

# The effect of pump parameters on dual-pump fiber optical parametric amplifier

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**Abstract.** The impact of pump parameters on dual-pump (2-P) fiber optical parametric amplifier (FOPA) is investigated. The four-wave model of coupled amplitude equations with fiber losses and pump depletion are solved numerically for the calculation of the parametric gain. Simulation results indicate that an increase in pump powers does not only enhances the parametric gain but also flattening the amplification bandwidth. Moreover, separating the pumps wavelengths further from each other can also improve the flatness of the bandwidth. Besides that, the parametric gain flatness can be improved when the separation between the pump central wavelength and zero-dispersion wavelength is small. In essence, the optimal performance of 2-P FOPA can be achieved when the pump parameters are carefully tailored.

## 1 Introduction

Four-wave mixing (FWM) is a nonlinear effect which involves the parametric process, where a signal is amplified with the pump waves and consequently the new wave name idler is generated. This effect is detrimental in some of the applications. Nevertheless, FWM is still favorable for a few optical applications such as FWM-assisted lasers [1], optical regenerators [2] and parametric oscillators [3]. Fiber optical parametric amplifier (FOPA) is one of the devices that also exploits the effect of FWM [4]. There are two types of FOPA, i.e. one-pump (1-P) FOPA and dual-pump (2-P) FOPA. Both types of FOPA are capable in providing adjustable gain spectra and center frequency, wavelength conversion, phase conjugation, pulse operation for signal processing and 0-dB noise figure [5]. These advantages of FOPA have surpassed the limitation of conventional amplifiers i.e. Raman amplifier (RA) and Erbium-doped fiber amplifier (EDFA), and consequently become the interest of researchers to explore the potential of FOPA in exceeding the current limit of optical communication systems.

Practically, a FOPA is required to demonstrate good performance i.e. high parametric gain and large amplification bandwidth. The parameters such as pump wavelength and pump power do contribute to the FOPA performance [6]. As for 2-P FOPA, the pumps wavelengths separation will also affect the performance of FOPA amplification bandwidth [7]. In addition, a wide amplification bandwidth of 2-P FOPA can be obtained by adjusting the separation of pump central frequency,  $\omega_c$  from zero-dispersion frequency. Besides that, a research conducted in [8] successfully verified that the amount of power for both pumps is crucial in determining the parametric gain of 2-P FOPA.

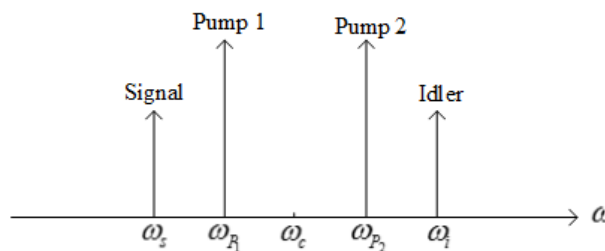


Fig. 1. Schematic of non-degenerate FWM in frequency domain.

This simulation work concentrate on four-wave model of FWM which is known as non-degenerate FWM. The schematic of the model is illustrated in Fig.1. The non-degenerate FWM process include the interaction of three waves which are two pump waves and a signal wave. The beat process of these three waves give rises to a new wave, idler. The aim of this paper is to numerically investigate the effect of pump parameters such as wavelength and power, on the four-wave model of 2-P FOPA. The performance of the parametric gain and amplification bandwidth are critically observed by varying the mentioned pump parameters. The highly-nonlinear dispersion shifted fiber (HNL-DSF) was used as a gain medium and pump depletion as well as fiber losses were taken into account. All simulations were carried on using Matlab 2014.

## 2 Mathematical model

The non-degenerate FWM process in Fig.1 can be represented by the amplitude equations for pump 1 ( $P_1$ ), pump 2 ( $P_2$ ), signal ( $s$ ) and idler ( $i$ ) along the fiber-length  $z$ . The equations are given by [5]

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$$\frac{dA_{P_1}}{dz} = i\gamma \left[ \left( |A_{P_1}|^2 + 2|A_{P_2}|^2 + 2|A_s|^2 + 2|A_i|^2 \right) A_{P_1} \right] + 2i\gamma A_{P_2}^* A_s A_i e^{i\Delta\beta z} - \frac{\alpha}{2} A_{P_1}, \quad (1)$$

$$\frac{dA_{P_2}}{dz} = i\gamma \left[ \left( |A_{P_2}|^2 + 2|A_{P_1}|^2 + 2|A_s|^2 + 2|A_i|^2 \right) A_{P_2} \right] + 2i\gamma A_{P_1}^* A_s A_i e^{i\Delta\beta z} - \frac{\alpha}{2} A_{P_2}, \quad (2)$$

$$\frac{dA_s}{dz} = i\gamma \left[ \left( |A_s|^2 + 2|A_{P_1}|^2 + 2|A_{P_2}|^2 + 2|A_i|^2 \right) A_s \right] + 2i\gamma A_i^* A_{P_1} A_{P_2} e^{-i\Delta\beta z} - \frac{\alpha}{2} A_s, \quad (3)$$

$$\frac{dA_i}{dz} = i\gamma \left[ \left( |A_i|^2 + 2|A_{P_1}|^2 + 2|A_{P_2}|^2 + 2|A_s|^2 \right) A_i \right] + 2i\gamma A_s^* A_{P_1} A_{P_2} e^{-i\Delta\beta z} - \frac{\alpha}{2} A_i, \quad (4)$$

where  $\gamma$  is the fiber nonlinearity,  $\alpha$  denotes the fiber loss and  $A_j^*$  for  $j \in \{P_1, P_2, s, i\}$  represent the complex conjugate of  $A_j$ . The linear phase-mismatch,  $\Delta\beta$  can be expressed as [9]

$$\Delta\beta = 2 \sum_{m=1}^{\infty} \frac{\beta_{2m}}{(2m)!} \left[ (\Delta\omega_s)^{2m} - (\Delta\omega_p)^{2m} \right], \quad (5)$$

where  $\beta_{2m}$  is higher-order dispersion coefficient given by the  $2m^{\text{th}}$  derivative of mode-propagation constant  $\beta(\omega)$ , at the central frequency  $\omega_c = (\omega_{P_1} + \omega_{P_2})/2 = (\omega_s + \omega_i)/2$ . Meanwhile,  $\Delta\omega_s = \omega_s - \omega_c$  and  $\Delta\omega_p = \omega_{P_1} - \omega_c = (\omega_{P_1} + \omega_{P_2})/2$ .

Generally, Eqs. (1)-(4) are solved numerically by using the fourth-order Runge-Kutta method. Then, the parametric gain (in dB) at the respective wavelength are calculated by the ratio of the output signal power,  $P_{s,out}$  to the input signal power,  $P_{s,in}$  such as

$$G = 10 \log \left( \frac{P_{s,out}}{P_{s,in}} \right), \quad (6)$$

where  $P_s = |A_s|^2$ , for both input and output signal powers.

### 3 Result and Discussions

In order to investigate the performance of 2-P FOPA effectively, the parametric gains which have been obtained by using (6) were plotted against the signal wavelengths. The parametric gains were computed by varying the parameters such as the power of  $P_1$  and  $P_2$ , the separation between two pumps wavelength,  $\Delta\lambda_p = \lambda_{P_2} - \lambda_{P_1}$  and the wavelength distance of the central wavelength from zero-dispersion wavelength (ZDW),  $\lambda_c - \lambda_0$ . A 500 m-length HNL-DSF of OFS company was used in this simulation work and the fiber

has ZDW at  $\lambda_0 = 1556.5$  nm,  $\alpha = 0.82$  dB/km and  $\gamma = 11.5$  W<sup>-1</sup>km<sup>-1</sup>.

Firstly, the parametric gain was computed by manipulating the power of both pumps. The other parameters were fixed as  $P_{s,in} = -40$  dBm,  $\lambda_{P_1} = 1548.1$  nm,  $\lambda_{P_2} = 1568.03$  nm and  $\lambda_c = 1558$  nm. The second-order and fourth-order dispersion coefficients at  $\lambda_c = 1558$  nm are  $\beta_2 = -1.97 \times 10^{-2}$  ps<sup>2</sup>/km and  $\beta_4 = 6.231 \times 10^{-5}$  ps<sup>4</sup>/km, respectively. The resulted parametric gains were plotted in Fig. 2. As predicted, the parametric gain increases as the pumps power increased. This is similar with 1-P FOPA behaviour when the pump power increases [10]. However, unlike in the 1-P FOPA, the increase of pump power in the 2-P FOPA does not only affects the amplification bandwidth but also its flatness. As is seen, when the power of  $P_1 = 1$  W, the bandwidth of 2-P FOPA is flatter if compared with the bandwidth of the lowest pump power,  $P_1 = 0.25$  W. This implies that rather than just increasing the parametric gain and amplification bandwidth the increasing pump power in 2-P FOPA also resulted in flatter gain spectrum.

Next, in order to attain optimum performance of 2-P FOPA, the selection of both pumps wavelengths are crucial. The selected pump wavelengths will determine the separation between two pumps wavelengths. Hence, this time the parametric gains were calculated while manipulating the distance between  $P_1$  and  $P_2$  wavelengths,  $\Delta\lambda_p$ . In the meantime, the other parameters value were assigned as  $P_1 = P_2 = 0.5$  W and  $\lambda_c \approx 1558$  nm, thus  $\lambda_c - \lambda_0 \approx 1.5$  nm. The value of  $\beta_2$  and  $\beta_4$  at  $\lambda_c$  are similar as before. The obtained parametric gain are

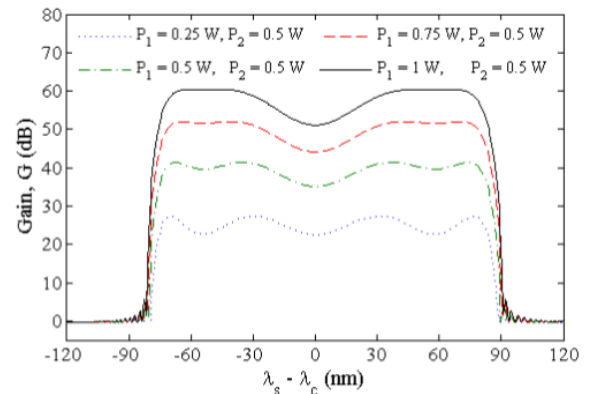


Fig. 2. Gain spectrum for different amount of pump power.

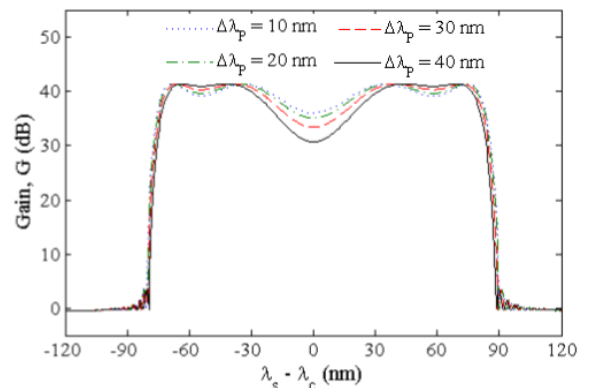
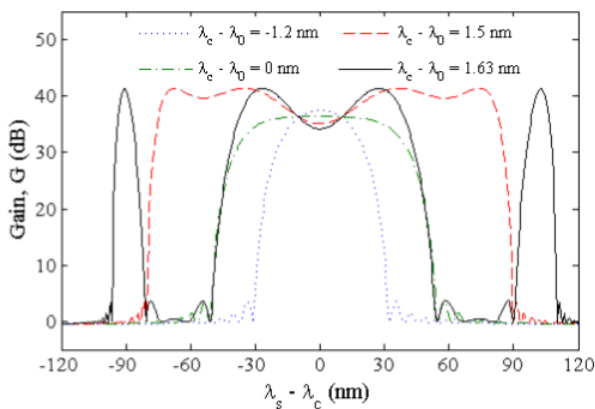


Fig. 3. Gain spectrum when varying the pump separation between two pumps wavelengths.

exhibited in Fig. 3. It shows that the flatness of amplification bandwidth changed when 2-P FOPA experience different values of  $\Delta\lambda_p$ . When the pumps wavelengths are positioned further from each other, it shows that the bandwidth flatness at the signal wavelength far from the central wavelength,  $\lambda_c$  is improved. However, the parametric gain corresponds to the signal wavelength near  $\lambda_c$  shows significant reduction as the  $\Delta\lambda_p$  increases.

Research in [8] proved that the flatness near the  $\lambda_c$  can be engineered by adjusting the  $\lambda_c$  position with reference to the ZDW of HNL-DSF. Thus, to overcome the reduction of the parametric gain near  $\lambda_c$ , the parametric gain was computed while varying the distance of  $\lambda_c$  from  $\lambda_0$ . The results were plotted in Fig. 4. The other parameters are fixed as in Fig. 3 except for the  $\lambda_{P_1}$ ,  $\lambda_{P_2}$  and the corresponding  $\lambda_c$  as well as  $\beta_2$  and  $\beta_4$ . Although the  $\lambda_{P_1}$  and  $\lambda_{P_2}$  are different in each calculation which depend on the desired  $\lambda_c$ , the  $\Delta\lambda_p$  is fixed to 20 nm. There are four different values of  $\lambda_c$  that are used in calculating the parametric gain, and the corresponding higher-order dispersion coefficients given as  $\beta_2 = 2.239 \times 10^{-2}$  ps<sup>2</sup>/km and  $\beta_4 = 6.022 \times 10^{-5}$  ps<sup>4</sup>/km for  $\lambda_c = 1555.3$  nm,  $\beta_2 = 0$  ps<sup>2</sup>/km and  $\beta_4 = 6.009 \times 10^{-5}$  ps<sup>4</sup>/km for  $\lambda_c = \lambda_0 = 1556.5$  nm,  $\beta_2 = -3.169 \times 10^{-2}$  ps<sup>2</sup>/km and  $\beta_4 = 6.292 \times 10^{-5}$  ps<sup>4</sup>/km for  $\lambda_c = 1558.13$  nm, and as for  $\lambda_c = 1558$  nm the value of  $\beta_2$  and  $\beta_4$  are similar as previous. As is seen, by bringing  $\lambda_c$  close to  $\lambda_0$  i.e.  $\lambda_c - \lambda_0 = 1.5$  nm, it is possible to attain broader and flatter amplification bandwidth far from  $\lambda_c$  as well as higher gain. Noteworthy, the parametric gains near  $\lambda_c$  are slightly increase. Conversely, by increasing the distance of  $\lambda_c - \lambda_0$ , the 2-P FOPA gain spectrum totally loses its uniformity. However, the assignment of  $\lambda_c$  in the normal regime (less than or exactly at  $\lambda_0$ ) i.e.  $\lambda_c - \lambda_0 = 0$  nm and  $-1.2$  nm, need to be avoided. This is because in the normal regime the resulted phase-mismatch is large, and as a consequence, the poor gain spectrum is obtained. Hence,  $\lambda_c - \lambda_0$  need to be positive and small if a wide and flat 2-P FOPA spectrum is desired.



**Fig. 4.** Gain spectrum when varying the wavelength distance between the central wavelength and ZDW.

## 4 Conclusion

This paper has numerically investigated the impact of pump parameters on 2-P FOPA. The optimum parametric gain require high pump powers. The high pump powers also lead to a flatter amplification bandwidth. The flatness of the amplification bandwidth can also be enhanced by positioning the pumps wavelengths further from each other. However, the parametric gains near the central wavelength experience a reduction as the distance between two pumps wavelengths become larger, hence reduced the bandwidth flatness near the central wavelength. This problem can be overcome by adjusting the central wavelength close to ZDW, then a flatter 2-P FOPA amplification bandwidth can be attained.

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