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Investigation Of Dual-Pump Fiber Optical Parametric Amplifier Performance Driven by Energy Transfer Between Four-Wave Mixing Process

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ARTICLE INFO	**ABSTRACT**

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Fiber optical parametric amplifier (FOPA) is operated based on energy transfer from pump waves to signal wave and at the end of the fiber, an idler wave is generated. This process is called four-wave mixing (FWM). Even though effects of higher-order dispersion coefficients, fiber length, fiber nonlinearity, fiber attenuation, pump powers, pump wavelength separation $\Delta\lambda_p$ and distance of central pump wavelength with ZDW $\lambda_c - \lambda_0$ on gain profiles have been examined by previous researchers, but on different fiber or numerically studied using the Optisys system, analytical model or different amplitude equations. Thus, in this study, the above-mentioned parameters on the gain performance of dual pump fiber optical parametric amplifier (FOPA) using highly nonlinear shifted fiber (HNL-DSF) as a medium will be numerically investigated using ode45 function in Matlab. The gain at a certain wavelength can be obtained by solving 4 coupled amplitude equations with fiber loss and pump depletion that govern the four-wave mixing (FWM) process of pumps, signal and idler waves. Simulations results indicate positive β_2 gives poor or no gain, meanwhile, an addition of β_4 to negative β_2 widens the bandwidth, but there is no significant effect with the addition of β_6. Besides, an increase of fiber length, nonlinearity and pump powers improve gain performance, but an increase of fiber loss decays the gain amplitude. Increment of pump separation will enhance flatness of gain at wavelength far from central wavelength but results in an increase of gain reduction at the central wavelength. Lastly, $\lambda_c - \lambda_0$ must be positive, not too small and not bigger than 1.125nm to get a high, broader and lesser ripples gain.

Keywords:
2p-FOPA; gain; higher-order dispersion; fiber parameters; pump parameters; energy transfer; FWM

1. Introduction

The demand for ultra-fast telecommunication system has been dramatically increased due to the pandemic of COVID-19 which reduces face to face meeting and traveling but an increase of online meeting, teaching, presentation and training. Fiber-optical parametric amplifier (FOPA) which offers high flat gain and broad bandwidth of 10 to 100nm [1,2] can increase the transport capacity of fiber

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communication systems. Besides, FOPA also provides other functionalities such as adjustable center frequency and gain spectra, phase conjugation, wavelength conversion, pulsed operation for signal processing and 0-dB noise figure [3] has made FOPA overcome conventional amplifier such as RAMAN amplifier and (RA) and Erbium-doped fiber amplifier (EDFA). In a research conducted by Saris *et al.,* [4] to enhance the gain of dual pump EDFA using OptiSystem software version 13, they have shown that dual pump EDFA has better gain performance at lower input signal power if compared to single pump EDFA.

Similarly, there are, 1p and 2p-FOPAs. In practice, a good FOPA must exhibit high and flat gain as well as wide bandwidth. Even though 1p- FOPA has a simple configuration but has poor flatness if compared to 2p-FOPA [5]. Contrary, 2p-FOPA can offer a higher, broader and flatter gain if compared to 1p-FOPA [6]. Hence, in this study, 2p- FOPA was considered. Energy cannot be created nor destroyed but can be transferred [7]. The process of energy transfer from dual pump waves with angular frequencies ω_{p1} and ω_{p2} to a signal wave with angular frequency ω_s and at the end an idler wave with angular frequency ω_i is generated is illustrated as shown in Figure 1. This process is called four wave mixing (FWM) such as $\omega_{p1}+\omega_{p2}=\omega_s+\omega_i$.

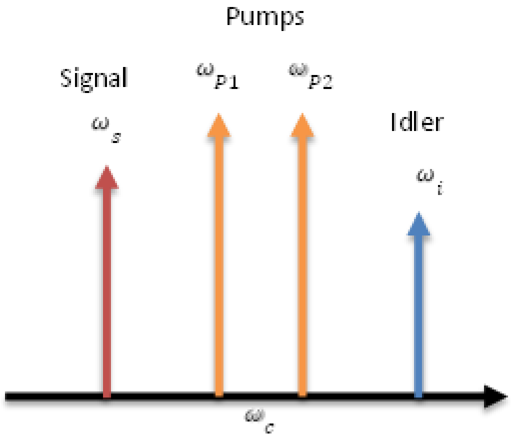

Fig. 1. Schematic diagram of FWM with two pump lights in the frequency domain

The performance of FOPA is influenced by fiber length, pump power, pump wavelength [8], fiber nonlinearity [9] and fiber attenuation [10]. For 2p-FOPA, pump separation ($\Delta\lambda_p$) and center wavelength of two pump deviations from the fiber zero-dispersion wavelength ($\lambda_c-\lambda_0$) do contribute to gain profile [9]. Boggio *et al.,* [11] investigated experimentally gain characteristics of 2p FOPA using conventional dispersion-shifted fiber. They obtained 37dB gain with ± 1.5 dB ripple over 47nm bandwidth.

Chen *et al.,* [9] inspected effects of higher-order dispersion coefficients, β_4, fiber nonlinearity, fiber length, pump power, $\Delta\lambda_p$, $\lambda_c-\lambda_0$ towards the gain performance of 2p-FOPA using HNLF. They concluded that smaller and negative β_4 gives wider bandwidth, whereas longer fiber length improves gain but does not increase bandwidth. Meanwhile, an increment of fiber nonlinearity wider bandwidth, increase gain but reduce flatness., Similarly, an increase of pump power improves gain and bandwidth but reduce flatness. While large pump separation (100nm) reduces the central gain to approximately zero. Contrary, when $\lambda_c-\lambda_0=0$, the gain bandwidth is broader, but when

$\lambda_c - \lambda_0 = 1$nm, the gain increases but its bandwidth decrease whereas if $\lambda_c - \lambda_0 = -1$nm, the bandwidth decease but its gain maintains.

Researchers [12] examined the performance of 2p FOPA using HNLF in terms of fiber nonlinearity, fiber length, higher-order dispersion up to order four using numerical simulation. They concluded that an increase of fiber nonlinearity improves the flatness and gain of 2p-FOPA, meanwhile an increase of fiber length and β_4 improves the gain. They obtained a net gain of 40 dB and 62 dB over a bandwidth >100nm on 400 m and 600 m fiber length respectively.

Performances of 1p and 2p FOPA using Optisys software were investigated in [13]. They obtained parametric amplification over a 50nm gain bandwidth and 31dB gain using 500 m highly nonlinear fiber (HNLF) for 1p FOPA, whereas 26.5dB gains over a 50nm gain bandwidth for 2p FOPA. Even though 2p- FOPA gain is lower, but they give flat gain if compared to 1p-FOPA.

Similarly, the influence of fiber nonlinearity, fiber length, fiber attenuation, β_2 on the performance of 2p-FOPA was studied in [10] using an analytical model. They concluded that gain amplitude increased with the increase of fiber nonlinearity, fiber length and negative β_2 while gain decrease with an increase of fiber attenuation. Based on their simulation results, they used the optimized parameter and obtained 38 dB gain over a wide bandwidth of 228 nm using short length Photonic crystal Fibers (PCFs) with γ>50.

Othman [14] examined the effect of pump parameters on 2p FOPA using HNL-DSF. The reported that high pump power increase gain and flatness of gain especially far from the central wavelength. Meanwhile, an increase of $\Delta\lambda_p$ flattening the gain far from the central wavelength but reduces gain at the center. Lastly, they suggested $\lambda_c - \lambda_0$ must be positive and small to get a wide and flat gain.

Even though the effects of several parameters that contribute to the gain characteristic of 2p-FOPA have been studied either experimentally, or numerically, but on different fiber or numerically studied using the Optisys system, analytical model or different numerical model if compared to Mathematical Model in the next section. Thus, in this study, the effects of fiber length, fiber nonlinearity, fiber attenuation, higher-order dispersion coefficients up to β_6, pump powers, $\Delta\lambda_p$ and $\lambda_c - \lambda_0$ will be examined on the gain characteristic of 2p-FOPA using HNL-DSF.

2. Mathematical model

The non-degenerate FWM induced by 2 continuous-wave (CW) pump 1 (P_1) and pump 2 (P_2) which transfer the energy to a signal wave (*s*) and at the end an idler wave (*i*) is generated is governed by conventional four-coupled amplitude equations as below:

$$\frac{dA_{p1}}{dz} = i\gamma[(|A_{p1}|^2 + 2|A_{p2}|^2 + 2|A_s|^2 + 2|A_i|^2)A_{p1}] + 2i\gamma A_{p2}^* A_s A_i e^{i\Delta\beta z} - \frac{\alpha}{2}A_{p1} \tag{1}$$

$$\frac{dA_{p2}}{dz} = i\gamma[(|A_{p2}|^2 + 2|A_{p1}|^2 + 2|A_s|^2 + 2|A_i|^2)A_{p2}] + 2i\gamma A_{p1}^* A_s A_i e^{i\Delta\beta z} - \frac{\alpha}{2}A_{p2} \tag{2}$$

$$\frac{dA_s}{dz} = i\gamma[(|A_s|^2 + 2|A_{p1}|^2 + 2|A_{p2}|^2 + 2|A_i|^2)A_s] + 2i\gamma A_i^* A_{p1} A_{p2} e^{i\Delta\beta z} - \frac{\alpha}{2}A_s \tag{3}$$

$$\frac{dA_i}{dz} = i\gamma[(|A_i|^2 + 2|A_{p1}|^2 + 2|A_{p2}|^2 + 2|A_s|^2)A_i] + 2i\gamma A_s^* A_{p1} A_{p2} e^{i\Delta\beta z} - \frac{\alpha}{2} A_i \tag{4}$$

where z is propagation distance, γ denotes the fiber nonlinearity, α represents the fiber loss, $\Delta\beta$ is linear phase − mismatch, A_j represents amplitude for j∈$\{p_1, p_2, s, i\}$ and A_j^* for j∈$\{p_1, p_2, s, i\}$ indicates the complex conjugate of A_j. The linear phase-mismatch is given by [15] as

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

where β_{2m}, is the dispersion coefficient given by the $2m^{th}$ derivative of mode-propagation constant $\beta(\omega)$, at the central frequency ω_c=$(\omega_{p1} + \omega_{p2})/2$=$(\omega_s + \omega_i)/2$. Meanwhile, $\Delta\omega_s$=$\omega_s - \omega_c$ and $\Delta\omega_p$=$\omega_{p1} - \omega_c$= $(\omega_{p1} - \omega_{p2})/2$.

By taking m up to 3 in expression (4), $\Delta\beta$ up to the sixth order dispersion coefficient β_6 is expressed as:

$$\Delta\beta = \beta_2[(\Delta\omega_s)^2 - (\Delta\omega_p)^2] + \frac{\beta_4}{12}[(\Delta\omega_s)^4 - (\Delta\omega_p)^4] + \frac{\beta_6}{360}[(\Delta\omega_s)^6 - (\Delta\omega_p)^6] \tag{6}$$

For m up to 3, β_2, β_4 and are illustrated respectively by [16] as

$$\beta_{2m} = \sum_{n=2m}^{\infty} \frac{\beta_{n0}}{(n-2m)!}(\omega_p - \omega_0)^{n-2m} \tag{7}$$

Where $\beta_{n0} = \left.\frac{d^n\beta(\omega)}{d\omega^n}\right|_{\omega=\omega_0}$ is the dispersion coefficients calculated at the zero-dispersion frequency ω_0.

By combining (5) and (6) for m = 1 to 3, the Δβ can be written as:

$$\begin{aligned}\Delta\beta = {} & \beta_2[(\Delta\omega_s)^2 - (\Delta\omega_p)^2] + \frac{\beta_4}{3}\left[2(\omega_c - \omega_o)^2][(\Delta\omega_s)^2 - (\Delta\omega_p)^2] + \frac{1}{4}(\Delta\omega_s)^4 - (\Delta\omega_p)^4\right] \\ & + \frac{\beta_6}{24}\left[(\omega_c - \omega_o)^4][(\Delta\omega_s)^2 - (\Delta\omega_p)^2] + \frac{1}{15}(\Delta\omega_s)^6 - (\Delta\omega_p)^6\right]\end{aligned} \tag{8}$$

Here coefficients of β_2, β_4 and β_6 can be computed as given in [17].

Lastly, Eqs. (1)-(4) and (8) can be solved using fourth-order Runge-Kutta method [17-18], but in this study, ode45 function in Matlab was used due to its simplicity. Then, the parametric gains (in dB) at the respective wavelength are calculated as:

$$G = 10\log\frac{\left|A_{s,out}\right|^2}{\left|A_{s,in}\right|^2} \tag{9}$$

Where $A_{s,out}$ and $A_{s,in}$ are output and input of amplitude signals using parameters in Table 1.

Table 1
Parameters

Parameter	Value	Unit
Fiber length (L)	500	m
Fiber nonlinearity	11.5	$\mathrm{W}^{-1}\mathrm{Km}^{-1}$
Fiber loss α	0.82	dB/km
Pump1 wavelength (λ_{p1})	1552	nm
Pump2 wavelength (λ_{p2})	1563.25	nm
Central wavelength (λ_c)	1557.625	nm
ZDW (λ_0)	1556.5	nm
Second order dispersion coefficient β_2	$-2.1108 * 10^{-2}$	ps^2/km
Fourth order dispersion coefficient β_4	$6.2307 * 10^{-5}$	ps^4/km
Sixth order dispersion coefficient β_6	$1.1783 * 10^{-8}$	ps^6/km
Pump1 power P_1	1	W
Pump2 power P_2	0.75	W
Power signal (P_s)	-40	dBm

3. Results

Parametric gain spectrum depends on linear phase-mismatch Eq. (8) while Eq. (8) depends on higher-order dispersion coefficient. Also, researchers [19] show an improvement of the bandwidth of FOPA using Photonic Crystal Fiber (PCF) if high order dispersion up to β_6 was considered. Thus, to determine the impact of higher-order dispersion on 2p-FOPA with HNL-DSF, 6 variations of higher-order dispersion were simulated while other parameters follow Table 1 as follows

Case 1: β_2 only (black plot)
Case 2: β_2 and β_4 only (cyan plot)
Case 3 β_2, β_4 and $-\beta_6$ (magenta plot)
Case 4: $-\beta_2$ only (green plot)
Case 5: $-\beta_2$ and β_4 only (red plot)
Case 6: $-\beta_2$, β_4 and $-\beta_6$ (dotted blue plot)

Figure 2 tells that positive β_2 gives poor gain as shown in the black color plot. If positive β_4 (cyan color plot), was added to positive β_2, it worsens the gain that obtained in positive β_2 case. Even negative β_6 (magenta color plot) was added to compensate the positive β_4 and β_2. It gives the same plot as case two due to the small magnitude of β_6 fails to make any changes. On the other hand, if only negative β_2 (greed plot) was considered in linear phase-mismatch as given in the green color plot, it gives better gain than in the first case of positive β_2 inclusion. Further addition of β_4 and negative β_2 terms (red plot) in linear phase-mismatch widen the bandwidth and reduce the ripples if compared to the inclusion of negative β_2 (green plot) term only as reported in [20]. However further inclusion of β_6, β_4 and negative β_2 (dotted blue plot) gives almost same plot to the case 5 due to the small magnitude of β_6. It is well known that phase matching occurs when $\kappa = \Delta\beta + \gamma(P_1 + P_2) = 0$ which implies $\Delta\beta = -\gamma(P_1 + P_2)$. As $\gamma(P_1 + P_2)$ is always positive and Eq. 8 indicates β_2 must be positioned in anomalous region so that β_2 is negative to have a good parametric gain. Besides, real parametric gain takes place if $-4\gamma(P_1+P_2)<\Delta\beta<0$ [14]. As portrayed in Figure 3, when β_2 is positive, $\Delta\beta$ is positive, that is why it gives poor gain as shown in Figure 2. When β_2 is negative, $\Delta\beta$ is in negative region as shown in Figure 3. Inclusion of β_4 to negative β_2 or case 6 gives wider bandwidth as $\lambda_s-\lambda_c<-75.62$, β_2 not in the range of $-4\gamma(P_1+P_2)<\Delta\beta<0$, but inclusion of β_4 to negative β_2 or case 6 still in the range of $-4\gamma(P_1+P_2)<\Delta\beta<0$.

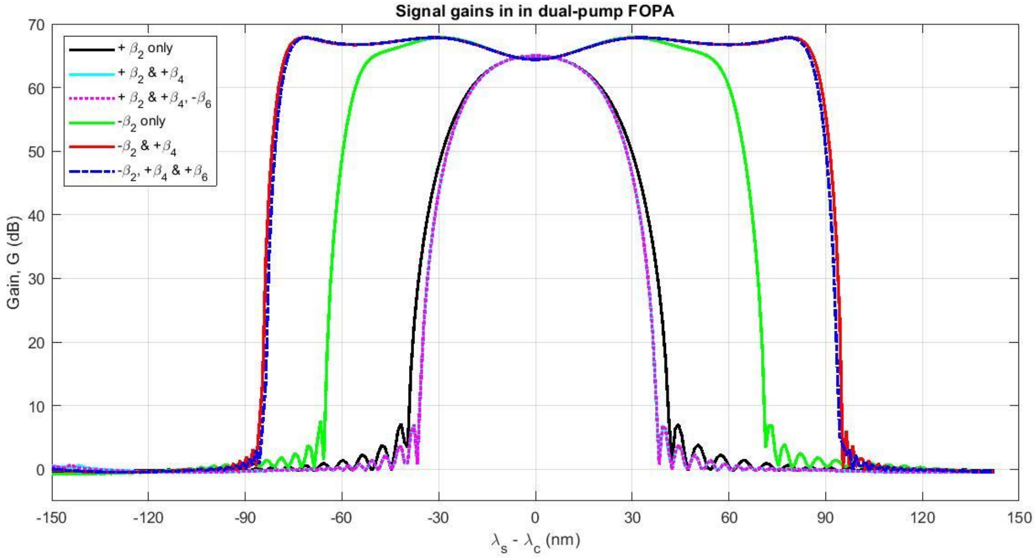

Fig. 2. Effect of higher-order dispersion coefficients

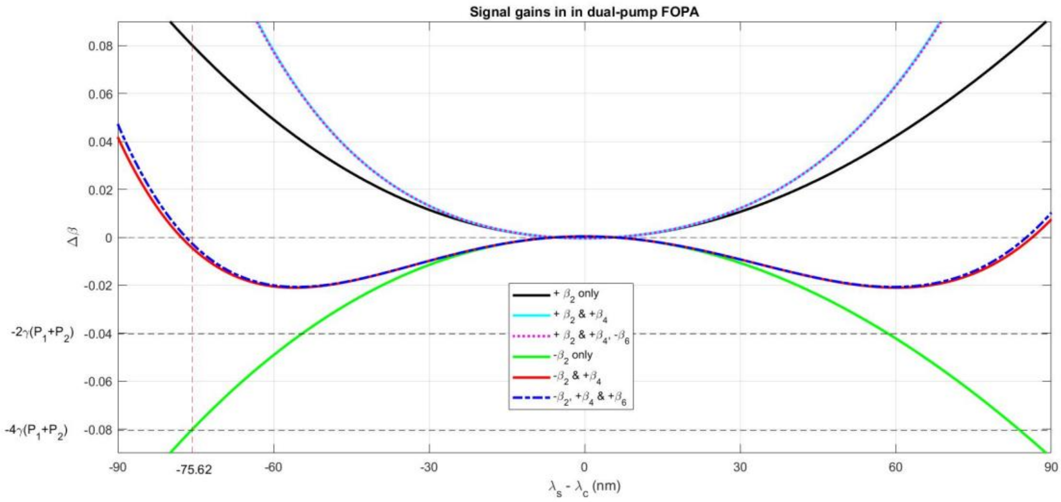

Fig. 3. $\Delta\beta$

In the afford to study effect of fiber length on the gain spectrum, fiber length was varied from 100m to 500m with and increment of 100m, while other parameters were fixed as given in Table 1. Figure 4 reveals that by increasing the length of the fiber, the gain will be increased, but the flatness of the gain and bandwidth are reduced. Fiber length 100m gives the flatness and widest bandwidth but it has the lowest gain if compared to others.

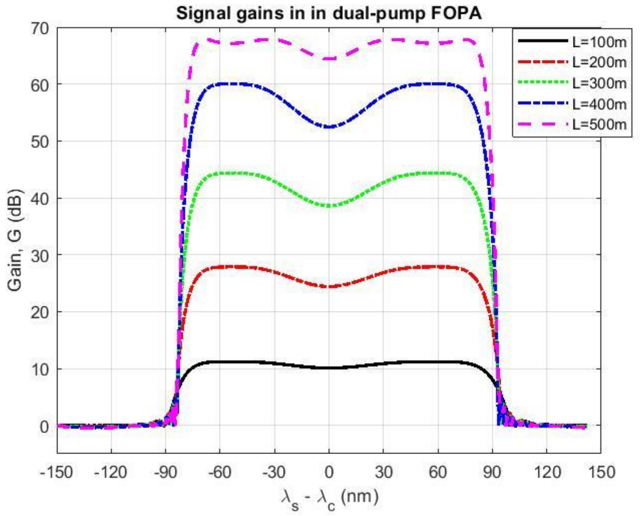

Fig. 4. Effect of fiber length on the gain spectrum

To investigate the impact of the fiber nonlinearity on gain profile, fiber nonlinearity was varied from 7.5 W^{-1} km^{-1} to 11.5 W^{-1} km^{-1} with an increment of 1 W^{-1} km^{-1}, while other parameters are the same in Table 1. Figure 5 shows by increasing the values of the nonlinearity of 2 continuous wave pump FOPA, the gain will be increased, flattened and bandwidth is slightly broader. The increase of gain as γ increases is evidently from Eq. (3).

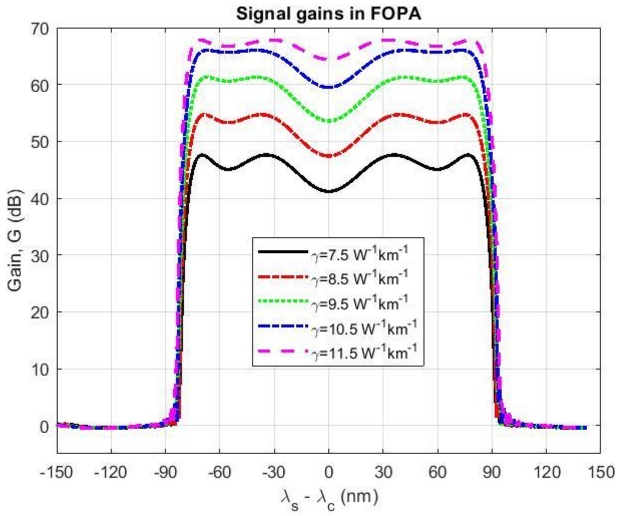

Fig. 5. Effect of fiber nonlinearity

In practice, fiber attenuation exists in fiber optic, thus to study the effect of fiber attenuation on the 2p-FOPA gain spectrum, fiber attenuation was varied from 0.82 dB/km, 2dB/km. 3 dB/km, 4dB/km and 5dB/km as displayed in Figure 6 while other parameters were fixed as given in Table 1. The gain damps as fiber attenuation is increased. It is due to if only the last term in RHS of Eq. 3 is focused, an increase of fiber attenuation α will give a decay of the amplitude of the signal because of the negative sign of Eq. (9) and thus gain as gain *G* depends on A_s.

$$\frac{dA_s}{dz} = -\frac{\alpha}{2} A_s \tag{9}$$

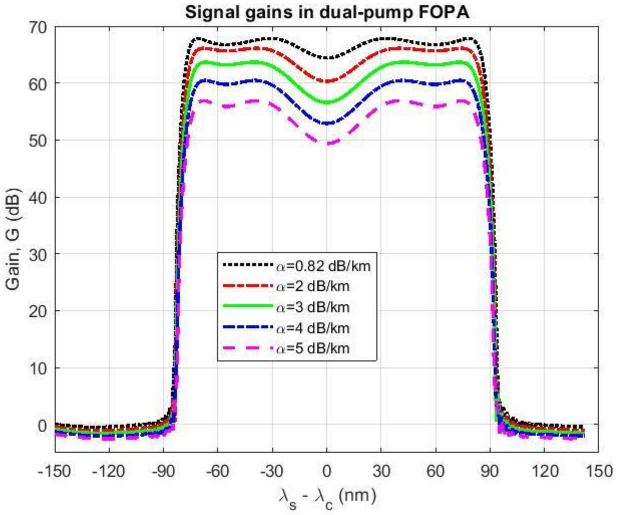

Fig. 6. Effect of fiber loss

Figure 7 gives the influence of pump power by fixing pump power P_1 to 1W, while varying pump power P_2 from 0.2W to 0.8W with an increment of 0.2W. The other parameters follow Table 1. It tells that increase of power will increase gain, flatten gain at wavelength far from the central wavelength and reduce the gain drops at a wavelength near the central wavelength. It is well known that maximum gain occurs if total phase mismatch $\kappa = 0$. Figure 8 shows κ for the case of P_1 = 1W and P_2 = 0.8W is the closest to zero if compared to the other three cases, so its gain drops at its wavelength near the central wavelength drops is the minimum.

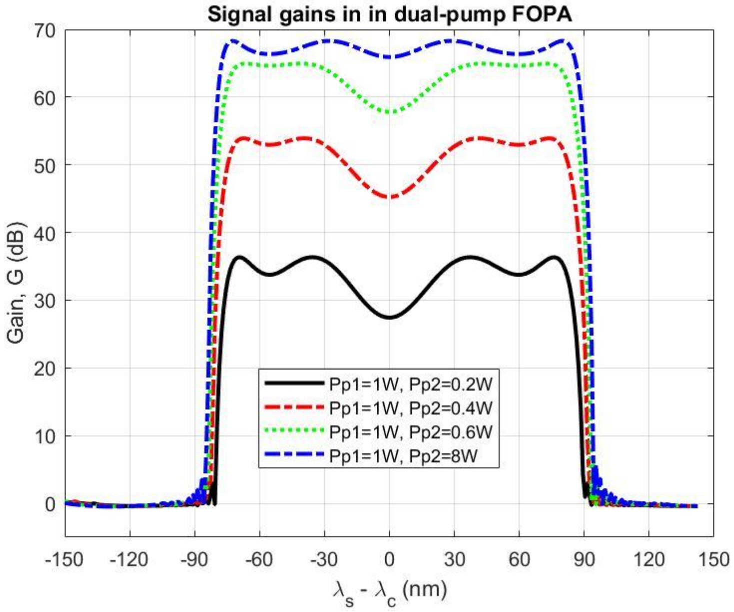

Fig. 7. Effect of pump powers

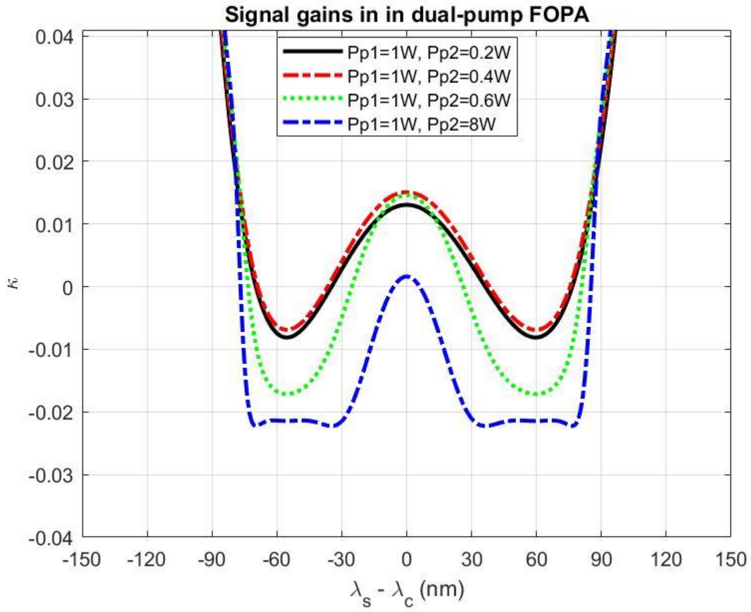

Fig. 8. Effect of pump powers

It is crucial to determine pump wavelength that would represent the minimal pump wavelength separation $\Delta\lambda_p = \lambda_{p2} - \lambda_{p1}$ to the ZDW of the HNLF to ensure that high, flat and broad gain as possible. It is because if the pumps are placed far from the ZDW, lower gain will be obtained [2]. To optimize $\Delta\lambda_p$, $\Delta\lambda_p$ was varied from 11.25nm to 41.25nm with an increment of 10nm, while λ_c and other parameters were fixed as given in Table 1. Figure 9 tells as $\Delta\lambda_p$ increases, the reduction of gain at the central wavelength is significantly increased too, but gain at wavelength far from the central wavelength is flattened similar to [14].

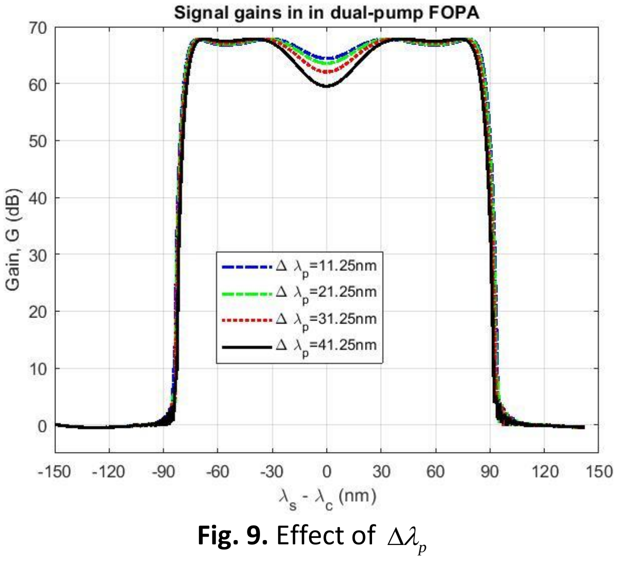

Fig. 9. Effect of $\Delta\lambda_p$

The placement of pump wavelength will determine the central wavelength λ_c and hence $\lambda_c - \lambda_0$ which has an impact on gain performance [21]. For this purpose, by maintaining $\Delta\lambda_p = 11.25$ nm and other parameters as given in Table 1 while varying λ_{p1} and λ_{p2}, a total 8 cases of $\lambda_c - \lambda_0$ were investigated as seen in Figure 10. Table 2 gives values of $\beta_2, \beta_4, \beta_6$ for each case of $\lambda_c - \lambda_0$. Figure 9 shows when $\lambda_c - \lambda_0$ is negative or zero, there is poor gain as positive β_2 value shows it is in a normal dispersion region which yields poor gain if compared to in the anomalous dispersion region (negative β_2 value). An increase of $\lambda_c - \lambda_0$ from 0.5nm to 2nm yields an increase of bandwidth of gain, however there is a significant reduction of gain at wavelength far from central wavelength for the cases of $\lambda_c - \lambda_0 = 1.5$ nm, 1.625nm and 2nm. The case $\lambda_c - \lambda_0 = 2$ nm shows the highest reduction of gain at wavelength far from central wavelength until it forms both-side narrow gain.

Table 2
Values of $\beta_2, \beta_4, \beta_6$

$\lambda_c - \lambda_0$ (nm)	β_2 (s^2/m)	β_4 (s^4/m)	β_6 (s^6/m)
-1.125	2.2169×10^{-29}	6.0182×10^{-56}	1.1602×10^{-83}
0	4.9139×10^{-29}	6.1241×10^{-56}	1.1692×10^{-83}
0.5	-9.1182×10^{-29}	6.1714×10^{-56}	1.1733×10^{-83}
1	-1.8712×10^{-29}	6.2188×10^{-56}	1.1773×10^{-83}
1.125	-2.1108×10^{-29}	6.2307×10^{-56}	1.1783×10^{-83}
1.5	-2.8291×10^{-29}	6.2664×10^{-56}	1.1814×10^{-83}
1.625	-3.0883×10^{-29}	6.2783×10^{-56}	1.1824×10^{-83}
2	-3.7854×10^{-29}	6.3141×10^{-56}	1.1854×10^{-83}

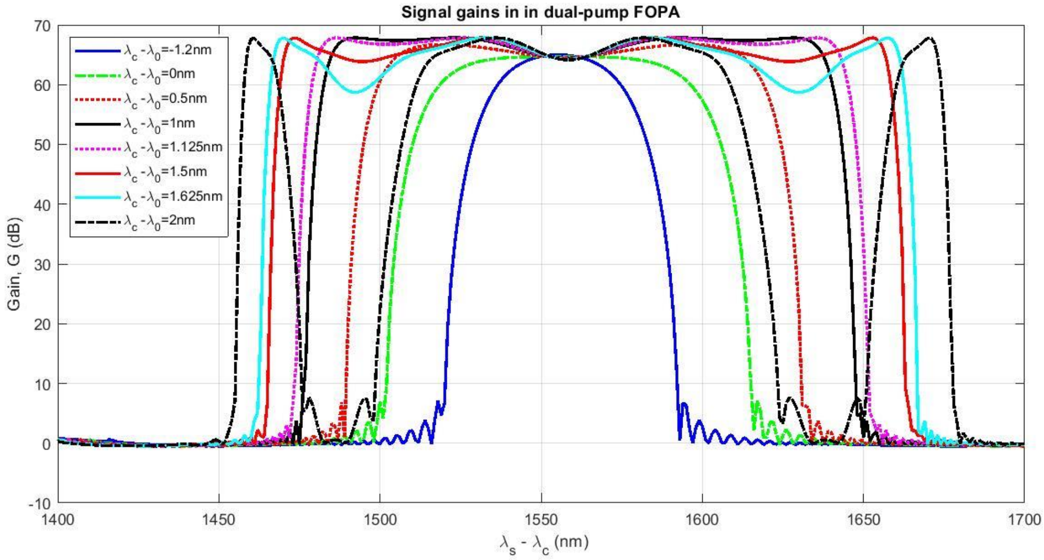

Fig. 10. Effect of $\lambda_c - \lambda_0$

4. Conclusions

Seven parameters (higher-order dispersion coefficients, fiber length, fiber nonlinearity, fiber attenuation, pump powers, pump wavelength separation $\Delta\lambda_p$ and distance of central pump wavelength with ZDW $\lambda_c - \lambda_0$) which have influenced the gain (9) performance of 2p- FOPA have been numerically investigated by solving the four coupled amplitude equations (1-4) which governs the process of FWM with linear phase mismatch (8) using ode45 function of Matlab 2019b. It is found that positive β_2 gives poor or no gain. Meanwhile, the addition of positive β_4 to positive β_2 worsens the gain. Even negative β_6 was added to both positive β_4 and β_2, it still gives the same gain as in the addition of positive β_4 and positive β_2 only. This may due to the small magnitude of β_6 doesn't make any changes. The addition of β_4 to negative β_2 widens the bandwidth, but there is no significant effect with the addition of β_6. An increment of fiber length, fiber nonlinearity and pump powers give a significant gain improvement, but when fiber attenuation is increased, the gain amplitude drops. An increase of pump separation improves signal gain at wavelength far from the central wavelength but give reduction at the central wavelength. Lastly, $\lambda_c - \lambda_0$ must be positive and not > 1.125nm to get a broader gain and not gain reduction at wavelength far from the central wavelength.

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