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# Investigation of Multiwavelength Performance Based on Different SOAs

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**Abstract:** We investigated multiwavelength fiber laser (MWFL) performance using different types of semiconductor optical amplifiers (SOAs) utilizing Lyot filter as comb filter. The lasing performances of linear SOA (LSOA), nonlinear SOA (NLSOA) and booster optical amplifier (BOA) at different current settings were observed. Among the three SOAs, LSOA has the best lasing performance due to the lowest peak power difference with the highest number of lasing lines, a high ER value of 42 dB and considerable high peak power of -14.1 dBm at 550 mA. The multiwavelength laser is stable within 60 minutes at power fluctuation of less than 0.2 dB. The output spectra at 550 mA for all the SOAs are 70 nm to 80 nm wavelength difference from the ASE spectra.

**Keywords:** Multiwavelength fiber laser, semiconductor optical amplifier, Lyot filter

## 1. Introduction

In optical fiber communications, the best performance of dense wavelength division multiplexing (DWDM) is a critical requirement to achieve good internet transmission speed and capacity as the technology is widely used [1]. MWFL has been the main attraction since it has a simple and compact configuration that will reduce the cost of building the system and low insertion loss. The generation of MWFL involves two components: the gain medium and the comb filter used to slice the amplified spontaneous emission (ASE). Since decades ago, many studies have been carried out to find the best combination of the two gain media. An erbium-doped fiber amplifier (EDFA) has been studied widely due to its less sensitivity with polarization effect, high saturation power and low threshold value [2,3]. However, it is difficult to achieve stable lasing lines as EDFA has a strong mode competition, which resulted from its natural homogeneous gain broadening. To solve that, extensive studies have been carried out using a different kind of techniques such as introducing a nonlinear effect into the laser cavity such as stimulated Brillouin scattering effect [4], utilized a hole burning effect that is generated by polarization-dependent devices [5] and applied a nonlinear polarization rotation (NPR) effect [6,7]. As a result, the EDFA laser system becomes more complicated and might increase costs [8]. SOA is the best option to replace EDFA as it has its advantages [9] of having an inhomogeneous gain broadening to suppress the strong mode competition, allowing

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**Corresponding author: nelidya.kl@utm.my* the generation of stable and flat lasing lines [10-12]. Besides that, SOA has a simpler setup than EDFA since it does not require optical pumping. Based on SOA's advantage, there is an increasing number of studies on the generation of multiwavelength SOA fiber lasers with different comb filters [10,13-15].

Studies have been reported on many types of comb filters used to generate multiwavelength lasers in recent years. Researchers have researched a specific gain medium using different types of comb filters [3,8]. In 2017, a two-stage Lyot filter was applied to erbium-doped fiber laser (EDFL) by Yuan Li et al [16]. They managed to switch and tune the channel spacing and spectral range with the adjustment of PCs. Later in 2019, Zhou et al. proposed a switchable multiwavelength EDFL based on a parallel dual Lyot filter [3]. By PC adjustment, they can demonstrate single, dual and triple laser wavelengths. However, the stability performance is not outstanding since the power fluctuation is relatively high, around 2.6 dB within 60 minutes. Recently, Sulaiman et al. demonstrated using a Sagnac loop mirror [SLM] interferometer, producing 164 lasing lines by adjusting the PCs [17]. Other than the studies mentioned earlier, fiber Bragg grating (FBG) [15] and Mach-Zehnder interferometer (MZI) [18] also received significant interest from other researchers. There are also studies on the combination of two comb filters in a system [8,19-20]. However, none of the studies of MWFL conducted before comparing different types of SOAs using the same comb filter.

In this study, we investigated multiwavelength spectra's performance based on three different SOAs using a Lyot filter. The behaviour of multiwavelength laser performance at different SOA nonlinearity and gain is unpredictable in the ring cavity, thus interesting to be investigated. The number of lasing lines, extinction ratio (ER), peak power, flatness and stability are observed. Overall, LSOA has the best performance with 14 lasing lines within 5 dB uniformity, ER of 42 dB and peak power at -14.1 dBm. The flatness value is 3.8 dB and good stability with a maximum peak power deviation of 0.2 dB.

## 2. Experimental Setup and Principle of Operation

The experimental setup is as illustrated in Fig. 1. The laser setup is configured in a ring cavity structure consisting of an SOA as the gain medium and a Lyot filter as the comb filter. The Lyot filter is constructed from the combination of a PC and a PMF. An isolator is used to ensure the light flows in a unidirectional direction. A 10/90 coupler is utilized to circulate 90% of the light in the cavity to continue laser oscillation. In contrast, another 10% is connected to an optical spectrum analyzer (OSA) manufactured by Yokogawa (model number AQ6370B) to view the laser output using a constant resolution of 0.02 nm and sampling data point of 10001.

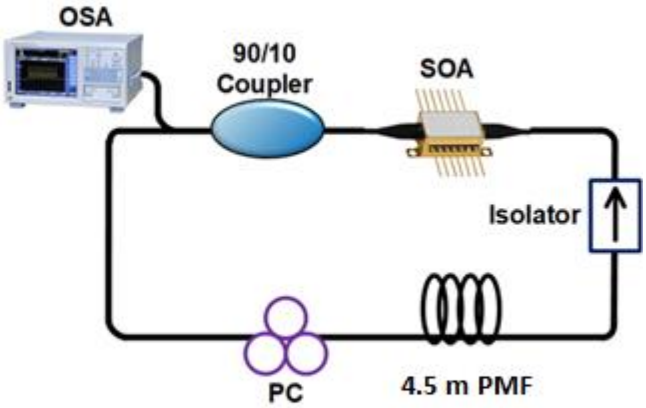

**Fig. 1 - The experimental setup of MWFL based on SOA and Lyot filter**

All three SOAs were characterized to check their ASE spectrum before being inserted into the ring cavity to generate the multiwavelength spectrum. The gathered ASE spectrum is discussed in Section 3.4. Table 1 shows the important specification of the SOAs used in the study. LSOA and NLSOA is inline SOA with low and high nonlinearity, respectively. Inline amplifier usually used in the middle of transmission line to amplify decreased optical signal due to attenuation. BOA is a booster amplifier, typically used right after transmitter to boost the optical signal. These SOAs have different parameters such as operating bandwidth, saturated output power and gain. Since MWFL uses SOA to provide ASE signal, those parameters surely influence the multiwavelength generation. BOA and LSOA have similar saturated output power but different operating bandwidth. Although LSOA and NLSOA have similar bandwidth, their saturated power is significantly different. From the best of our knowledge, investigation of multiwavelength performance based on different SOAs was hardly reported previously. Even though each SOA has different parameter values, the multiwavelength output based on different SOAs in the laser cavity is unpredictable.

**Table 1 - Information from the datasheet of the SOAs**

| **Parameters** | **Linear SOA** | **Non-Linear SOA** | **Booster SOA** |
|---|---|---|---|
| Manufacturer | **Thorlabs** | **Thorlabs** | **Thorlabs** |
| Model number | **SOA1103S** | **SOA1117S** | **BOA1004S** |
| Nonlinearity | Low | High | High |
| Category | Inline | Inline | Booster |
| Maximum Signal Gain (dB) | 13 | 20 | 27 |
| Center Wavelength (nm) | 1500 | 1550 | 1550 |
| Saturation Output Power (@ -3 dB) (dBm) | 14 | 9 | 15 |
| Small Signal Gain (Over C-Band @ Pin = -20 dBm) (dB) | 13 | 20 | 27 |
| Usage in Transmission Link | Amplify the optical signal in every 80 to 100 km | | Boost the input power |

The PMF is a birefringence device which produces an interferometry effect for the generation of multiwavelength laser. The ASE signal from SOA acts as the source of light. When the polarization direction of the incoming light towards PMF is set to 45° in between PMF axes via PC, the refracted light is produced inside PMF's birefringence medium. Constructive interference occurs when the refracted light is combined in-phase with the ordinary light. The constructive interference defines the multiwavelength spectrum and has a phase shift given by;

$$\varphi = 2\pi BL/\lambda \tag{1}$$

where B is the birefringence of PMF, L is the PMF length and λ is the operating wavelength. The channel spacing is determined by using the following equation:

$$\Delta\lambda = \lambda^2 BL \tag{2}$$

## 3. Results and Discussions

Using the same setup and exact value of B and L, the SOA current was varied and by adjusting the PC, the best multiwavelength output spectrum for all three SOAs were captured one after the other. Later, the spectra at every 6 minutes were gathered for one hour to check the laser stability. Then, comparisons are made between ASE spectrum and the best multiwavelength spectrum at 550 mA. The performance of the three SOAs are discussed and compared to find the best multiwavelength performance.

Fig. 2 illustrates the multiwavelength spectrum from 1550 nm to 1600 nm wavelength range while varying the input current from 150 mA to 550 mA. The higher the input current, the spectrum exhibits a broader wavelength range and better flatness. Further observation was done to the output spectra at lower SOA currents, as we found that at higher LSOA current of 150 mA, 250 mA, 350 mA and 450 mA, the lasing lines within 5 dB bandwidth is increased to 4, 7, 10, 14 and the ER is 49 dB, 50 dB, 50 dB and 57 dB, respectively. Meanwhile, the peak power and wavelength bandwidth is -16 dBm, -13 dBm, -14 dBm, -14 dBm and 1.3 nm for all input currents at 150 mA, 250 mA, 350 mA and 450 mA of SOA current, respectively. The multiwavelength flatness is determined from the difference between the highest peak power and lowest peak power. With the SOA current increment, the flatness values are 4.2 dB, 3.1 dB, 5 dB and 4.53 dB. From our observation, the flatness of MWFL is independent with the rise of SOA current. We proved that the intensity in the ring cavity influences the lasing lines and ER from the experiment.

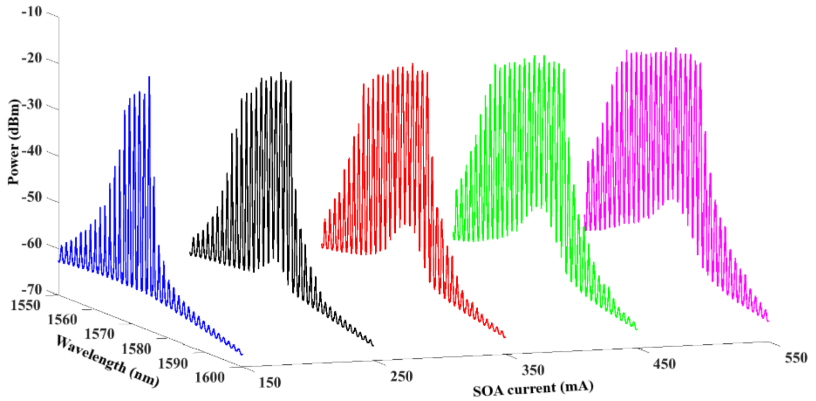

**Fig. 2 - The multiwavelength spectrum at different LSOA current**

Further analysis of the multiwavelength spectrum at the best current setting is shown in Fig. 3. The center wavelength is at 1572.7 nm. Using Equation 2, where the operating wavelength used is the center wavelength, B is 4.1x10$^{-5}$ and L is 4.5 m, the calculated wavelength spacing is 1.3 nm. The magnified view as in Fig. 3(b) shows the measured wavelength spacing that is 1.3 nm, which matches the calculated value. The ER is 42 dB while the generated number of lasing lines within 5 dB uniformity is 14. The highest peak power is -14.1 dBm and the spectrum flatness is 3.8 dB.

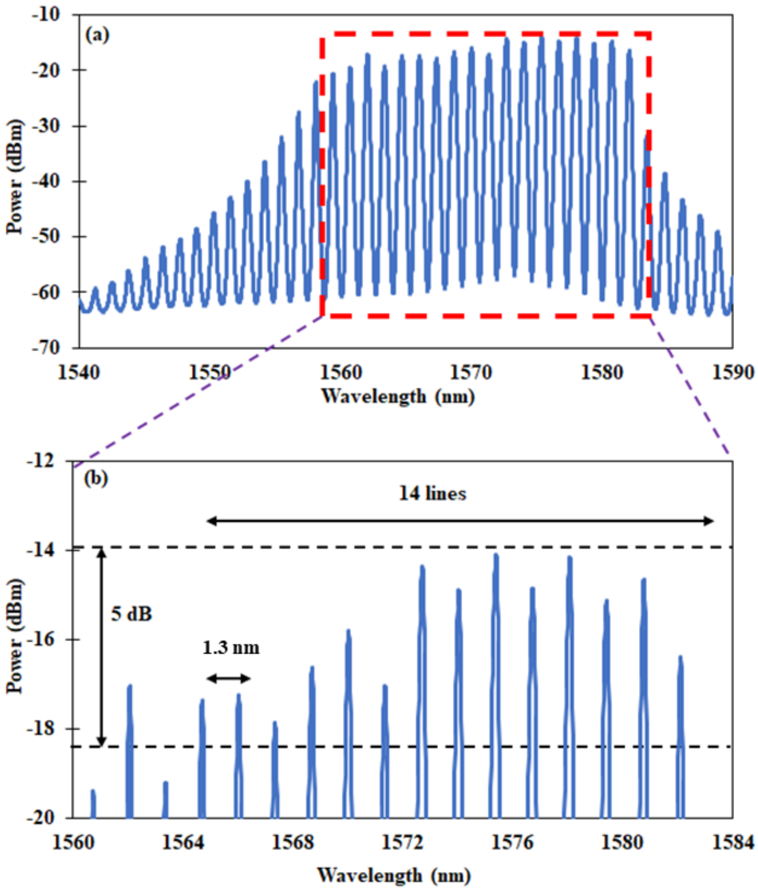

**Fig. 3 - (a) The multiwavelength spectrum at 550 mA of SOA current for LSOA and (b) magnified view within dashed lines of (a)**

In order to verify the stability of the multiwavelength fiber laser, the spectra were captured for every 6 minutes within one hour. Fig. 4 illustrates 11 spectra at 10 nm wavelength span from 1560 nm to 1570 nm. The experimental results show that the entire output spectra's entire profile has slight fluctuations during the whole measurement process. Fig. 5 shows two lasing wavelengths at 1565 nm and 1569 nm for further analysis of the peak power fluctuation. At 1565 nm, the highest peak power is at -18.2 dBm and the lowest peak power at -18.5 dBm, which makes a difference of 0.3 dB. Meanwhile, the highest power deviation of 0.2 dB occurs from 12th minute to 18th minute, while the lowest power deviation is 0.1 dB from zeroth to 6th. The other selected lasing wavelength has the highest and lowest peak power at -20.2 dBm and -20.5 dBm, respectively with 0.3 dB difference. From 48th minute to 54th minute, we can find that the highest peak power deviation is 0.3 dB, while the lowest peak power deviation is 0.2 dB which occurs from 12th minute to 18th minute.

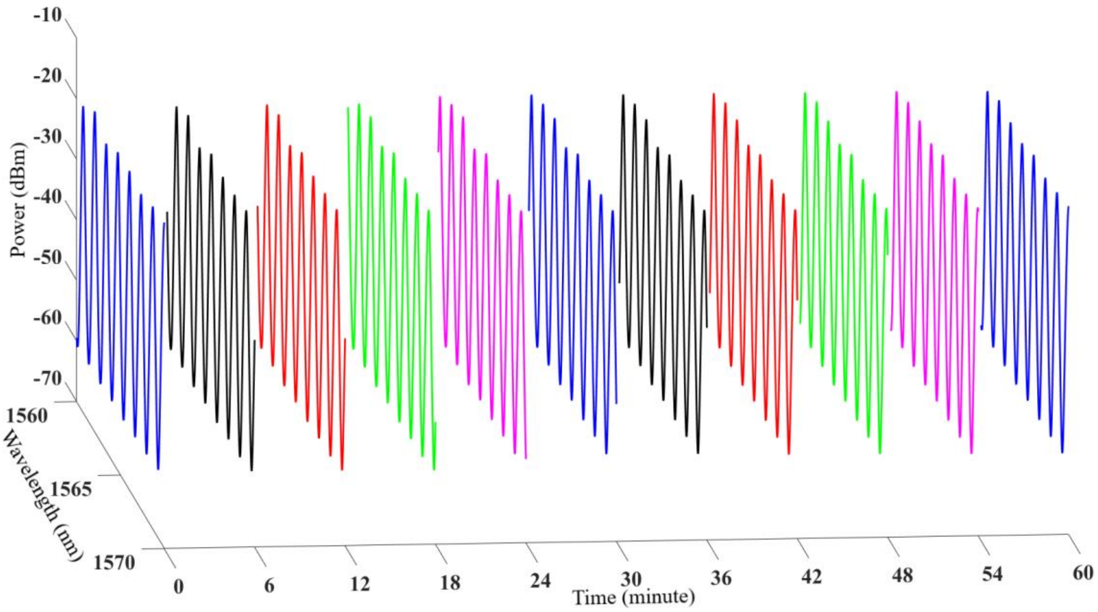

Fig. 4 - Repeated scans to check the stability of the LSOA within one hour

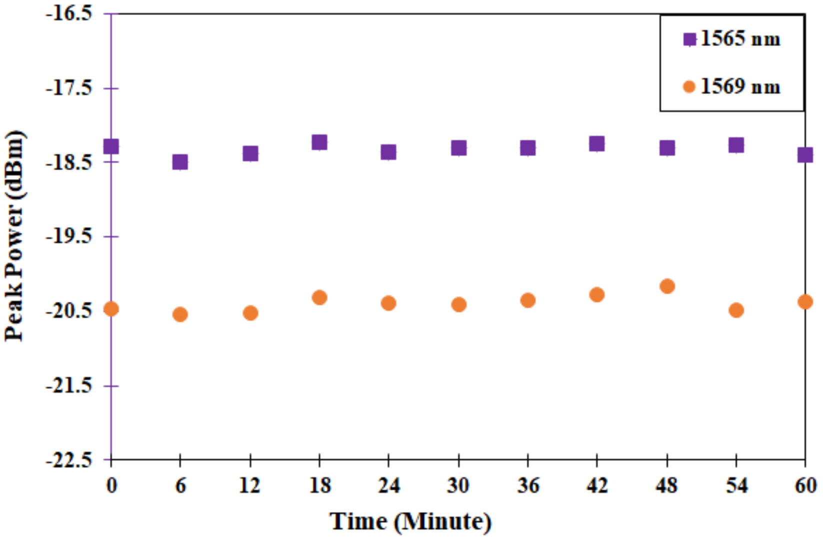

Fig. 5 - Peak power variations of two lasing wavelengths within 60 minutes for LSOA

Fig. 6 depicts the multiwavelength spectrum based on NLSOA at current increment of from 150 mA to 550 mA. From the figure, the multiwavelength spectrum is broader at the highest current setting. Analyses were also made at lower SOA input current of 150 mA, 250 mA, 350 mA and 450 mA. At 150 mA, no lasing lines is observed. At 250 mA, the number of lasing lines is 1 with a flatness peak power of 5.7 dB. The peak power is -13 dBm and ER is 46.5 dB. At 350 mA, the MWFL is further improved with 6 lasing lines and flatness value of 2.6 dB. The peak power and ER is slightly reduced to -16 dBm and 30 dB. At 450 mA, the MWFL lasing line is 8 with flatness value of 4.5 dB. The peak power is -16 dBm and ER is 27 dB. The flatness value is increased with the rise of SOA current after 450 mA.

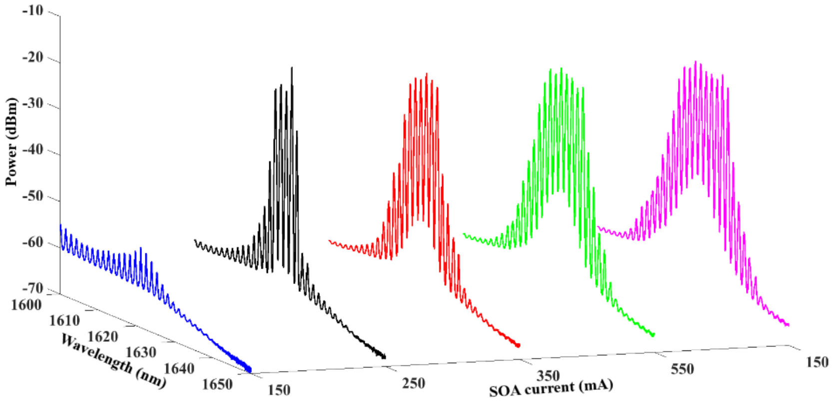

**Fig. 6 - The multiwavelength spectrum at different NLSOA current**

Fig. 7 depicts further analysis on the multiwavelength spectrum when the SOA current is set to 550 mA. The wavelength spacing is 1.4 nm, similar to the calculated spacing by using Equation (2). From the plot, the center wavelength is 1626.95 nm and the ER is 26 dB. The generated number of lines is 9 within 5 dB uniformity and maximum peak power is -17.1 dBm. The lowest peak is -19.9 dBm which contributes to 2.8 dB flatness of the multiwavelength spectrum.

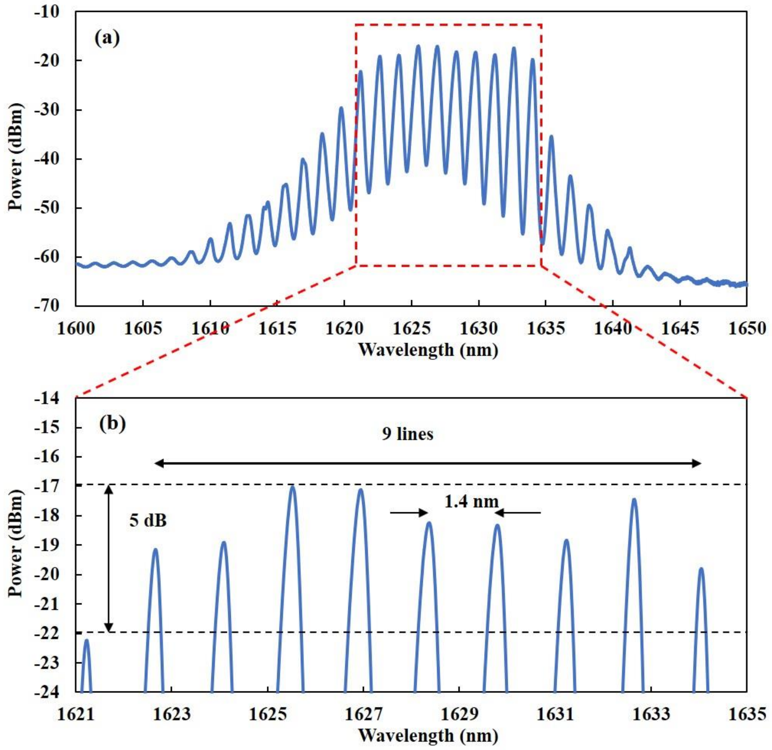

**Fig. 7 - (a) The multiwavelength spectrum at 550 mA of SOA current for NLSOA and (b) magnified view within dashed lines of (a)**

Fig. 8 illustrates 11 spectra at 10 nm wavelength span from 1620 nm to 1630 nm. The experimental results show that the entire profile of the output spectra has some peak power fluctuations during the whole measurement process. For further analysis, Fig. 9 shows peak power fluctuation of two lasing wavelengths of 1623 nm and 1626 nm. At 1623 nm, the highest peak power is at -17.0 dBm and lowest is at -18.8 dBm, which gives differences of 1.8 dB. Meanwhile, the highest peak power deviation of 1.74 dB occurs from 54th to 60th minute, while the lowest peak power deviation is at 1.5 dB from 12th minute to 18th minute. At 1626 nm wavelength, the highest and lowest peak power is at -17.4 dBm and -18 dBm, respectively with 1.4 dB difference. From 30th minute until the 36th minute, the highest deviation occurs at 1.0 dB, while the lowest of 0.8 dB occurs from 12th to 18th.

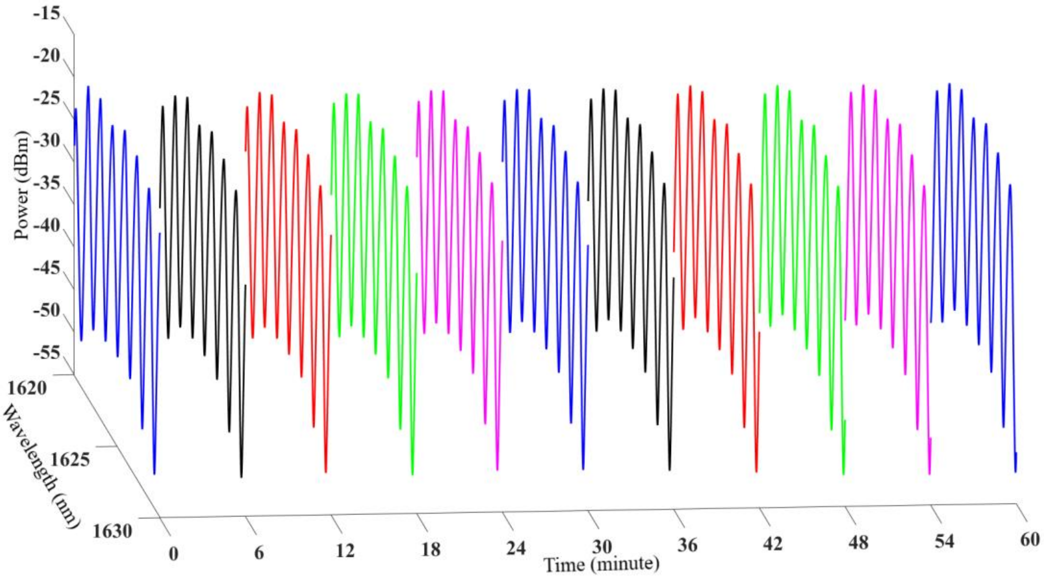

**Fig. 8 - Repeated scans to check the stability of the NLSOA within one hour**

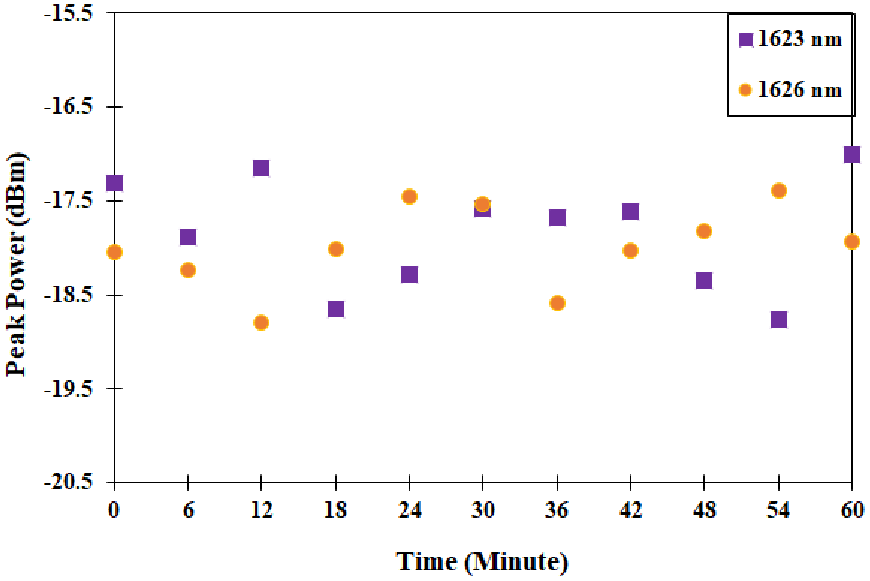

**Fig. 9 - Peak power variations of two lasing wavelengths within 60 minutes for NLSOA**

Fig. 10 illustrates the multiwavelength spectrum using BOA at variation of current setting from 150 mA to 550 mA. With higher BOA current, spectrum range is wider and flatness is much better. When the SOA current is increased to 150 mA, 250 mA, 350 mA and 450 mA, the generated number of lasing lines is 4, 1, 8 and 11, while the ER is 28 dB, 26 dB, 24 dB and 25 dB, respectively. When the BOA current is increased to 150 mA, 350 mA and 450 mA, the wavelength bandwidth is also increased to 4.2 nm, 9.6 nm and 13.8 nm, respectively. Using the same BOA current order, the multiwavelength flatness is 3.9 dB, 4.7 dB, 4.2 dB, and 4.7 dB.

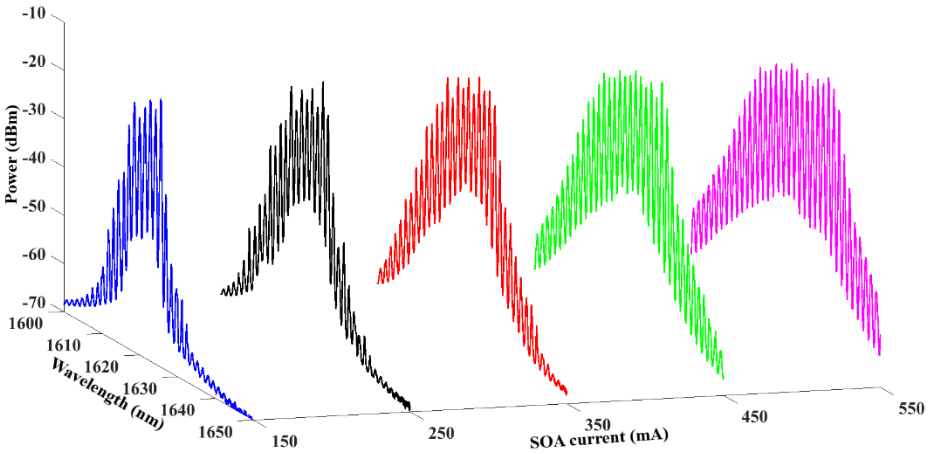

**Fig. 10 - The multiwavelength spectrum at different BOA current**

Fig. 11 exhibits further analysis on the output power when the BOA current is fixed at 550 mA. From the experiment, the center wavelength is at 1630.78 nm. By using Equation (2) the calculated wavelength spacing is 1.4 nm which is the same as measured from the output spectra (Fig. 11(b)). From the figure, the ER is 33 dB, the number of lasing lines is 12 within 5 dB uniformity and the maximum peak power is -12 dBm. The flatness value is also measured at 3.9 dB.

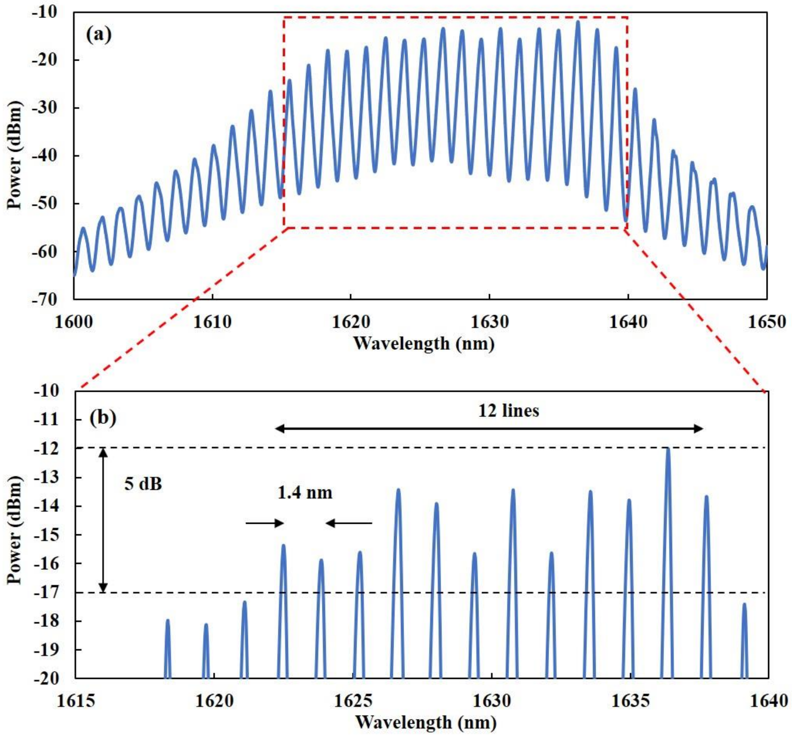

**Fig. 11 - (a) The multiwavelength spectrum at 550 mA of SOA current for BOA and (b) magnified view within dashed lines of (a)**

Fig. 12 illustrates 11 spectra at 10 nm wavelength span from 1620 nm to 1630 nm. The experimental results show that the output spectra's entire profile has some peak deviation within one hour evaluation period. For further analysis, Fig. 13 shows peak power fluctuation of two laser wavelengths at 1621 nm and 1625 nm. At 1621 nm, the highest peak power is at -16.5 dBm and lowest is at -17.7 dBm, a mere 1.2 dB difference. The highest power deviation occurs at 24th to 30th minutes while the lowerst power deviation is 0.02 dB occurs at 48th to 54th minute. At 1625 nm, the highest and the lowest peak power is at -15.33 dBm and -16.63 dBm, respectively with 1.3 dB difference. The largest deviation occurs at zeroth to 6th minute (1.02 dB), while the lowest occurs from 48th to 54th minute.

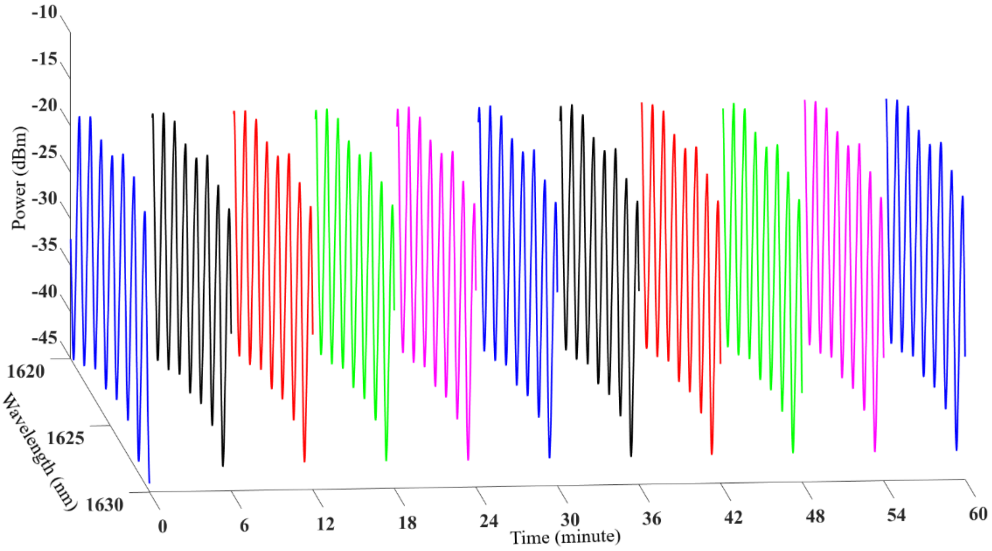

**Fig. 12 - Repeated scans to check the stability of the BOA within one hour**

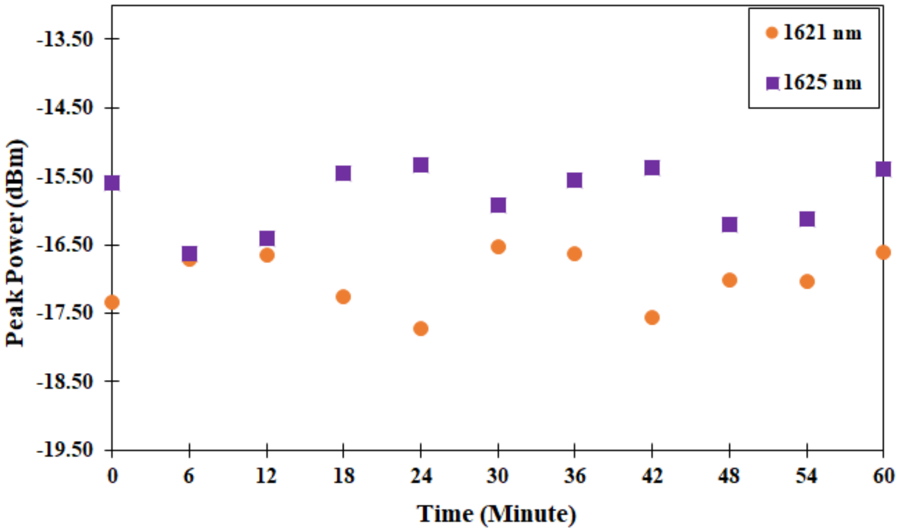

**Fig. 13 - Peak power variations of two lasing wavelengths within 60 minutes for BOA**

The ASEs from the experimental work is then compared with the lasing lines for the three SOAs, as depicted in Fig. 14. From our observation, ASE's center wavelength for LSOA is at 1490 nm, while for the lasing lines is at 1570 nm, with 80 nm of wavelength difference. The center wavelength of ASE and lasing lines for NLSOA is 1555 nm and 1628 nm, respectively. Thus, 73 nm wavelength difference is observed. For BOA, there is a 70 nm wavelength difference as the center wavelength for ASE is 1560 nm, while 1630 nm is the center wavelength for the multiwavelength spectrum. From the three SOAs, the lasing spectrum was found to have a wavelength difference at around 70 nm to 80 nm from its peak wavelength of ASE. These behaviors show that the lasing lines are more dominant at 70 nm to 80 nm from the ASE's center wavelength. Note that the number of lasing lines depends on the ASE range. As depicted in Fig. 14, the number of lasing lines for BOA are higher than NLSOA because of broader ASE in BOA compared to NLSOA. The multiwavelength spectrum cannot be tuned because there is only one PC used in the setup which is for controlling the spectrum flatness.

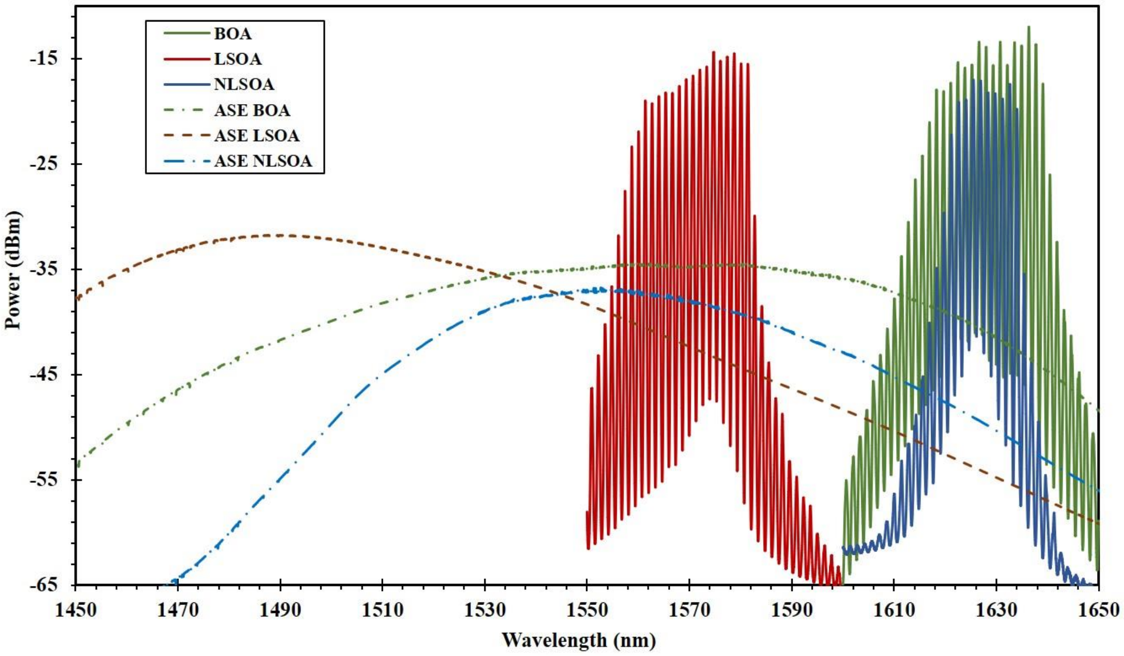

**Fig. 14 - Comparison between ASEs and multiwavelength spectra for LSOA, NLSOA and BOA**

Table 3 summarizes the performance of LSOA, NLSOA and BOA based on the experimental work of this study. The wavelength spacings from the experimental work are tally with the calculated wavelength spacing for each SOAs. It is worth noting that each SOA has a different center wavelength. Based on Equation (1), the wavelength spacing changes with operational wavelength when the PMF length is fixed. The measured center wavelength for each SOAs is found to be at approximately 70 nm to 80 nm from the center wavelength of the ASE spectrum.

The parameters to be discussed are crucial to select the best SOA. LSOA has 42 dB of ER value and 14 lasing lines which are the highest among the three SOAs. The ER value and the number of lasing lines for NLSOA are 30 dB and 9, respectively. While for BOA, the ER is 33 dB with 12 lasing lines. However, BOA has the highest peak power at -12 dBm, followed by LSOA at -14.1 dBm and the lowest is -17.1 dBm by NLSOA. NLSOA has the best flatness value at 2.8 dB, while LSOA and BOA show almost the same flatness at 3.8 dB and 3.9 dB, respectively. The stability performance of LSOA is the best as the maximum peak power fluctuation is only 0.2 dB, while the minimum peak power fluctuation is 0.1 dB. Low peak power deviations represent a high stability of MWFL because it represents the gap between the maximum and minimum of the multiwavelength spectrum within one hour of stability test. NLSOA and BOA are less stable than LSOA with 1.5 dB and 0.9 dB minimum peak power deviation, respectively. At the meantime, the maximum peak power deviation for NLSOA and BOA are 1.7 dB and 1.2 dB, respectively.

**Table 3 - The MWFL performance from three types of SOAs**

| **Parameter** | **LSOA** | **NLSOA** | **BOA** |
|---|---|---|---|
| Wavelength Spacing (nm) | 1.3 | 1.4 | 1.4 |
| Center Wavelength (nm) | 1572.70 | 1626.95 | 1630.78 |
| ER (dB) | 42 | 26 | 33 |
| Number of Lasing Lines | 14 | 9 | 12 |
| Peak Power (dBm) | -14.1 | -17.1 | -12 |
| Flatness value (dB) | 3.8 | 2.8 | 3.9 |
| Minimum peak power deviation (dB) | 0.1 | 1.5 | 0.9 |
| Maximum peak power deviation (dB) | 0.2 | 1.7 | 1.2 |

## 4. Conclusion

We have demonstrated multiwavelength performance based on different SOAs utilizing Lyot filter. Overall, LSOA possesses the best performance as compared to NLSOA and BOA. LSOA has the highest ER value at 42 dB followed by BOA and NLSOA with 33 dB and 26 dB, respectively. LSOA, BOA and NLSOA generate 14, 12 and 9 lasing lines respectively, at 550 mA of SOA current. BOA's peak power is the highest at -12 dBm, followed by -14.1 dBm by LSOA and -17.1 dBm by NLSOA. NLSOA exhibits the best flatness at 2.8 dB, while LSOA and BOA slightly has higher flatness. In terms of stability, LSOA shows the best performance with a peak power deviation of less than 0.2 dB, while for NLSOA and BOA it is above 0.9 dB. Stability of the multiwavelength spectrum is represented by the peak power deviations with a stable spectrum having low variation between the spectrum's maximum and minimum peak power. This MWFL setup could be useful in many MWFL applications, such as DWDM and optical sensing.

## Acknowledgement

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