

Optimizing of Raman Gain and Bandwidth for Dual Pump Fiber Optical Parametric Amplifiers Based on Four-Wave Mixing

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ABSTRACT: Fiber Optic Parametric Amplifiers (FOPAs) are very important for future fiber optical amplifiers because of their high gains, broad gain bandwidth and relatively low noise figure. Recently, Fiber-optic parametric amplifiers (FOPAs), which are based on Four-Wave Mixing (FWM) occurring inside optical fiber, have got lots of attentions due to its wide gain bandwidth, flat gain spectrum and low noise because they can provide broadband amplification and can thus replace erbium-doped fiber amplifier used commonly for signal amplification. In this paper, we proposed an efficient dual pump optical parametric amplifiers which enjoy the following new features: (1) providing a uniform gain over a relatively wide bandwidth when they are pumped at two wavelengths located on each side of Zero Dispersion Wave-Length (ZDWL), (2) Maximizing repeater spacing and (3) providing broadband and high gain in high speed long-haul wavelength division multiplexing (WDM) transmission. Our results show that the maximum gain is 61.6454 dB and broadband is 350 nm compared with previous works which the gain is computed over the spectral optical wavelengths ($1.35\mu\text{m} \leq \lambda_{\text{signal}} \leq 1.75\mu\text{m}$).

KEYWORDS: Fiber Optic Parametric Amplifiers (FOPAs), Wavelength Division Multiplexing (WDM), Dual Pump FOPA and Four-wave Mixing (FWM).

I. INTRODUCTION

The optical amplifier played a crucial role in the communications revolution that began two decades ago. The development of fiber optic parametric amplifiers (FOPA) has significantly increased the transmission capacity of fiber communication systems [1].

Fiber optic amplifiers (FOAs) with flat gain spectra and wide bandwidth are very promising for fully optical signal processing applications such as signal generation, broadband conversion, optical sampling, switching, and wavelength division multiplexing (WDM). [2]

The optical amplifiers are of great importance to fiber optic amplifiers in the future due to their high gain, wide bandwidth and relatively low noise value. FOAs can be used as an optical amplifier as well as in signal processing such as waveform conversion, optical multiplexing, and sampling. Fiber-optic amplifiers (FOAs), which are based on mixing four waves within optical fibers, attract considerable attention as they can provide amplification of the broadband and thus can replace the erbium fiber amplifier commonly used to amplify the signal [3]. The most important feature of the FOA double pump is that it can provide relatively flat gains on a much wider bandwidth than is possible with a single FOA pump [4].

Recently, the fiber optic parametric amplifiers (FOPA) which relies on four-wave nonlinear processing mixing has received a lot of attention because of its wide gain bandwidth, flat spectrum gain and low noise [5].

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Vol. 8, Issue 2, February 2019

In the present paper, we processed: gain and bandwidth of dual pump optical parametric amplifier and also, we show the affecting parameters on dual pump optical parametric amplifier gain and bandwidth to obtain a large and broadened bandwidth. The gain is computed over the spectral optical wavelengths ($1.35\mu\text{m} \leq \lambda \text{ signal} \leq 1.75\mu\text{m}$).

II. RELATED WORK

The work in [1] address the analysis of gain flatness in 2-pump Fiber Optical Parametric Amplifiers (FOPA) based on four-wave mixing (FWM) using numerical simulations. The influence of highly nonlinear fiber (HNLF) and higher order dispersion parameters is closely looked into. Results show that the nonlinear coefficient, γ affect the gain flatness of a FOPA. The third order and fourth order dispersion parameters play a vital role in predicting the gain profile of the FOPA. Polarization Mode Dispersion (PMD) is found to induce fluctuations that alter the FOPA gain magnitude and bandwidth. It is also found that amplifier gain increases with respective increase in fiber length. These results help in improving the transmission capacity of long haul system and dense wavelength division multiplexing (DWDM). A net gain of 40 dB and 62 dB is reported over a bandwidth $>100\text{nm}$ on 400 m and 600 m fiber length, respectively. An increase in the nonlinear coefficient improves the flatness of the gain. The FOPA gain is increased by the significant increase in the intensity and number of FWM products brought about by the nonlinear coefficient and the fiber length increase. Higher order dispersion parameters affect the phase shifting thus directly influencing the gain. The third order dispersion limits the gain of the signals close to ZDW and the gain bandwidth is strongly limited by the fourth-order dispersion because of phase matching condition. PMD induces fluctuations altering the gain. These results should help in improving the data integrity in DWDM systems.

The work in [3] shows a performance analysis of single-pumped and dual- pumped parametric optical amplifier and present the analysis of gain flatness in dual- pumped Fiber Optical Parametric Amplifier (FOPA) based on four-wave mixing (FWM). Result shows that changing the signal power and pump power give the various gains in FOPA. It is also found out that the parametric gain increase with increase in pump power and decrease in signal power. Moreover, in this paper, the phase matching condition in FWM plays a vital role in predicting the gain profile of the FOPA because the parametric gain is maximum when the total phase mismatch is zero, single-pumped parametric amplification over a 50nm gain bandwidth is demonstrated using 500 nm highly nonlinear fiber (HNLF) and signal achieves about 31dB gain. For dual-pumped parametric amplification, signal achieves 26.5dB gains over a 50nm gain bandwidth. Therefore, dual-pumped parametric amplifier can provide relatively flat gain over a much wider bandwidth than the single-pumped FOPA.

III. PROPOSED MODEL OF DUAL-PUMP FOPA

Fiber Optical parametric amplifiers are based on Four Wave Mixing (FWM) effect which transfers power from strong pump fields to weak signal and idler fields. Governed by conservation of energy principle idler generation is expressed as [1] [3] [6]:

$$\omega_i = \omega_a + \omega_b - \omega_s \tag{1}$$

Where, $\omega_a, \omega_b, \omega_s$ and ω_i two pump frequencies, signal frequency and the idler frequency which are in hertz.

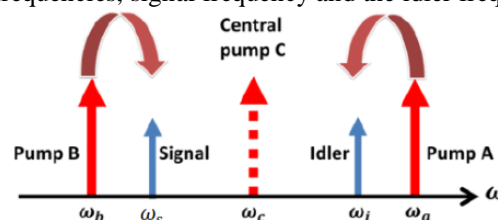


Fig., 1. Schematic diagram of dual-pump FOPA configuration

The parametric signal gain (G) in dual-pump FOPA configuration is given by equation (2) (3).

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 8, Issue 2, February 2019

$$G = \left[1 + \left(1 + \frac{K^2}{4g^2} \right) \sinh^2(gL) \right] \times e^{-\alpha L} \quad (2)$$

, where g is the unitless gain coefficient shown in equation (2), γ is nonlinear coefficient of the fiber in w/km and L is the fiber length in km [7].

$$g^2 = 4\gamma^2 P_1 P_2 - \left(\frac{K}{2} \right)^2 \quad (3)$$

Where, P_1 and P_2 are powers in mW of the pumps used. The parametric amplification is governed by phase matching condition given as:

$$K = \Delta\beta + \gamma(P_1 + P_2) \quad (4)$$

Where, K is standard phase mismatches³/km and $\Delta\beta$ is linear phase mismatches³/km, while 2nd term represents non-linear phase mismatch. For perfect phase mismatch, total phase 'K=0' which gives maximum gain and is achievable around ZDWL. The power growth in both signal and idler is assumed to be same by Manley-Rowe relation, leading to equal power depletion in both the pumps [8].

$$\Delta\beta = \beta_3(\omega_c - \omega_0)[(\omega_s - \omega_c)^2 - \omega_d^2] \quad (5)$$

Where, the frequencies ω_c and ω_d in hertz are given as follow: $\omega_c = \frac{\omega_{p1} + \omega_{p2}}{2}$ and $\omega_d = \frac{\omega_{p1} - \omega_{p2}}{2}$ and β_3 is the third-order dispersion in s³.

As shown in Fig. 1, ω_s and ω_i are the signal and idler frequencies, respectively. They locate at the positions that the condition of $\omega_a + \omega_b = \omega_s + \omega_i$ is satisfied. The signal and idler gain spectra are symmetric with respect to the center frequency. It is convenient to use ω_c and $\Delta\omega_d$ as the two independent parameters, the total phase mismatch K should be equal to zero or when, $\Delta\beta = -\gamma(P_1 + P_2)$, and this occurs at signal frequencies that satisfy the well-known phase matching condition [9] [10] [11]:

$$\Delta\beta = -\gamma(P_1 + P_2) = 0 \quad (6)$$

, and the linear phase mismatch $\Delta\beta$ is given by:

$$\Delta\beta = \beta_s + \beta_i - \beta_{p1} - \beta_{p2} = \beta_2 [(\Delta\omega_s)^2 - (\Delta\omega_d)^2] \quad (7)$$

$$\beta_2 \cong \beta_3(\omega_c - \omega_0)^2 \quad (8)$$

Where β_s, i, p_1, p_2 the signal, idler are, pump one and pump two phase propagation constants in s³/km, respectively, Where the linear phase mismatch $\Delta\beta$ in equation (5) is expressed by:

$$\Delta\beta(\lambda_c) = \left(R_1 \left(\frac{\Delta\lambda_c}{\lambda_o \lambda_c} \right) \right) \left(\left(\frac{\lambda_c - \lambda_3}{\lambda_3 \lambda_c} \right)^2 \right) - \left(\frac{B/2}{\lambda_c^2 - (B/2)^2} \right)^2 \quad (9)$$

Where, $R_1 = \beta_3(2\pi c)^3$, $\Delta\lambda_c = \lambda_c - \lambda_o$, $\lambda_1 = \lambda_o - B/2$, $\lambda_2 = \lambda_o + B/2$ and $B = \lambda_2 - \lambda_1$ is the bandwidth, generally provided by manufacturers and measured in μm , ω_0 is the zero-dispersion wavelength ZDWL in μm . Therefore, adjusting separately each the pump central wavelength, ZDWL and two pump wavelengths, the magnitude

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Vol. 8, Issue 2, February 2019

and shape of the gain spectrum can be optimized. The B term contributes only when two pumps are used and is independent of the signal and idler frequencies.

IV. SIMULATION RESULTS AND DISCUSSION

A. Effect of Dual Pumping Wavelength on Gain and Bandwidth

Figure 2, represents simulation at different values of dual pump wavelengths at assumed set of operating parameters: attenuation constant $\alpha=0.1$ dB//km, pumping power $P_1=0.6$ mw and $P_2 = 0.4$ mW, fiber length $L= 0.15$ Km, non-linear coefficient $\gamma=25$ w/km and phase mismatched $\beta=0.0006$ s³/km. In this case we adjust the dual pumping wavelength with the assumed set of operating parameters to obtain the maximum gain and bandwidth.

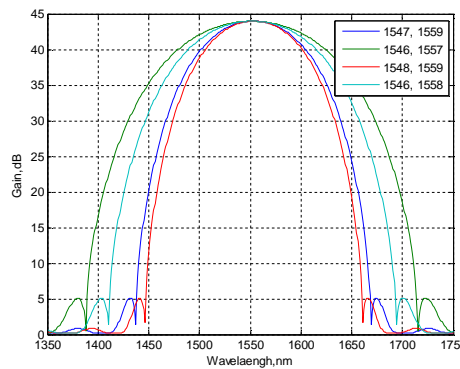


Fig., 2, Variations of Gain against wavelength at different values of dual pumping

From figure 2, we get the optimum results occurs at dual pump wavelength $\lambda=1546$ nm and $\lambda=1557$ nm where, the maximum gain is 43.9941 dB and the maximum bandwidth is 290nm.

B. Effects of Non-linear Coefficient on Gain and Bandwidth

Figure 3; shows the relation between gain of amplifier and wavelength at different values of non-linear coefficient.

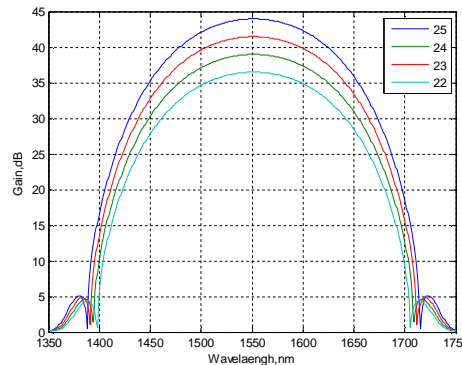


Fig.,3, Variations of Gain against wavelength at different values of non-linear coefficient

Also from figure 3, we get the non-linear coefficient γ affects the amplifier gain characteristics. As γ increases the maximum gain and bandwidth increases. The operating parameters are: attenuation constant $\alpha=0.1$ dB/km, pumping power $P_1=0.6$ mw and $P_2 = 0.4$ mW, fiber length $L= 0.15$ Km, phase mismatched $\beta=0.0006$ s³/km and dual pump

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Vol. 8, Issue 2, February 2019

wavelengths $\lambda_1=1546$ nm and $\lambda_2=1557$ nm. Also we get maximum gain is 43.966 dB is attained at the highest value of $\gamma= 25$ w/km and the bandwidth is 290nm.

C. Effect of Phase mismatch on Gain and Bandwidth

Figure 4; shows the relation between amplifier gain and wavelength at different values of phase mismatch β .

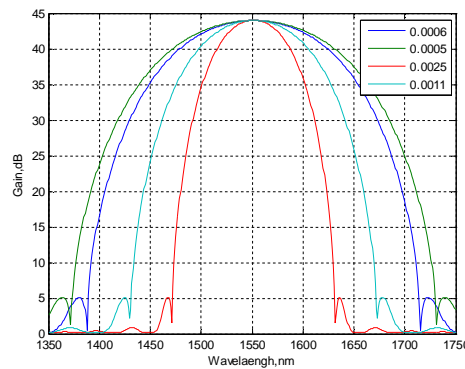


Fig., 4, Variations of Gain against wavelength at different values of phase mismatch β

From figure 4, we get the coefficient of phase mismatch β affects the amplifier gain characteristics. Approximate the gain constant with beta but the bandwidth has little variation whether increase or decrease of β . The figure draw at assumed set of operating parameters attenuation constant $\alpha=0.1$ dB/km, pumping power $P_1=0.6$ mw and $P_2 = 0.4$ mW, fiber length $L= 0.15$ Km, non-linear coefficient $\gamma=25$ w/km and dual pump wavelengths $\lambda_1=1546$ nm and $\lambda_2=1557$ nm. In this case the best result has get maximum gain of 44.0293 dB is attained at β equal to $0.0005\text{s}^3/\text{km}$ and the bandwidth is 319nm at the assumed set of operating parameters.

D. Effect of Fiber Length on Gain and Bandwidth

Figure 5; shows the relation between the amplifier gain and wavelength at different values of fiber length.

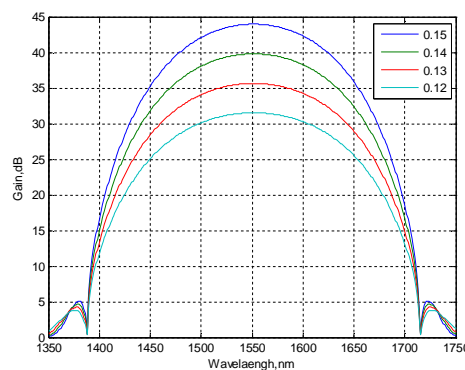


Fig., 5, Variations of Gain against wavelength at different values of fiber lengths

The operating parameters are: attenuation constant $\alpha=0.1$ dB/km, pumping power $P_1=0.6$ mw and $P_2 = 0.4$ mW, dual pump wavelengths $\lambda_1=1546$ nm and $\lambda_2=1557$ nm, non-linear coefficient $\gamma=25$ w/km and phase mismatched $\beta=0.0006\text{s}^3/\text{km}$. We get that the Fiber length L affects the amplifier gain characteristics. As the fiber length increases the maximum gain increases but the bandwidth has a little variation whether increasing or decreasing the fiber length. Maximum gain of 43.966 dB is attained at fiber length equal to 0.15 km and the bandwidth is 292nm. The optimum results occur at length of fiber $L=0.15$ km.

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 8, Issue 2, February 2019

E. Effect of Attenuation on Gain and Bandwidth

Figure 6, shows the relation between amplifier gain and wavelength at different values of the attenuation α , where attenuation affects the amplifier gain characteristics. As the attenuation increases or decreases the maximum gain increases. The bandwidth has a little variation whether increasing or decreasing the attenuation.

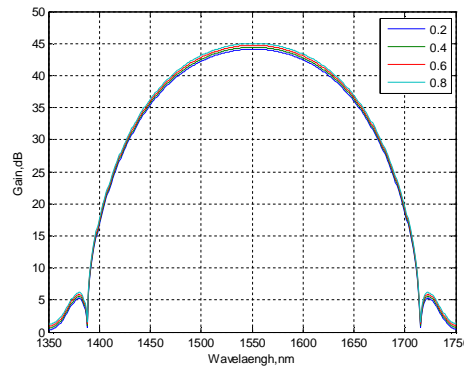


Fig., 6, Variations of Gain against wavelength at different values of attenuation α

Figure 6, was drawn at assumed set of operating parameters: fiber length $L = 0.15\text{Km}$, pumping power $P_1 = 0.6\text{mW}$ and $P_2 = 0.4\text{mW}$, dual pump wavelengths $\lambda_1 = 1546\text{nm}$ and $\lambda_2 = 1557\text{nm}$, non-linear coefficient $\gamma = 25\text{w/km}$ and phase mismatched $\beta = 0.0006\text{s}^3/\text{km}$. The best result has get at $\alpha = 0.8\text{dB/km}$ where maximum gain is 44.016 dB and bandwidth is 296 nm.

F. Effect of Dual Pumping Power on Gain and Bandwidth

Figure 7, shows the relation between amplifier gain and wavelength at different values of dual pumping power at assumed set of operating parameters: attenuation constant $\alpha = 0.1\text{dB/km}$, dual pump wavelengths $\lambda_1 = 1546\text{nm}$ and $\lambda_2 = 1557\text{nm}$, fiber length $L = 0.15\text{Km}$, non-linear coefficient $\gamma = 25\text{w/km}$ and phase mismatched $\beta = 0.0006\text{s}^3/\text{km}$. In this case we adjust the dual pumping power with the assumed set of operating parameters to obtain the maximum gain and bandwidth. The optimum results occur at dual pumping power $P_1 = 0.6\text{mW}$ and $P_2 = 0.6\text{mW}$ where, the maximum gain is 60.5954dB and the maximum bandwidth is 348nm.

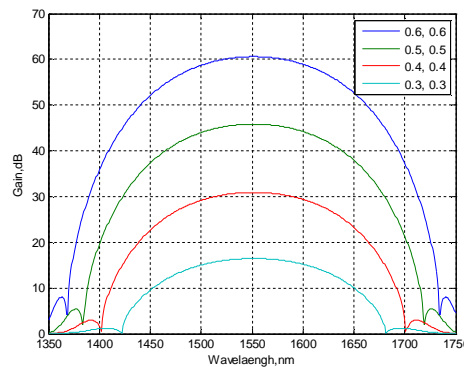


Fig., 7, Variations of Gain against wavelength at different values of dual pumping power

G. Optimum Results of Gain and Bandwidth

Figure 8; shows the variations of amplifier gain against the wavelength. The operating parameters of maximum gain and bandwidth are summarized in table 1.

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

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Vol. 8, Issue 2, February 2019

Table 1, a set of operating parameters that uses in simulation

λ_1	1546 nm	λ_2	1557 nm
P1	0.6 W	P2	0.6 W
L	0.15 Km	β	0.0006 s ³ /km
α	0.8 dB/km	γ	25 w/km

We can get maximum gain =61.6454 dB and bandwidth BW=350 nm.

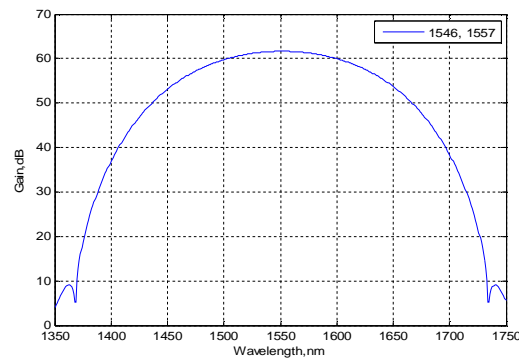


Fig., 8, Variations of Gain against wavelength for assumed set of operating parameters at dual pump wavelengths $\lambda_1=1546$ nm and $\lambda_2=1557$ nm

In this section we discuss different parameters that effect dual pump optical parametric amplifier gain and bandwidth such as pump wavelengths, pump power, non-linear coefficient, phase mismatch, fiber length and attenuation, to obtain maximum gain and bandwidth.

V. CONCLUSIONS

In this work, we have investigated dual pump parametric amplifiers for gain variation using analytical model. The analysis shows feasibility of dual pump parametric amplifiers as wideband amplifiers with large gain. It was found that the center to zero wavelength of FOPA is very important property to enhance the FOPA gain. By properly selecting the pump wavelengths and associated powers the amplifier can be tailored to demonstrate 61.6454 dB gains, with a 350 nm bandwidth. We have shown the factors that affect the gain in FOPAs. It was also found out that the gain of a FOPA is dependent on fiber length, dual pump wavelength and pump power, phase mismatch, nonlinear coefficient and attenuation. Therefore, the magnitude and shape of the gain can be optimized by tuning the fiber of all parameter values. These results should help in improving the transmission capacity of WDM and parametric amplification in long haul fiber optic communication systems.

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