Performance Investigation of Dual pump Fiber Optical Parametric amplifier for Flat gain over 220 nm Gain Bandwidth

Gaganpreet Kaur[1,a], Gurmeet Kaur[1,a], Sanjay Sharma[2]

1 ECE Department, Punjabi University, Patiala
2 ECE Department, Thapar University, Patiala
Email: [a]preetkgagan@gmail.com

Abstract. We 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. Type of fiber and its characteristics strongly affect the peak gain and bandwidth of the dual pump FOPA. We attempt to optimize the fiber parameters for maximized gain in dual pump FOPAs. Simulation results are based on analytical modeling of dual pump FOPA. Based on these investigation results we demonstrate a flat gain amplifier with peak gain of 38 dB over wide bandwidth of 228 nm using short length Photonic crystal Fibers (PCFs) with high non-linearity (γ>50). We also demonstrate improved gain saturation in dual pump over single pump FOPA.

Keywords: Parametric amplifiers, broadband amplification, Flat gain, Dual pump, Gain saturation.

1. Introduction

Fiber Optical Parametric amplifiers are broadband amplifiers based on non-linear phenomenon of Four Wave Mixing (FWM). Parametric amplification in optical fibers was first observed by Stolen in 1975 [1]. Due to wide gain and low amplification noise FOPAs attracted considerable attention in research. In [2], Marhic et al demonstrated, wide gain bandwidths of order of hundreds of nanometers using single pump FOPA. Flexibility to tune pump wavelengths near Zero dispersion wavelength (ZDWL) added to its broad band gain capabilities. Flat gain of nearly 12 dB over 100 nm is achieved [3] using multi-section in-line FOPA with single low-power pump of 500 mW in dispersion-tailored highly non-linear fiber (HNLF). Gain bandwidth of more than 400-nm with on–off gain of 65 dB is achievable using high power pump [4], in highly Non-linear Fibers (HNLF). Wong et al [5] reviewed the progress on FOPA emphasizing on its advantages- High Gain, large variety of gain spectra, large gain bandwidth up to 400 nm and tunable gain.

Advent of micro-structured Photonic Crystal fibers (PCFs) enhanced flat gain capabilities of FOPAs due to high non-linear coefficient. Parametric amplification using PCFs has been demonstrated to obtain continuous-wave bandwidth of more than 20 THz [6]. A maximum of 58 dB gain over bandwidth of 140 nm has been achieved using parametric amplification, in (PCFs) though gain minima of 30 dB made gain flatness a concern [7]. In [8] gain of 29.2 dB has been achieved using high repetition rate pulsed pump with 0.63 W power. Tao et al [9] demonstrated peak gain of 91.4 dB in highly nonlinear PCF with minimal effect of ZDWL fluctuations and low dispersion slope over a very wide spectral range. The impact of ZDWL fluctuations on gain of dual pump has been analyzed in [10]. Results established reducing the wavelength separation between the two pumps minimizes the effect of ZDWL fluctuations on gain but at the cost of reduced amplifier bandwidth. Broadband capabilities of Single pump FOPAs have been investigated for Wavelength division multiplexed systems too [11]. Jazayerifar et al demonstrated feasibility single pump FOPAs up to 750 km for Dense Wavelength Division Multiplexed (DWDM) transmission systems. But as number of WDM channels becomes large, the nonlinear cross-talk due to the FOPA becomes the dominant cause of performance degradation at large power levels. So, single pump powers were not sufficient to maintain minimum signal to noise ratio. This directed research towards dual pumped FOPAs. Shoaie et al [12] demonstrated use of dual-pump FOPA for generation of uniform pulses with duty cycle of 0.265 and 5 GHz pulse repetition rate over 40 nm bandwidth by bounding the phase mismatch between $-3\gamma P_0$ and γP_0 to achieve a constant peak gain. Boggio et al [13] investigated 10 X64 Gbps WDM system for dual pump FOPAs and achieved gain as high as 22dB. In this paper we investigate dual pump parametric amplifier and its performance for long haul DWDM systems. Analytical Model of PCF based Dual pump FOPA has been simulated to achieve a flat gain of 38 dB over 228 dB Bandwidth.

2. Theoretical model

Fiber Optical parametric amplifiers are based on Four Wave Mixing (FWM) effect wherein power is transferred from strong pump fields to weak signal and idler fields. Governed by conservation of energy principle idler generation is expressed as [14]:

$$\omega_4 = \omega_1 + \omega_2 - \omega_3 \tag{1}$$

where, ω_1, ω_2, ω_3 and ω_4 are two pump frequencies, signal frequency and the idler frequency.

The propagation of waves in fiber is governed by Non-Linear Schrodinger equations (NLSE)[14].The amplitude of signal can be expressed as:

$$\frac{dB_3}{dz} = \frac{i}{2}KB_3 + 2i\gamma B_1 B_2 B_4^* \tag{2}$$

where B_3 is scalar field amplitude of the signal and B_1, B_2, B_4 are amplitudes of pumps two and idler respectively. The parametric amplification is governed by phase matching condition given as:

$$K = \Delta\beta + \gamma(P_1 + P_2) \tag{3}$$

Where 'γ' is non-linear co-efficient of the fiber and P_1 and P_2 are powers of the pumps used, Δβ is linear phase mismatch 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 [15], leading to equal power depletion in both the pumps.

$$\Delta\beta = \beta_3\,(\omega_c - \omega_0)[(\omega_s - \omega_c)^2 - \omega_d^{\,2}] \tag{4}$$

Where $\omega_c = \frac{\omega_{P1}+\omega_{P2}}{2}$ and $\omega_d = \frac{\omega_{P1}-\omega_{P2}}{2}$.

For length 'L' of HNLF used for parametric amplification gain of signal is expressed as:

$$G = \left|{}^{B_3(L)}\!\big/_{B_3\,(0)}\right|^2 \tag{5}$$

Which is given as,

$$G(\omega_3) = \left[1 + \left(1 + {}^{K^2}\!\big/_{4g^2}\right)\sinh^2(gL)\right] \tag{6}$$

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

3. Results and Discussions

We attempt to achieve flat gain over wide bandwidth in dual pump FOPAs. All our investigations are based on analytical model which has been simulated using MATLAB. Our analytical model uses gain expressions for dual pump FOPA derived in equations (3)-(6). We assume HNLF for fiber parametric amplification. To maximize the gain and minimize the gain ripple we optimize the parameters of HNLF. First we investigate the optimized parameters of HNLF required for flat gain. Then based on these optimized parameters we demonstrate dual pump parametric amplification in PCFs to achieve wide gain bandwidth as high as 228 nm. Flat gain in dual pump FOPAs can be achieved over single pump parametric amplifiers [7] but at the cost of bandwidth as can be seen from Fig. 1. Dual pump FOPA can be used to achieve flat gain over nearly 100 nm is using careful tuning of pump wavelengths and optimizing the dispersion characteristics of HNLF used in parametric amplification [15]. To optimize dual pumped FOPA gain we need to study the dependence of gain on all parameters. Tuning of pump wavelength has effect on gain profile of parametric amplifiers in terms of gain magnitude, its flatness and gain bandwidth. Tuning pump wavelengths near ZDWL gives flatter gain. As the pump wavelengths difference increases and they are detuned farther from ZDWL, the gain profile changes to give peaks near pump regions and very low gain flat region in between. This can be clearly seen in Fig. 2. Further, symmetrically chosen pump wavelengths have better gain flatness than asymmetrically placed pumps with respect to ZDWL. Gain peaks (spikes) are generated using asymmetrically placed pumps. Amongst its dependence on fiber characteristics, gain of parametric amplifiers depends on fiber dispersion, nonlinear coefficient ‘γ’, and fiber length ‘L’ [4]

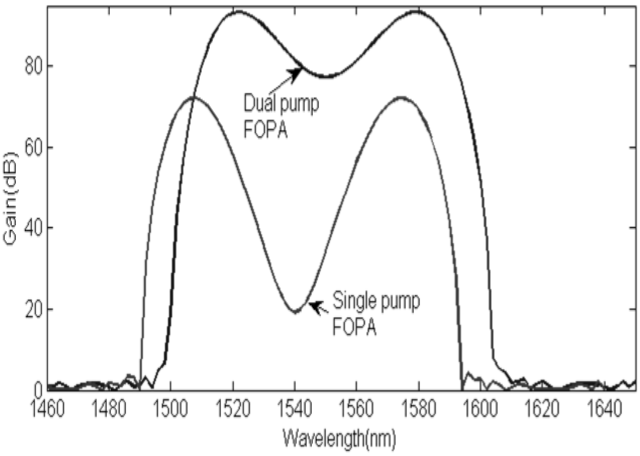


Fig. 1 Single Vs dual pump gain variation for pump powers of 1W in 100 m of HNLF, γ=10 $W^{-1}Km^{-1}$, β_2=-2.2X$10^{-2}$$ps^2/km^2$, β_4=1.34X10^{-4} ps^4/km^4, λ_0= 1550, λ_1= 1540.2, λ_2= 1560 in nm.

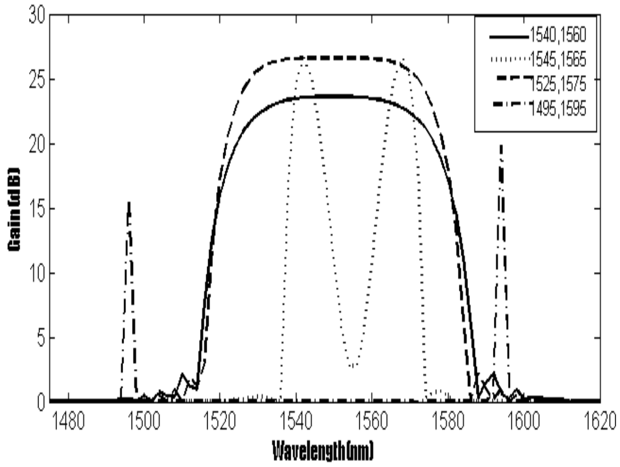
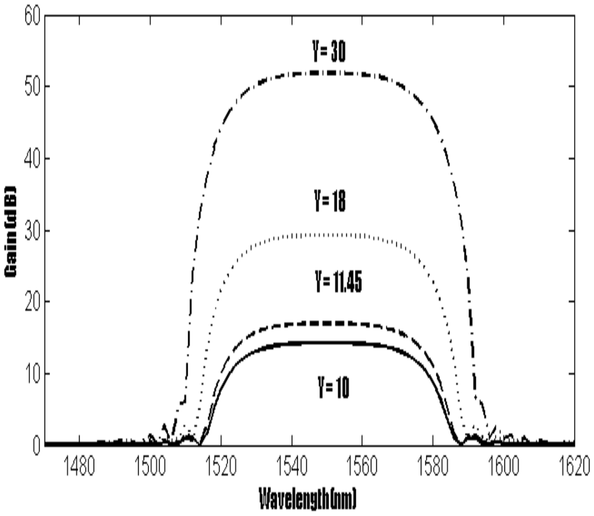
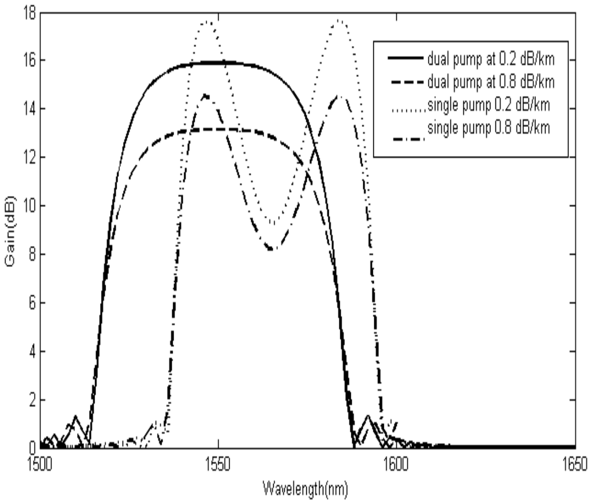


Fig. 2 Variation of dual pump FOPA with P_1=P_2=0.25 W, L=500 m, β_3=0.12 $ps^3km^{-1}$and β_4=2.5X10^{-4} ps^4km^{-1} and γ= 15

The non-linear coefficient ‘γ’ plays a significant effect on fulfillment of phase mismatch condition and hence on gain characteristics of parametric amplifiers. For HNLF ‘γ’ varies from 10-30. Effect of non-linear coefficient results in increase of gain as can be seen in Fig. 3. For non-linear coefficient value of 10, the maximum gain achievable is 14.22 dB at 1548 nm. As ‘γ’ is increased to 11.45 maximum gain increases to 16.94 dB across bandwidth of 52 nm from 1524 nm to 1576 nm. Maximum gain of 51.86 dB is attained for high value of gamma of 30.

For given fiber parameters amplifier gain decreases for increase in attenuation. For HNLFs the attenuation varies between 0.3 to to 1 dB/km. Effect of attenuation on gain is not much pronounced in dual pump parametric amplifiers as for single pump amplifiers. Gain variations in Fig. 4 shows gain Vs attenuation variation for both single and dual pump FOPA. For





same value of attenuation single pump gain decreases from 17.67 dB to 14.54 dB. For shorter lengths attenuation effect is negligible. So in PCF based FOPAs effect of attenuation is generally ignored as fiber lengths as small as 50 m are used.

Fig. 3 Gain variation of dual pump FOPA with γ $P_1=P_2=0.25$ W, L=500 m, $\beta_3=0.12$ ps^{3}km^{-1}and $\beta_4=2.5X10^{-4}$ ps^{4}km^{-1}, $\lambda p_1=1540$ nm, $\lambda p_2=1560$ nm

Fig. 4 Variation gain at different values of attenuation (α) at $P_1=P_2=0.25$W, $\beta_3=$ -0.6, $\beta_4=1.34$ X10^{-4} ps/nm^4/km with $\lambda_1=1540$ nm and $\lambda_2=1560$ nm, γ=11.45,L=500m.

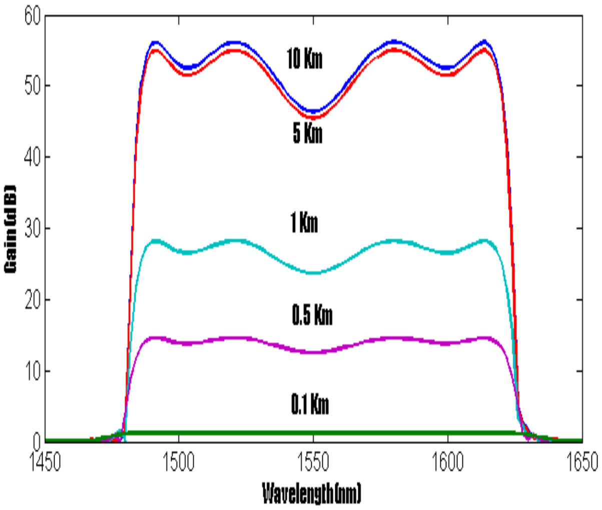


Fig. 5 Variation of dual pump gain for varying Fiber Length having $P_1=P_2=0.25$W, $\lambda_1=1540$ nm, $\lambda_2=1560$ nm, γ=15.

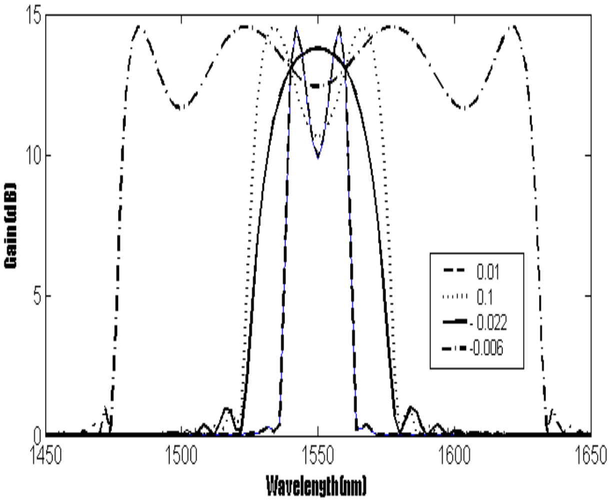


Fig. 6 Variation of dual pump gain for different values of β_2 at $P_1=P_2=0.25$W,L=500m, $\lambda_1=1540$, $\lambda_2=1560$, γ=15

Generally short length HNLF fibers are used for amplification in FOPAs. The gain of parametric amplifiers increases with fiber length to an extent but increase in gain is very less at fiber lengths higher than few km. The maximum gain ceases to increase at higher lengths as can be seen from the results in Fig. 5. For increase in HNLF length beyond 10 km no increase in gain is observed which is expected due to increased non-linear crosstalk in fiber with increased interaction length. Also the ripple in gain curve around ZDWL increases with increase in fiber length.

To achieve maximum gain phase matching condition is required to be satisfied, that is 'K' =0 which is achieved when $\Delta\beta= -\gamma (P_1 + P_2)$. $\gamma (P_1 + P_2)$ is always a positive quantity. This in turn implies that for maximum gain amplifier should be in negative dispersion regime where β_2 is negative. Smaller the negative value of β_2 more the bandwidth shrinks though the flatness improves. This is shown in Fig. 6. Vedadi et al [16] has drawn from his investigation of dual pump FOPAs that to reduce ripple in the gain curve the gain of flat region between two pumps should be higher than outer region gain. This can be ensured using positive values of β_4. Dual pump should be so optimized that fourth order dispersion β_4 should be positive value around '10^{-4}'.

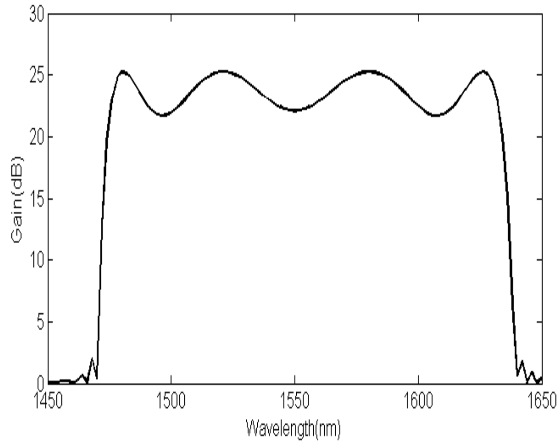


Fig. 7 Flat gain of dual pump FOPA with optimized parameters at P_1, P_2=0.25 W , β_2=-0.8 X10^{-2} β_4=1X10^{-4} ps/nm^4/km, L=400m, λ_1=1540 nm, λ_2=1560nm

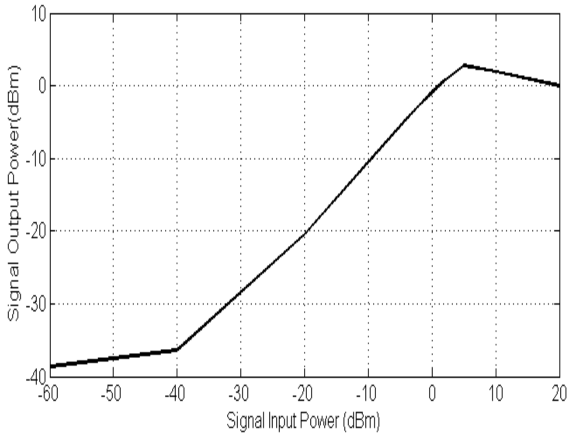


Fig. 8 Gain characteristics of dual pump FOPA with at P_1, P_2=0.25W, λ_1=1545 nm, λ_2=1555 nm in HNLF of L=500m.

If both β_2 and β_4 are negative it increases the anomalous regime characteristics and multiple low gain regions surface in gain profile. So with β_2=-0.8 X10^{-2} ps/nm^2/km and β_4=1X10^{-4} ps/nm^4/km are the optimal values which achieve peak gain of 25.255 dB over 156 nm bandwidth extending from 1476 nm to 1632 nm with gain ripple of 3.47 dB. Even peak to peak gain variation is uniform across entire band with 3.47 dB as maximum gain variation as seen in Fig. 7.

Another important characteristic of FOPA which may lead to signal distortion during amplification is gain saturation [17, 18]. The ultra fast response of FOPA to gain saturation makes them a potential candidate for all optical processing applications [19, 20]. To understand the gain saturation of dual pump FOPA we consider a signal at 1552.52 nm modulated by 2^7 -1 bits PRBS using a Mach-Zender modulator. The dual pumps are placed close to ZDWL of 1550 nm at 1545 nm and 1555 nm with 250 mW pump power each in a HNLF of length 500 m, D = 0.02 ps/km/nm and dispersion slope = 0.019 ps/km^2/nm, n_2= 5.11 X 10^{-20} m^2/W. The gain saturation occurs for input powers around 4 dBm as shown in figure 8, which is higher than conventional single pump FOPA where gain begins to saturate around –4 dBm [21]. So output enhancement of 8 dB is achieved under saturation conditions using dual pump FOPA over conventional single pump parametric amplification.

Class of fibers, PCFs or micro-structured fibers have recently shown improved gain and broad bandwidth for parametric amplification [7, 15]. PCFs have very high non-linearity coefficient ($\gamma > 50$) which makes them suitable for parametric amplification. In our simulation results based on analytical modeling, maximum gain of 37.4091 dB is achieved using short fiber length of 25 m only. Results in fig. 9 shows gain falls to minimum of 32.8398 dB over wide bandwidth of 228 nm from 1444 nm to 1672 nm which is highest gain over wide bandwidth of 228 nm. So gain ripple is 4.57 which is minimum ripple reported in gain bandwidth extending over 228 nm. Wang et al [14] demonstrated parametric gain of 8 dB over bandwidth of 260 nm, which is far less than our results achieved.

Results achieved have shown significant improvement both in terms of Gain as well as bandwidth when compared to cascaded hybrid of Raman-FOPA proposed in [22]. Using Raman FOPA cascade, maximum gain of 22.1 dB was achieved with un-optimized dual pump FOPA parameters over flat gain bandwidth of 90 nm. On the other hand with optimized parameters of dual pump FOPA much higher gain and bandwidth have been achieved in this work. So careful optimization of dual pump FOPAs can be used to give more than 200 nm wide bandwidth with gain more than 37 dB in PCFs as compared to single pump conventional FOPAs with nearly 100 nm achievable flat bandwidth [23].

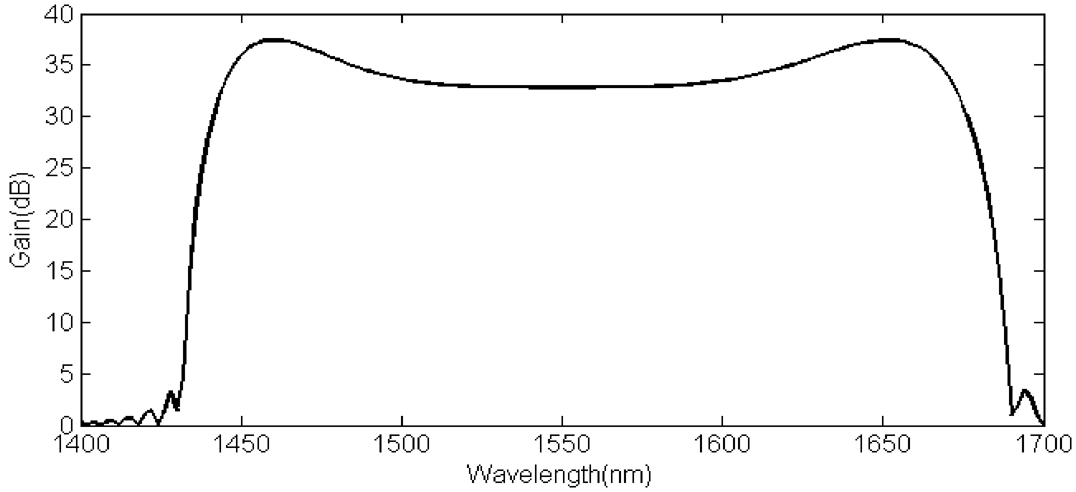


Fig. 9 Flat gain of dual pump FOPA with optimized parameters P_1, P_2=1W PCF, β_3= 0.67, β_4=-12X10^{-5} ps/nm^4/km, L= 25m λ_1=1540, λ_2=1560 nm, γ =100 W/km.

4. Conclusion

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. Dual pump FOPA exhibit improved gain saturation over conventional FOPAs making them attractive for all optical signal processing applications. Use of PCFs is expected to play a significant role in evolving parametric amplifiers and oscillators as their high non-linearity ($\gamma > 50$) is expected to give high parametric gain with small length fibers of less than 50 m. Gain ripple be further improved in PCF based parametric amplifiers through careful phase sensitive operation or use of multi-section dual pump FOPAs could be an effective solution to future wideband low ripple and high gain parametric amplifiers.

References

[1] R.H. Stolen, "Phase-matched-stimulated four-photon mixing in silica fiber waveguides", IEEE Journal of Quantum Electronics, Vol. 11, No. 3, pp. 100-103, 1975.

[2] M.E. Marhic, N. Kagi, T.K. Chiang and L.G. Kazovsky, "Broadband fiber optical parametric amplifiers", Optics Letters, Vol. 21, No. 8, pp 573-575, 1996.

[3] L. Provino, A. Mussot, E. Lantz, T. Sylvestre and H. Maillot, "Broadband and flat parametric gain with a single low-power pump in a multi-section fiber arrangement", Optical Fiber Conference and Exhibit, pp 125-126, Anaheim, CA, USA, 17th -22nd March, 2002.

[4] M.E. Marhic, K. K. Y. Wong and L. G. Kazovsky, "Wideband tuning of the gain spectra of one-pump fiber optical parametric amplifiers", IEEE Journal of Selected Topics in Quantum Electronics, Vol. 10, No. 5, pp.1133-1143, 2004.

[5] K.K.Y. Wong, M. E. Marhic, G. Kalogerakis, L. G. Kazovsky, "Recent Advances in the Design and Experimental Implementation of Fiber Optical Parametric Amplifiers", , Proceedings of SPIE-International Society of Optical Engineering, Vol. 5623, pp 693-704, January, 2005.

[6] A. Mussot, A. Kudlinski, R. Habert, I. Dahman, G. Mélin, L. Galkovsky, A. Fleureau, S. Lempereur, L. Lago, D. Bigourd, T. Sylvestre, M. W. Lee, and E. Hugonnot, "20 THz-bandwidth continuous-wave fiber optical parametric amplifier operating at 1 µm using a dispersion-stabilized photonic crystal fiber", Optics Express, Vol. 20, No. 27, pp. 28906-28912, 2012.

[7] Lei Zhang, S. Yang, X. Wang, D. Gou, W. Chen, W. Luo, H. Chen, M. Chen, and S. Xie, "Photonic Crystal Fiber Based Wavelength-Tunable Optical Parametric Amplifier and Pico-second Pulse Generation", IEEE Photonics Journal, Vol.6, No.5, *open access*, 2014.

[8] G. Kalogerakis, K. Shimizu, M. E. Marhic, K. K. Y. Wong, K. Useaka and L. G. Kazovsky, "High-repetition rate pulsed-pump Fiber OPA for amplification of communication Signals", IEEE Journal of Lightwave Technology, Vol. 24, No. 8, pp. 3021-3028, 2006

[9] S. Tao, L. ZengJi, Y. Peng and C. Jianping , " Numerical analysis of fiber optical parameter amplifier based on triangular photonic crystal fiber", SCI China series F: Info Sciences, Vol. 52, No. 7, pp. 1272-1278, 2009.

[10] F. Yaman, Q. Lin, S. Radic and G. P. Agrawal, "Impact of Fiber dispersion fluctuations on Dual-pump Fiber Optical Parametric Amplifiers", IEEE Photonics Technology Letters, Vol. 16, No. 5, pp. 1292-1295, 2004.

[11] M. Jazayerifar, S.Warm, R. Elschner, D. Kroushkov, I. Sackey, C. Meuer, C. Schubert, C. and K. Peterman, "Performance Evaluation of DWDM Communication Systems With Fiber Optical Parametric Amplifiers", IEEE Journal of Lightwave Technology, Vol. 31, No. 5, pp. 1454-1462, 2013.

[12] M. A. Shoaie, A. Mohajerin-Ariaei, A. Vedadi and C. Brès, "Wideband generation of pulses in dual-pump optical parametric amplifier: theory and experiment", Optics Express, Vol. 22, No. 40, pp. 4606- 4620, 2014.

[13] J.M. Chavez Boggio, P. Dainese and H.L. Fragnito, "Performance of a two-pump fiber optical parametric amplifier in a 10 Gb/s X 64 channel dense wavelength division multiplexing system", Optics communications , Vol. 218, pp 303-310, 2003.

[14] Agrawal, G. P., "Fiber-optic Communication Systems", 3rd edition, Wiley, New York, 2002.

[15] J. Wang, M. Gao, C. Jiang and W. Hu, "Design and parametric amplification analysis of dispersion-flat photonic crystal fibers", Chinese Optics Letters, Vol. 3, No. 7, pp 380-382, 2005.

[16] A. Vedadi, M. E. Marhic, E. Lantz, H. Maillotte and T. Sylvestre, "Investigation of gain ripple in two-pump fiber optical parametric amplifiers, Optics Letters, Vol. 33, No. 19, pp.2203-2205, 2008.

[17] F. Da Ros, R. Borkowski, D. Zibar and C. Peucheret, "Impact of Gain Saturation on the Parametric Amplification of 16-QAM Signals", European Conference and Exhibition on Optical Communication, OSA Technical Digest Series, 2012…………………….

[18] Z. Lali-Dastjerdi, F. Da Ros, K. Rottwitt, M. Galili, and C. Peucheret, "Pulse Distortion in Saturated Fiber Optical Parametric Chirped Pulse Amplification", IEEE Conference on Lasers and Electro-Optics , 2012………………

[19] M. Matsumoto, M. and T. Kamio, "Nonlinear Phase Noise Reduction of DQPSK Signals by a Phase-Preserving Amplitude Limiter Using Four-Wave Mixing in Fiber", IEEE Journal of Selected Topics in Quantum Electronics, Vol. 14, No. 3, pp 610-615, 2008.

[20] M. Gao, J. Kurumida and S. Namiki, "Wavelength-tunable optical parametric regenerator", Optics Letters, Vol. 35, No. 20, pp 3468- .3470, 2010

[21] X. Guo, X Fu and C. Shu, "Gain Saturation in Raman-assisted Fiber Optical Parametric Amplifier", Optics Letters, Vol. 38, No. 21, pp. 4405- 4408, 2013.

[22] G. Kaur, G. Kaur and S. Sharma, "Enhanced Gain using Raman-FOPA hybrid amplifier for L-Band 96 X 100 Gbps DWDM systems", IEEE Conference on Next Generation Computing Technologies, 2015 , Dehradun, Sept 4th-5th 2015.*(to be published by IEEE Xplore).*

[23] T. Torounidis and P. Andrekson, "Broadband Single-Pumped Fiber-Optic Parametric Amplifier", IEEE Photonics Technology Letters, Vol. 19, No. 9, pp. 1194-1196, 2006.