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Multiwavelength based on nonlinear optics of intensity and phase modulators

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Abstract. This paper presents a simple method for generating multiwavelength using a nonlinear effect of cascaded intensity and phase modulators. Both of the modulators are driven by sinusoidal waveform. The multiwavelength lasing can be achieved by setting the ideal value of the amplitude of the sinusoidal waveform, and the flatness of the generated wavelengths can be improved by setting an optimum value of the direct current (DC) bias of intensity modulator. Moreover, single-mode fiber along with Raman scattering effect is needed to amplify and suppress the side bands; hence, a customized number of wavelengths can be achieved. Results show that more flatness wavelengths could be achieved when the DC bias to amplitude ratio is within the range ($\alpha = 0.1$ to 0.14). Moreover, α to phase modulator's voltage ratio should be 0.1. [DOI: 10.1117/1.OE.56.1.016104]

Keywords: multiwavelength lasing; Raman amplification; intensity modulators; phase modulator.

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1 Introduction

Generation of a multiwavelength fiber laser around 1.5 μm and many different techniques used to generate lasing have been widely studied. Most of the methods used to generate multiwavelength lasing based on nonlinear effects, such as four-wave mixing and Brillouin.[1–7] Turitsyn et al.[8], demonstrate a fiber laser with a mirrorless open cavity that operates via Rayleigh scattering, amplified through the stimulated Raman scattering effect in a long-distance single-mode fiber (SMF), and they were able to generate a narrow spectrum. Recently, an erbium-doped fiber laser based on random distributed feedback through Rayleigh scattering in 5- to 30-km SMF was demonstrated by Wang et al.[9] and dual wavelengths were achieved by using two fiber Bragg grating (FBGs) with different reflection wavelengths to collaborate with the distributed Rayleigh output mirror. In the same year, Huang et al.[10] implemented the same configuration using chirped FBG and obtained multiwavelength random fiber laser with flattened output spectra; up to five output channels with a spacing of about 0.088 nm and a linewidth of about 0.02 nm were recorded. More work was done in 2015, where Dong et al. succeeded in obtaining narrow line-width Eribum-doped fiber (EDF) laser using a random distributed Bragg grating array feedback.[11] An ultrashort random fiber laser based on an FBG with multiple random phase shifts distributed along an Er/Yb-codoped fiber was reported as the shortest random fiber laser.[12] In the same year, a different configuration was implemented to report an ultralong, low threshold, and high-stability random distributed feedback fiber laser based on EDF and SMF as a distributed mirror in combination with FBG.[13] Unfortunately, most of the multiwavelength lasing techniques based on EDF failed to achieve stable output with small wavelength spacing at room temperature due to the homogeneous line broadening of the EDF at room temperature, which leads to strong competition among the generated wavelengths.[14] Phase modulator (PM) was considered a solution to overcome this problem. Therefore, generating multiwavelength using phase modulation becomes more interesting due to its frequency spacing tunability and high stability.[15] Stable multiwavelength lasing-based Erbium-doped fiber ring laser incorporating a semiconductor optical amplifier-based PM was experimentally implemented.[14] Moreover, single-PM in a loop was used to generate broadband multiwavelength.[16]

In this article, a simple scheme will be used for multiwavelength lasing using a nonlinear effect of cascaded intensity and PMs along with the SMF and Raman amplification effect to customize the number of wavelengths. The effects of direct current (DC) bias and the amplitude of the sinusoidal waveform on the performance of the multiwavelength laser are also investigated.

2 System Description

The configuration of the multiwavelength lasing system is shown in Fig. 1. The lasing cavity contains a cascade of intensity modulator (IM) and PM, and both are driven by a sinusoidal source with a frequency of 50 GHz, which modulated a continuous wave laser wavelength at 1550 nm with −30 dBm. The PM is connected to SMF with a length 10 km, and a laser pump at 1447.86 nm with 0.1 W is injected into the fiber for Raman gain medium purpose. Both of the modulators are needed in this configuration to achieve a large number of sidebands, as shown in the following section. In addition to increasing the number of sidebands, the IM will also help to flatten the sidebands by setting an optimum value of DC bias of the IM.

Since the input signal of the IM is a sinewave signal with an amplitude V_A, and frequency f_m, the optical signal has a central frequency f_0, and the output field of IM is controlled by a DC bias V_{DC}, it can be expressed by[17]

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$$E_{\mathrm{IM}}(t) = \cos\left\{\frac{\pi}{2}\left[\left(1+\frac{V_{\mathrm{DC}}}{V_\pi}\right)+\frac{V_{\mathrm{A}}}{V_\pi}\cos 2\pi f_{\mathrm{m}}t\right]\right\}\cos 2\pi f_0 t, \tag{1}$$

where V_π is the PM's voltage. This expression is further expanded with Bessel functions to present a clear explanation on how sidebands are generated

$$\begin{aligned} E_{\mathrm{IM}}(t) = {} & \frac{1}{2}J_0\left(\frac{\pi V_{\mathrm{A}}}{2V_\pi}\right)\cos\left[\frac{\pi}{2}\left(1+\frac{V_{\mathrm{DC}}}{V_\pi}\right)\right]\cos 2\pi f_0 t \\ & - \sum_{\substack{n=-\infty \\ n\neq 0 \\ n=\pm1,\pm3,\pm5\ldots}}^{\infty} J_n\left(\frac{\pi V_{\mathrm{A}}}{2V_\pi}\right)\sin\left[\frac{\pi}{2}\left(1+\frac{V_{\mathrm{DC}}}{V_\pi}\right)\right] \\ & \times\cos 2\pi(f_0 \pm n f_{\mathrm{m}})t \\ & + \sum_{\substack{n=-\infty \\ n\neq 0 \\ n=\pm2,\pm4,\pm6\ldots}}^{\infty} J_n\left(\frac{\pi V_{\mathrm{A}}}{2V_\pi}\right)\cos\left[\frac{\pi}{2}\left(1+\frac{V_{\mathrm{DC}}}{V_\pi}\right)\right] \\ & \times\cos 2\pi(f_0 \pm n f_{\mathrm{m}})t. \end{aligned} \tag{2}$$

Clearly the output spectrum is centred at f_0 and generated sidebands are separated by f_{m}. The even components of Eq. (2) along with the main carrier f_0 can be totally suppressed only when the DC bias is set at the minimum transmission point, which leads the modulator biased at V_π. Since the purpose of this paper to generate sidebands as much as we can, then DC bias value should be studied carefully. Although the number of sidebands will only be reduced at the minimum transmission point, DC bias helps to improve the sidebands power and flatten the output spectrum. Furthermore, at a certain value of DC bias, the amplitude of the components that are far away from the central frequency f_0 can be reduced as compared to the one near the f_0. This will help to keep only two customized sidebands, and when these sidebands hit a photodiode, we can generate millimeter-wave signal with frequency equal to the spacing between these sidebands.

According to Fig. 1, IM output [i.e., Eq. (2)] is one of the input signals to the PM, and the second input is the sinusoidal signal with an amplitude V_{A}, and frequency f_{m}. Hence, the output of the PM can be expressed as

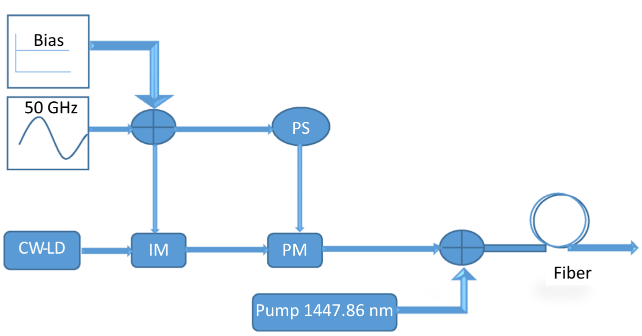

Fig. 1 Configuration of multiwavelength lasing (CW-LD, continuous wave-laser source; IM, intensity modulator; PM, phase modulator; and PS, phase shift).

$$E_{\mathrm{PM}}(t) = E_{\mathrm{IM}}(t)e^{\left(j\frac{\pi V_{\mathrm{A}}}{V_\pi}\cos 2\pi f_{\mathrm{m}}t\right)}, \tag{3}$$

where V_{A}/V_π represents the phase modulation index. More sidebands can be obtained as this factor increases, in other words, when the amplitude of the sinusoidal signal applied on the PM increases, as is shown in the following section.

3 System Evaluation

From the simulation results, the system manages to achieve many wavelengths with 0.4-nm spacing (i.e., 50 GHz), which is the frequency of the sinusoidal wave. The output of the PM is connected to the SMF fiber along with the Raman amplification effect to suppress the unwanted wavelengths that have low power. Figure 2 shows the spectrum before and after 10 km of SMF at different values of sinusoidal amplitude. The DC bias and PM's voltage are set at 0.5 and 5 v, respectively. With Raman amplification, the power of each channel with a bandwidth of 0.4 nm is around −45 dBm. The results show that three parameters should be considered for generating a large number of wavelengths with flat spectrum. The first parameter relates to the amplitude of the microwave signal, which is responsible for increasing the sideband. Clearly, as the amplitude of the sinusoidal increases, more wavelengths are generated. Unfortunately, the generated wavelengths do not have the same amount of power, and using EDFA here does not help to flatten them. Consequently, instead of using filters or other technique such as arrayed waveguide gratings in Ref. 18 to filter out the undesired weak wavelengths, I used 10 km of SMF along with Raman pump. This could help to amplify the customized wavelengths by choosing the right pump wavelength, so these customized wavelengths can get the maximum gain while the weak wavelengths will be eliminated, as shown in Figs. 1(c) and 1(d).

The second parameter is the DC bias of IM, which could help to increase the power of the generated sidebands and, at the same time, flatten these sidebands. Figure 3 shows the spectrum before and after SMF at different DC bias values, while the amplitude of the sinusoidal and PM's voltage were set at 3 and 5 v, respectively. It is worth noting that Figs. 2(b) and 3(a) are the same where the DC bias is set at 0.5 v. Fortunately, when the DC bias increases, as shown in Fig. 3(b), the sidebands' power improves, meanwhile some sidebands are suppressed according to Eq. (2). Because of this, we have to study the relationship between the DC bias and the amplitude of the sinusoidal. Finally, the weak sidebands were eliminated after the SMF, as shown in Fig. 3(d).

In addition, there is a strong relationship between the DC bias and the amplitude of the sinusoidal wave. More wavelengths can be generated when the optimum value of the DC bias and the sinusoidal amplitude are used. Figure 4 proves that more spectrum can be achieved only when the DC bias to amplitude ratio is within the range ($\alpha = 0.1$ to 0.14). In addition, the DC helps to flatten the output spectrum, and it was noted that the sinusoidal amplitude should be large enough to have more wavelengths.

In previous works, dispersion decreasing fiber of 2 km and normal group velocity dispersion highly nonlinear fiber of 247 m were both used along with PM to achieve broadened optical frequency comb, where self-phase modulation

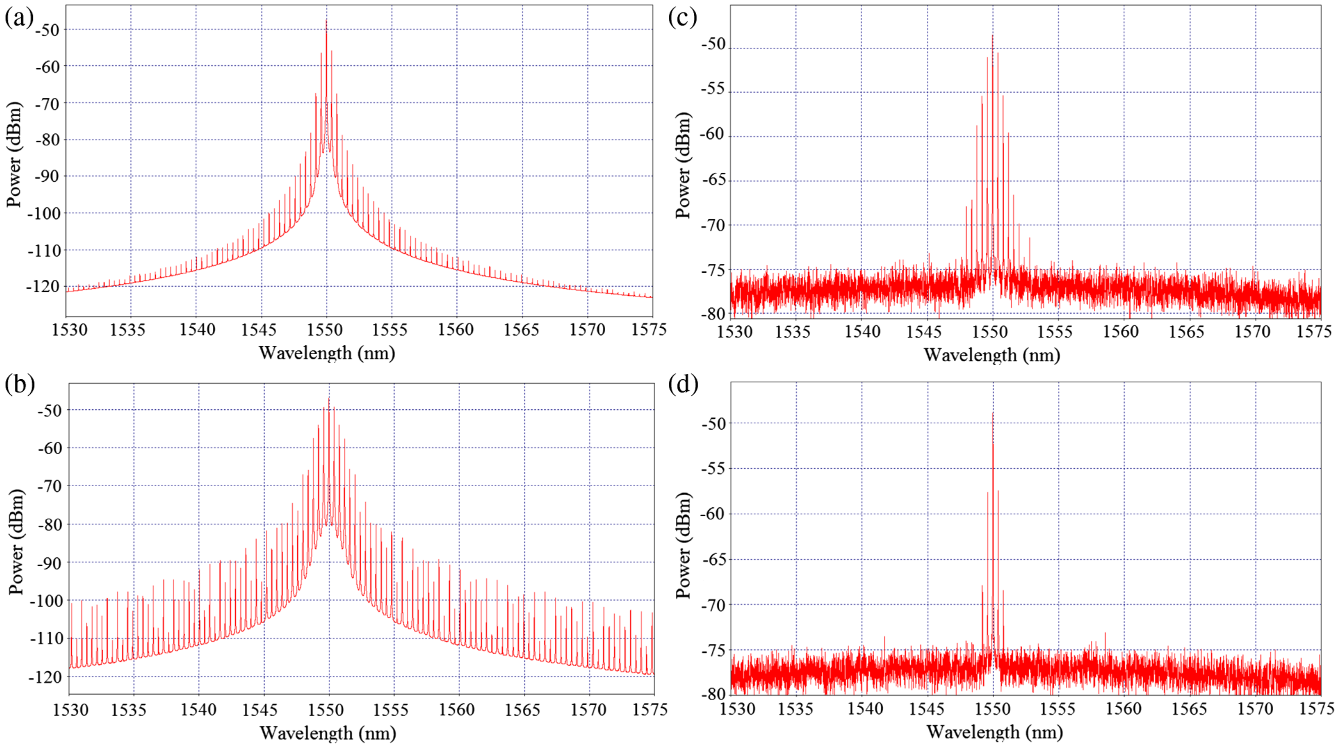

Fig. 2 Received spectrum (a, b) before SMF and (c, d) after SMF, when the amplitude of the sinusoidal is 0.5 and 2.9 v.

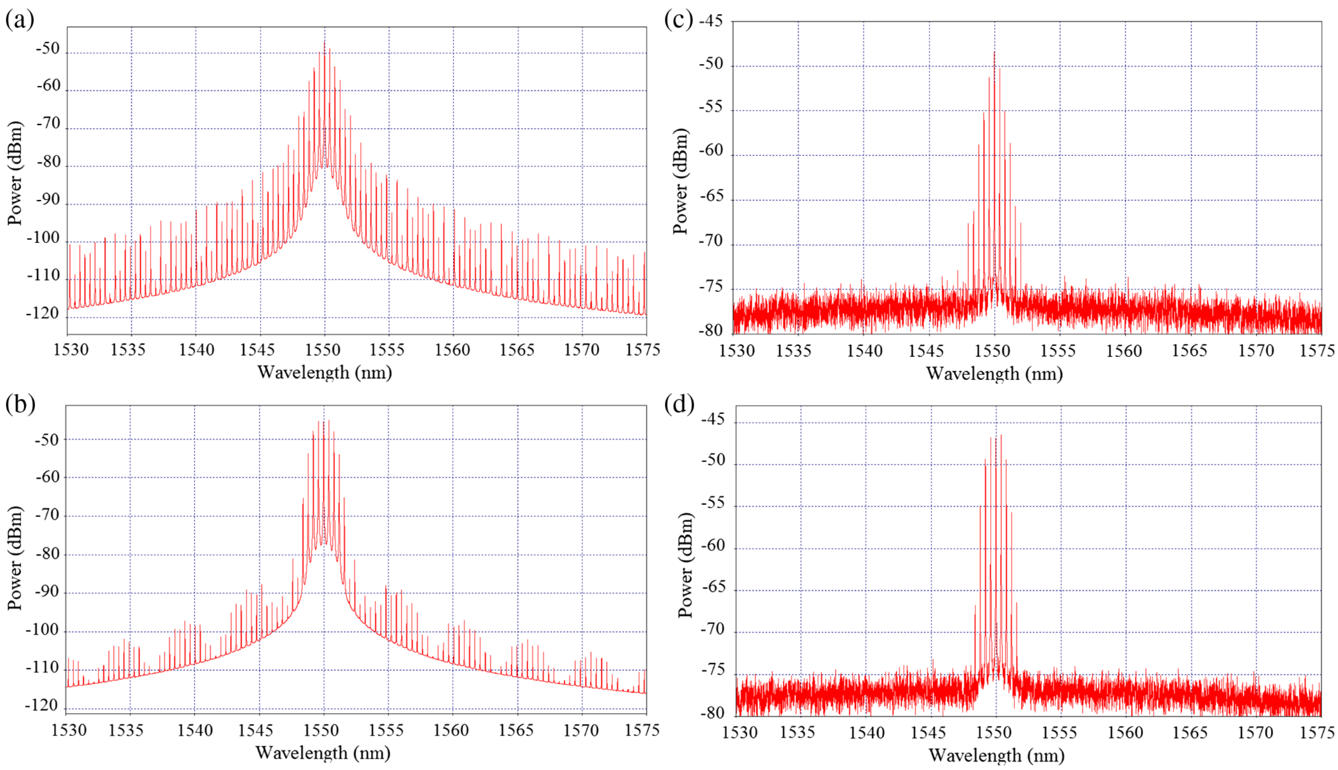

Fig. 3 Received spectrum (a, b) before SMF and (c, d) after SMF, when the DC bias 0.5 and 2.9 v.

was exploited as the broadening mechanism.[19] Wu et al. used two IM followed by one PM to achieve flat spectrum, and they successfully achieved 38 lines with power fluctuation 1 dB.[20] Chen et al. implemented a configuration almost the same as the one mentioned in Ref. 20 except with a single PM with two identical IM; their configuration was capable of achieving 29 lines within 0.5 dB.[21] In comparison to my simple configuration, I carefully chose the optimum value of

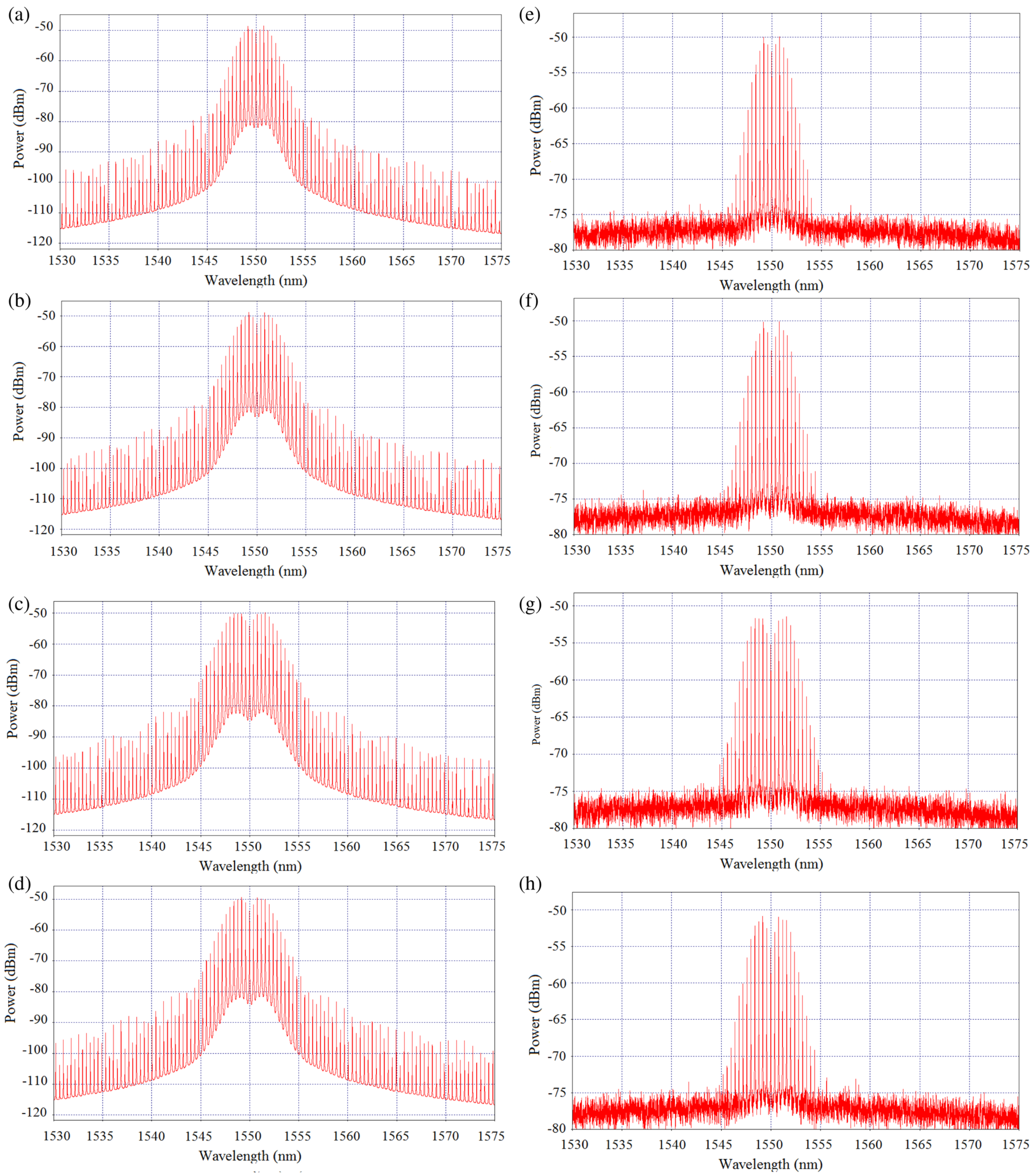

Fig. 4 Received spectrum (a–d) before SMF and (e–h) after SMF, when $\alpha = 0.14$, 0.12, 0.11, and 0.1.

the DC bias/amplitude ratio (α) and the (DC bias/amplitude) to PM's voltage ratio (i.e., $\gamma = \alpha/V_{\pi}$), and I managed to achieve 51 lines with power fluctuation 1.5 dB and 63 within 3.7 dB, as shown in Fig. 5. Subsequently, Fig. 5 presents the third parameter that helps to increase the generated sidebands, which is the ratio between the DC bias to amplitude (i.e., α) to PM's voltage (V_{π}). In addition I used Raman amplification to remove the weak sidebands and produce a customized number of sidebands. As a result, with a help of 10-km SMF, Raman could help to amplify a certain number of wavelengths, depending on the wavelength of the Raman pump laser source.

In summary, the number of generated wavelengths versus [DC bias/amplitude (α)] to PM's voltage ratio

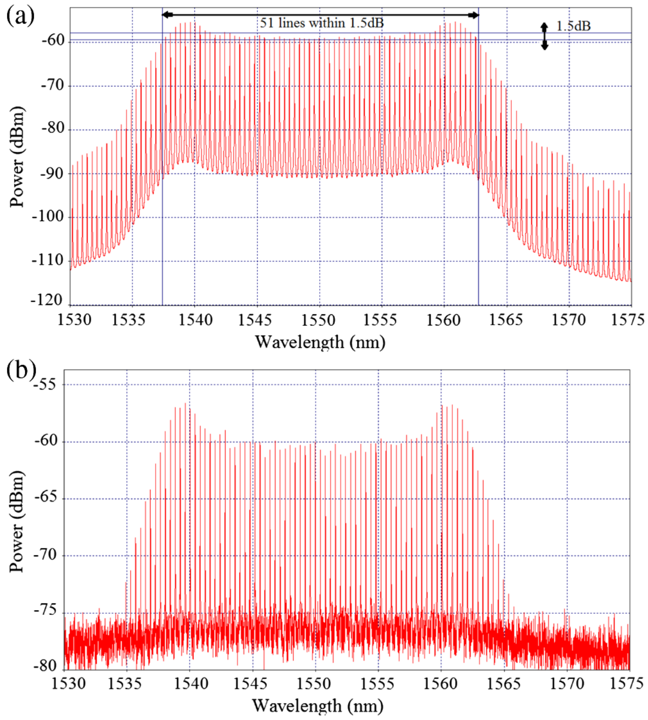

Fig. 5 Received spectrum (a) before SMF and (b) after SMF, when $\gamma = 0.1$.

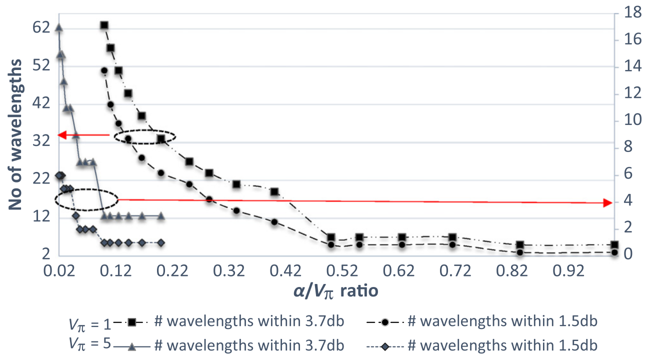

Fig. 6 Relation between number of generated wavelengths and $\gamma = \alpha/V_\pi$ ratio.

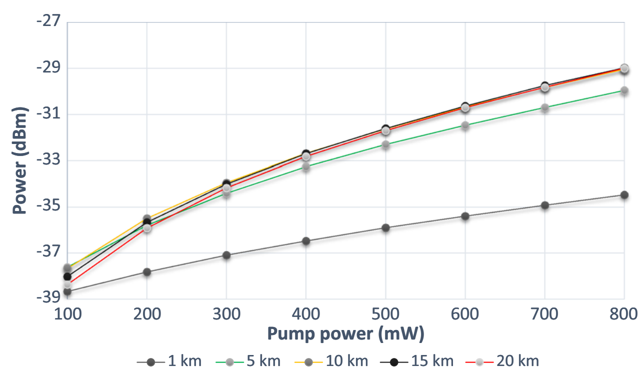

Fig. 7 Relation between the generated wavelengths power and Raman pump power at different fiber length.

(i.e., $\gamma = \alpha/V_\pi$) with an average power −45 dBm is shown in Fig. 6, when $V_\pi = 1$ and 5 v. Clearly, more wavelengths can be achieved when $V_\pi = 1$ v, which leads to $\gamma = 0.1$, as shown in Figs. 4–6. The figures also show the number of wavelengths with power fluctuation 1.5 and 3.7 dB. The average output power can be increased by increasing the pump power, as shown in Fig. 7, which also indicates that the suitable fiber length for Raman amplification is 10 km. For more than 10 km, no more amplification will occur where at 10 km the gain will reach saturation. Also, for less than 10 km, the length is not enough for the interaction between the signal and Raman pump.

4 Conclusion

This paper presented a new configuration for generating multiwavelength lasing based on the nonlinear effect of a cascaded intensity and PMs. The modulators are driven by sinusoidal waveform. To have more flat wavelengths, the results show that DC bias/amplitude ratio ($\alpha = 0.1$) and DC bias/amplitude to PM's voltage ratio ($\gamma = 0.1$). Moreover, a Raman pump is used for two purposes: amplification and suppression of the weak wavelengths. Hence, a customized number of wavelengths can be achieved. In addition, such configuration could be used to generate multiwavelengths that can be used in optical communication systems such as wavelength division multiplexing. In the future, more investigation could be conducted on generating millimeter-wave (mm-wave) frequencies for backhaul of telecommunications signals and wireless communication. By controlling the ratio between the DC bias, the sinusoidal amplitude, and PM's voltage and using SMF along with a Raman pump, we will be able to get only two wavelengths, and by beating these two wavelengths at a photodetector, we can easily get mm-wave with a frequency of the sinusoidal waveform.

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