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

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Abstract: Fiber optical 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 attention 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 μm ≤ λ signal ≤ 1.75μm).

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

1. Introduction

The optical amplifier played a crucial role in the communications revolution that began two decades ago. The development of optical fiber optic amplifiers (FOBA) 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, sampling, and reduction. 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 optical fiber parametric amplifier (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]. A 208 nm bandwidth fiber optical amplifier was achieved by overlapping the gain regions of optical parametric amplification (OPA) and Raman processes; a gain in excess of 10dB [6], while a 200 nm bandwidth with 20 dB gain and 4 dB ripple was described in [7]. Robert W. Boyd, Michael G. Raymer, Paul Narum, and Donald J. Harter presented and analysis of four-wave parametric amplification resulting from the nonlinear response of a two-level atomic system. The atomic dipole moment induced by weak optical fields at frequencies ω3 and ω4 in the presence of an optical field of arbitrary intensity at frequency ω1, where ω3+ω4=2ω1, is obtained by solving the density-matrix equations of motion with phenomenological damping constants. In addition, the solutions show an enhancement in the gain when |ω3−ω1|=|ω4−ω1|=Ω, where Ω is the generalized Rabi frequency associated with the driving of the atoms by the wave at frequency ω1 [8]. S. Peiris, N. Madamopoulos,
N. Antoniades, M.A. Ummy, R. Dorsinville and M. Ali by properly selecting the pump wavelengths and associated powers it is shown that can tailor the amplifier to demonstrate 13 dB gain, with a 190 nm bandwidth [9]. E. K. Rotich Kipnoo, D. Waswale, G. Amolo and A. W. R. Leitch analyzed the gain of a FOPA theoretically. It is found that a net gain of 40 dB is reported over a bandwidth >100nm [10]. Jian-Bo Li, Meng-Dong He, and Li-Qun Chen study theoretically four-wave parametric amplification arising from the nonlinear optical response of hybrid molecules composed of semiconductor quantum dots and metallic nanoparticles. It is shown that highly efficient four-wave parametric amplification can be achieved by adjusting the frequency and intensity of the pump field and the distance between the quantum dot and the metallic nanoparticle [11]. Mingyi Gao, Chun Jiang, Weisheng Hu, Jingyuan Wang present a new two-pump fiber optical parametric amplifier, which is composed of two section high nonlinear fibers. For many design parameters, such as pump powers and wavelengths, dispersion coefficient, nonlinear coefficient and length of HNLFs, govern the gain performance of FOPA, genetic algorithm is proposed to optimize these parameters, which is proved to be an effective method and a series of optimum results are obtained. With these optimum parameters, a two-pump FOPA using two-section HNLFs can theoretically provide flat gain of 20.3 dB with 346-nm bandwidth [12]. Jian-Bo Li, Shan Liang, Si Xiao and etc. investigate theoretically four-wave mixing (FWM) response and optical bistability (OB) in a hybrid nanosystem composed of a metal nanoparticle (MNP) and a semiconductor quantum dot (SQD) coupled to a nanomechanical resonator (NR). It is shown that the FWM signal is enhanced by more than three orders of magnitude as compared to that of the system without exciton-phonon interaction, and the FWM signal can also be suppressed significantly and broadened due to the exciton-plasmon interaction [13]. Gaganpreet Kaur, Gurmeet Kaur and Sanjay Sharma investigate dual pump Fiber Optical Parametric amplifier (FOPA) for wide gain bandwidth. With careful optimization of parameters of fiber used for amplification, dual pump FOPAs can effectively serve as high gain saturated broadband amplifiers. Simulation results are based on analytical modeling of dual pump FOPA. Based on these investigation results demonstrated a flat gain amplifier with peak gain of 38 dB over wide bandwidth of 228 nm [14]. Sandar Myint, Zaw Myo Lwin and Hla Myo Tun present a performance analysis of 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 various gains in FOPA. It is also found out that the parametric gain increase with increase in pump power and decrease in signal power. For dual-pumped parametric amplification, signal achieves 26.5dB gains over a 50nm gain bandwidth [15]. In the present paper, we processed: gain and bandwidth of dual pump optical parametric amplifier and also, we show a parameters affecting on dual pump optical parametric amplifier gain and bandwidth to obtain a large and broadened bandwidth such that pump wavelengths, pump power, non-linear coefficient, phase mismatch, fiber length and attenuation. The gain is computed over the spectral optical wavelengths (1.35μm ≤ λ signal ≤ 1.75μm).

2. 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 [11] [15] [16]:

\[
\omega_i = \omega_a + \omega_p - \omega_s
\]  

(1)

Where \(\omega_a\), \(\omega_p\), \(\omega_s\) and \(\omega_i\) are two pump frequencies, signal frequency and the idler frequency.

![Figure 1. Schematic diagram of dual-pump FOPA configuration.](image)

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

\[
G(\omega_i) = \left[ 1 + \left( 1 + \frac{K^2}{4g^2} \right) \sinh^2(gl) \right] e^{-\alpha l}
\]  

(2)

, where \(g\) is the gain coefficient shown in equation (2), \(\gamma\) is the nonlinear coefficient and \(L\) is the fiber length [17].

\[
g^2 = 4\gamma^2P_1P_2 - \left( \frac{K^2}{\gamma^2} \right)
\]  

(3)

The parametric amplification is governed by phase matching condition given as:

\[
k = \Delta \beta + \gamma(P_1 + P_2)
\]  

(4)
Where ‘γ’ is non-linear co-efficient of the fiber
and P₁ and P₂ are powers of the pumps used, ∆β
is linear phase mismatch while 2 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 [18].

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

(5)

Where \( \omega_c = \frac{\omega p_1+\omega p_2}{2} \) and \( \omega_d = \frac{\omega p_1-\omega p_2}{2} \)

As shown in Fig. 1, ω₀ and ω₀ are the signal and
idler frequencies, respectively. They locate at the
positions that the condition of \( \omega_s + \omega_i = \omega_s + \omega_i \)
is satisfied. The signal and idler gain spectra are
symmetric with respect to the center frequency.
It is convenient to use \( \omega_i \) and \( \Delta \omega_d \) as the two
independent parameters, instead of \( \omega_1 \) and \( \omega_2 \),
and to get maximum parametric gain in
Equation , 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 [19] [20]

\[ \Delta \beta = -\gamma(p_1 + p_2) = 0 \]  

(6)

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

\[ \Delta \beta = \beta_3 + \beta_1 - \beta p_1 - \beta p_2 \]

\[ = \beta_2[(\Delta \omega_s)^2 - (\Delta \omega_d)^2] \]  

(7)

\[ \beta_2 \equiv \beta_3(\omega_c - \omega_0)^2 \]  

(8)

Where \( \beta_2, \beta_1, p_1, p_2 \) the signal, idler are, pump
one and pump two propagation constants,
respectively.

\[ w_c = (\omega_1 - \omega_2)/2 \]  

(9)

\[ \Delta \omega_s = \omega_3 - \omega_c, \Delta \omega_d = (\omega_1 - \omega_2)/2 = \omega_c - \omega_c = \omega_2 - \omega_c \]  

(10)

The linear phase mismatch \( \Delta \beta \) in equation (5) is
expressed by:

\[ \Delta \beta(\lambda) = \left( R_1 \left( \frac{\Delta \lambda_c}{\lambda_o \lambda_c} \right) \right) \left( \frac{\lambda_c - \lambda_3}{\lambda_3 - \lambda_c} \right)^2 \]

\[ - \left( \frac{B/2}{\lambda^2_c - (B/2)^2} \right)^2 \]  

(11)

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

3. Simulation Results and Discussion

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

3.1 Effect of Dual Pumping Wavelength on
Gain and Bandwidth

Figure 2, simulated at different values of dual
pump wavelengths and the figure draw at
assumed set of operating parameters attenuation
constant \( a = 0.1 \) dB/km, pumping power \( p_1=0.6W \)
and \( p_2 = 0.4W \), fiber length \( L= 0.15Km \),
non-linear coefficient \( \gamma=25 \) w/km and phase
mismatched \( \beta=0.0006 \) s/km. In this case we
adjustment the dual pumping wavelength with
the assumed set of operating parameters to
obtain the maximum gain and bandwidth.

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.

The linear phase mismatch \( \Delta \beta \) in equation (5) is
expressed by:

\[ \Delta \beta(\lambda) = \left( R_1 \left( \frac{\Delta \lambda_c}{\lambda_o \lambda_c} \right) \right) \left( \frac{\lambda_c - \lambda_3}{\lambda_3 - \lambda_c} \right)^2 \]

\[ - \left( \frac{B/2}{\lambda^2_c - (B/2)^2} \right)^2 \]  

(11)

Where \( R_1 = \beta_3(2\pi c)^2, \Delta \lambda_c = \lambda_c - \lambda_o, \lambda_1 = \lambda_o - B/2, \lambda_2 = \lambda_o + B/2 \) and \( B = \lambda_2 - \lambda_1 \) is
the bandwidth, and \( \beta_3 \) is the third -order
dispersion, generally provided by manufacturers,
\( \omega_o \) is the zero-dispersion wavelength ZDWL.
Therefore, adjusting separately each the pump
central wavelength, ZDWL and two pump
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3. Simulation Results and Discussion

In this section we discuss different parameters
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3.1 Effect of Dual Pumping Wavelength on
Gain and Bandwidth

Figure 2, simulated at different values of dual
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and \( p_2 = 0.4W \), fiber length \( L= 0.15Km \),
non-linear coefficient \( \gamma=25 \) w/km and phase
mismatched \( \beta=0.0006 \) s/km. In this case we
adjustment the dual pumping wavelength with
the assumed set of operating parameters to
obtain the maximum gain and bandwidth.

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.

3.2 Effects of Non-linear Coefficient on Gain
and Bandwidth

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

Also from figure 3, we get the non-linear coefficient γ effects on the amplifier gain characteristics. As γ increased the maximum gain and bandwidth increased. The figure draw at assumed set of operating parameters attenuation constant α=0.1 dB/km, pumping power \( p_1 = 0.6 \text{ w} \) and \( p_2 = 0.4 \text{ W} \), fiber length \( L = 0.15 \text{Km} \), phase mismatched \( \beta = 0.0006 \text{s}/\text{km} \) and dual pump wavelengths \( \lambda_1 = 1546 \text{ nm} \) and \( \lambda_2 = 1557 \text{nm} \). Also we get maximum gain is 43.966 dB is attained at the highest value of \( \gamma = 25 \text{ w/km} \) and the bandwidth is 290nm.

3.3 Effect of Phase mismatch on Gain and Bandwidth

Figure 4; shown the relation between gain of amplifier and wavelength at different values of phase mismatch \( \beta \).

From figure 4, we get the coefficient of phase mismatch \( \beta \) effects on the amplifier gain characteristics. Approximate the gain constant with beta but the bandwidth has little variation whether increase or decrease of \( \beta \). The figure draw at assumed set of operating parameters attenuation constant \( \alpha = 0.1 \text{ dB/km} \), pumping power \( p_1 = 0.6 \text{ w} \) and \( p_2 = 0.4 \text{ W} \), fiber length \( L = 0.15 \text{Km} \), non-linear coefficient \( \gamma = 25 \text{ w/km} \) and dual pump wavelengths \( \lambda_1 = 1546 \text{ nm} \) and \( \lambda_2 = 1557 \text{nm} \). In this case the best result has get maximum gain of 44.0293 dB is attained at \( \beta \) equal to 0.0005s/km and the bandwidth is 319nm at the assumed set of operating parameters.

3.4 Effect of Fiber Length on Gain and Bandwidth

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

The figure 5, draw at assumed set of operating parameters attenuation constant \( \alpha = 0.1 \text{ dB/km} \), pumping power \( p_1 = 0.6 \text{ w} \) and \( p_2 = 0.4 \text{ W} \), 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 \( \beta = 0.0006 \text{ s}/\text{km} \). We get Fiber length \( L \) effects on the amplifier gain characteristics. As the fiber length increased the maximum gain increased 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 occurs at length of fiber \( L = 0.15 \text{km} \).

3.5 Effect of Attenuation on Gain and Bandwidth

Figure 6, show relation between the amplifier gain and wavelength at different values of the attenuation \( \alpha \), where attenuation effects on the amplifier gain characteristics. As the attenuation increased or decreased the maximum gain increased. The bandwidth has a little variation whether increasing or decreasing the attenuation.
3.6 Effect of Dual Pumping Power on Gain and Bandwidth

Figure 7, show the relation between the amplifier gain and wavelength at different values of dual pumping power and the figure draw at assumed set of operating parameters attenuation constant \( \alpha = 0.1 \) dB/km, dual pump wavelengths \( \lambda_1 = 1546 \) nm and \( \lambda_2 = 1557 \) nm, non-linear coefficient \( \gamma = 25 \) w/km and phase mismatched \( \beta = 0.0006 \) s/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 \( P_1 = 0.6 \) W and \( P_2 = 0.6 \) W where, the maximum gain is 60.5954 dB and the maximum bandwidth is 348 nm.

3.7 Optimum Results of Gain and Bandwidth

This figure 8, shows the variations of the gain of the amplifier against the wavelength. After studying the effect of all parameters affecting on the gain and bandwidth this is conclusion of previous study of all parameters. In this case we adjustment a set of operating parameters as shown in table 1, to obtained maximum gain and bandwidth.

| \( \lambda_1 \) | 1546 nm | \( \lambda_2 \) | 1557 nm |
|---|---|---|---|
| \( P_1 \) | 0.6 W | \( P_2 \) | 0.6 W |
| \( L \) | 0.15 Km | \( \beta \) | 0.0006 s/km |
| \( \alpha \) | 0.8 dB/km | \( \gamma \) | 25 w/km |

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

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

4. 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 of FOPA with respect to zero wavelength is very important property to enhance the FOPA gain. By properly selecting the pump wavelengths and associated powers we showed that we can tailor the amplifier 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 in WDM and parametric amplification in long haul systems in fiber optic communication.

References

1- E. K. Rotich Kipnno, D. Waswa, G. Amolo and A.W. R. Leitch "Gain Analysis for a 2-Pump Fiber Optical
Parametric Amplifier" The African Review of Physics, pp. 47-52, 2014.
2- T. H. Tuan, E. Samuel, T. Cheng, K. Asano, T. Suzuki and Y. Ohishi, "Optical parametric amplification in dual-pumped telluride hybrid microstructure fiber with engineered chromatic dispersion", Journal of Physics: Conference Series 619, pp. 1-4, 2015.
3- Sandar Myint, Zaw Myo Lwin, Hla Myo Tun, "Performance Analysis of Single-Pumped and Dual-Pumped Parametric Optical Amplifier" International Journal of Scientific & Technology Research, vol. 4, Issue 6, pp. 381-386, June 2015.
4- J. M. C. Boggio, J. D. Marconi and H. L. Fragnito, "Double-pumped fiber optical parametric amplifier with flat gain over 47-nm bandwidth using a conventional dispersion-shifted fiber", IEEE Photonics Tech. Lett., vol. 17, no. 9, pp. 1842-1844, 2005.
5- Lijia Zhang, Bo Liu, Xiangjun Xin, and Lei Liu, "Fiber Optical Parametric Amplified Optical Direct-Detection OFDM Signal with Intensity Modulation Transfer Blocking", Optics Express, vol. 22, no. 21, pp. 25580 – 25586, October 2014.
6- M.-C. Ho and et.al., "200-nm-bandwidth fiber optical amplifier combining parametric and Raman gain", J. Light wave Technology, vol. 19, no. 7, 2001.
7- X. Jiang and et.al., "Design of Raman-parametric fiber amplifier for wavelength division multiplex transmission system", Chinese Opt. Lett., vol. 6, no. 5, May 10, 2008.
8- Robert W. Boyd, Michael G. Raymer, Paul Norum, and Donald J. Harter, "Four-wave parametric interactions in a strongly driven two-level system", Phys. Rev. A., vol. 24, issue 1, 411, July 1981.
9- S. Peiris, N. Madamopoulos, N. Antoniades, M.A. Unmy, R. Dorsinville and M. Ali, "Extended Gain Bandwidth low Ripple Hybrid Raman Parametric Amplifier Design for PON Applications", IEEE, vol., 9, issue, 12, pp. 32-33, 2012.
10- E. K. Rotch Kipnoo, D. Waswa1, G. Amolo and A.W. R. Leitch, "Gain Analysis for a 2-Pump Fibre Optical Parametric Amplifier", the African Review of Physics, 9:0008, pp. 47-52, 2014.
11- Jian-Bo Li, Meng-Dong He, and Li-Qun Chen, "Four-wave parametric amplification in semiconductor quantum dot-metallic nanoparticle hybrid molecules", Optics Express, vol. 22, issue, 20, 24734, 2014.
12- Mingyi Gao, Chan Jiang, Weisheng Hu and Jingyuan Wang, "Optimized design of two-pump fiber optical parametric amplifier with two-section nonlinear fibers using genetic algorithm," OPTICS EXPRESS, vol. 12, no 23, November, 2004.
13- Jian-Bo Li, Shan Liang, Si Xiao and et. al., "Four-wave mixing signal enhancement and optical bistability of a hybrid metal nanoparticle-quantum dot molecule in a nanomechanical resonator", Optics Express, vol., 24, issue, 3, 2360, 2016.
14- Gaganpreet Kaur, Gurmeet Kaur and Sanjay Sharma, "Performance Investigation of Dual-pump Fiber Optical Parametric amplifier for flat gain over 220 nm Gain Bandwidth, " An International Journal of Engineering Sciences, vol. 17, pp. 451-457, January 2016.
15- Sandar Myint, Zaw Myo Lwin and Hla Myo Tun, "Performance Analysis of Single-Pumped And Dual-Pumped Parametric Optical Amplifier", INTERNATIONAL JOURNAL OF SCIENTIFIC & TECHNOLOGY RESEARCH, vol. 4, issue 06, pp. 381-386 JUNE 2015.
16- P. Kaminow and T. Li, "Optical Fibre Telecommunications IV B Systems and Impairment", Academic Press, fourth edition, 2002.
17- Gaganpreet Kaur, Gurmeet Kaur and Sanjay Sharma, "Performance Investigation of Dual pump Fiber Optical Parametric amplifier for Flat gain over 220 nm Gain Bandwidth", An International Journal of Engineering Sciences, vol. 17, pp. 451-457, January 2016.