. 5. Multiwavelength generation at decreased SOA current of (a) 375 mA and (b) 175 mA.

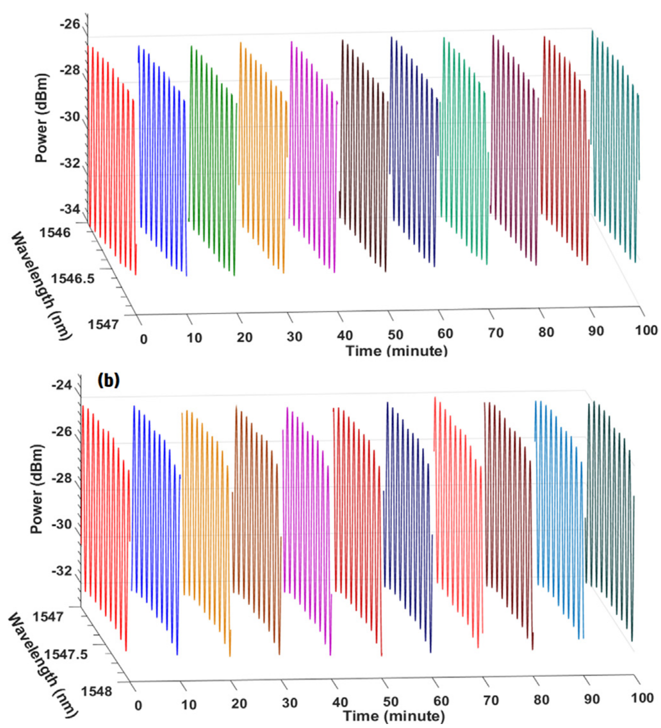

Fig. 6. The stability of the best multiwavelength spectrum in 100 min at (a) 1546 – 1547 nm and (b) 1547 nm – 1548 nm.

Conclusion

We have demonstrated a tunable multiwavelength performance based on bidirectional SOA and SLM interferometer at different PS adjustments. The best multiwavelength laser has 164 lasing lines within 3 dB uniformity with 11 dB of ER as well as high peak power around −20 dBm. The QWP angle of PC1 and PC2 is rotated to control the polarization direction before the light entering PMF and PBS, respectively. The change of the QWP angle of PC1 has affected the flatness and wavelength bandwidth of the lasing performance. Meanwhile, when the QWP of PC2 is changed, the multiwavelength spectrum is tuned without much deterioration of multiwavelength flatness. When the QWP of PC2 was set from 0° until 70°, the ER and lasing lines difference is only 2.4 dB and 48, respectively, to prove that the multiwavelength is almost maintained even with different QWP angles. The number of lasing lines reduces with lower SOA current. The laser stability is excellent with minimal power fluctuation within 100 min for the two observed multiwavelength regions.

CRediT authorship contribution statement

Abdul Hadi Sulaiman: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Nelidya Md Yusoff:** Investigation, Resources. **Fairuz Abdullah:** Formal analysis, Funding acquisition. **Mohd Adzir Mahdi:** Funding acquisition, Project administration, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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