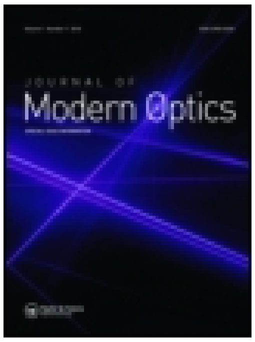

Journal of Modern Optics

ISSN: 0950-0340 (Print) 1362-3044 (Online) Journal homepage: http://www.tandfonline.com/loi/tmop20

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To cite this article: Gaganpreet Kaur, Gurmeet Kaur & Sanjay Sharma (2015): Multisection optical parametric–Raman hybrid amplifier for terabit+ WDM systems, Journal of Modern Optics, DOI: 10.1080/09500340.2015.1104390

To link to this article: http://dx.doi.org/10.1080/09500340.2015.1104390

Journal of Modern Optics, 2015
http://dx.doi.org/10.1080/09500340.2015.1104390

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Multisection optical parametric–Raman hybrid amplifier for terabit+ WDM systems

Gaganpreet Kaur[a]*, Gurmeet Kaur[a] and Sanjay Sharma[b]

[a]*Department of Electronics and Communication Engineering, Punjabi University, Patiala, India;* [b]*Department of Electronics and Communication Engineering, Thapar University, Patiala, India*

(*Received 7 September 2015; accepted 1 October 2015*)

We demonstrate flat-gain wide bandwidth Raman-Fiber optical parametric hybrid amplifier for wavelength division multiplexed systems (WDM). Raman-parametric amplifiers exploit system non-linearities which are otherwise inevitable in evolving WDM systems. Investigations show that the pumps of parametric amplifier and Raman amplifier can be carefully selected at wavelengths, to give gain over complementary bandwidth regions, resulting in wide bandwidth with low gain ripple. Results show a flat gain of 24.3 dB for 12 × 100 Gbps WDM system with lowest ripple of less than 2.78 dB reported over 220 nm bandwidth for Raman-FOPA hybrid.

Keywords: fiber optical parametric amplifiers; broadband amplification; four wave mixing; Raman effect; flat gain

1. Introduction

Fiber parametric optical amplifiers (FOPAs) have attracted considerable attention during recent years due to their capabilities to provide broad gain bandwidth and high gain, independent of modulation formats [1]. Indeed, it has been experimentally demonstrated that FOPAs can exhibit a gain bandwidth of more than 200 nm [2]. Gain of 49 dB with high conversion efficiency was demonstrated in [3] using FOPAs. Bandwidth of >400-nm region and on–off gain of 65 dB was achieved using highly non-linear fibers (HNLF) in single pump FOPA with pump power as high as 20 W [4]. Flat gain of nearly 12 dB over 100 nm was achieved [5] using multisection in-line dispersion-tailored HNLF arrangement using single low-power pump of 500 mW. For fixed non-linear coefficient γ and the pump power P_0 dispersion characteristics help determine the shape of the small-signal gain curve while fiber length can be used to control the magnitude of the gain. A maximum of 58 dB gain over bandwidth of 140 nm in 999–1139 nm band has been achieved using parametric amplification, in highly non-linear Photonic Crystal fibers (PCFs) but it falls to minimum value of 30 dB [6].

Raman amplifiers (RA) in WDM systems have recently received much more attention because of their greatly extended bandwidth and distributed amplification, with fiber itself as gain medium. Wide amplification bandwidths (>100 nm) with low gain ripple (<1.5 dB) have been achieved using multi-pump configurations for WDM applications [7]. To enable RA to achieve ultra-wide bandwidth, several pumps at different wavelengths are necessary. But each interacting pump draws energy from another leading to gain fluctuations. Also the accompanied noise of individual amplifiers gets multiplied when the number of pumps increases [8]. RA and hybrid Erbium doped fiber-Raman amplifier configurations have been widely used to achieve wide bandwidth amplification [9]. But EDFAs are only limited to 40 nm bandwidth around 1545 nm for a single amplifier and to 80 nm bandwidth around 1565 nm for a multiple stage amplifier [10]. The increase in demand for larger bandwidth and lower gain-ripple is limiting the spectrum of C+L bands characterized with low transmission loss and high gain. The need for wide bandwidths with high gain has made hybrid amplifiers an active area of research Polarization independent wide gain characteristics of RA hybrid with EDFA and its variants have been explored recently for gain enhancement by Singh and Kaler [11–14]. But optical parametric amplifiers and its hybrid amplifiers are more attractive than traditional EDFAs because of their flexibility of choosing pumping wavelengths for wide gain extending over entire communication bandwidth. However, the combined effect of Raman scattering and parametric amplification was limited due to lack of availability of high input laser sources. More recently, availability of high-power compact pump lasers, has given impetus to research in RAs and FOPAs for achieving flat gain over extended bandwidths. Golovchenko et al. [15] examined the phase mismatch parametric gain and have demonstrated that the gain depends strongly on the real part of the complex Raman susceptibility. In conventional RA–FOPAs, most energy from the Raman amplifier is trapped in the parametric pump at the output end of the amplifier. Wang et al. [16]

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*Corresponding author. Email: preetkgagan@gmail.com

proposed a hybrid fiber Raman/parametric amplifier constructed by cascading a FOPA after the RA–FOPA. Wang numerically demonstrated 70 dB peak small signal gain in 1-km HNLF with 1.5 W and 0.2 W Raman and parametric pump powers, respectively for eight channel WDM system resulting in gain enhancement of 34 dB compared to a conventional RA–FOPA for same parametric pump powers. Ummy et al. [17] demonstrated the extended flat gain of about 15 dB of with gain ripple of 5 dB, using combined Raman and parametric interaction in HNLF. Peiris et al. [18] demonstrated hybrid Raman-Optical Parametric amplifier in Tandem configuration for extended bandwidth, with gain more than 20 dB and extended gain bandwidth of 170 nm and gain ripple of less than 4 dB. The tandem configuration used concept of single pump FOPA for two sub-bands and and cross-talk of idlers controlled through multiplexer filter transfer function. In [19], improved performance with RA–FOPA for WDM system has been achieved with net gain of 20 dB and gain ripple of 1.9 dB for 10, 100 GHz spaced DFB lasers. Use of tunable non return-to-zero (NRZ) signals showed reduced susceptibility to saturation of gain in Raman-FOPAhybrid [20].

Kaur et al. [21] have demonstrated Raman-FOPAcascade for 96 × 100 Gbps system with 25 Ghz spacing to give gain of 13 dB. In this paper we investigate the novel Raman-FOPA hybrid with two-section parametric amplifier with input signal augmented by Raman gain before parametric amplification. The proposed system is analyzed for 12 channel WDM system having NRZ signals at 100 Gbps resulting in wide-band, flat gain. Results are improved than previously achieved both in terms of gain and gain ripple.

2. Experimental setup

Experimental set up is as shown in Figure 1.The transmitter consisted of 12 WDM, 20 nm spaced channels ranging from 1450 to 1670 nm. The channels are driven by NRZ 100 Gbps signal with total input power of 1 mW. In our model, the state of polarization of the input and pumps is assumed to be aligned, which may not always be true in practical system.

The signals are then input to Raman-FOPA amplifier. The input power per channel fed to amplifier black box is −18.5 dBm. The Raman-FOPA hybrid comprises Raman amplifier with two pumps at 1405 nm and 1359.5 nm with 0.9 W and 2.25 W pump powers respectively. The signal amplified is fed to HNLF section of 200 m with α = 0.8 dB/km, ZDWL at 1609 nm, dispersion of 1 ps nm^{-1} km^{-1} and dispersion slope 0.025 ps nm^{-2}. km^{-1} and λ_p = 1598 nm at 3 W power.

The next section of 100 m HNLF with ZDWL at 1550 nm is used at parametric pump of 1558.6 nm with power of 2 W, at dispersion −0.75 ps nm^{-1} km^{-1} and dispersion slope 0.025 ps nm^{-2} km^{-1}. Tunable continuous wave laser sources were used as parametric pumps to have reduced gain saturation effects [20] on parametric gain.

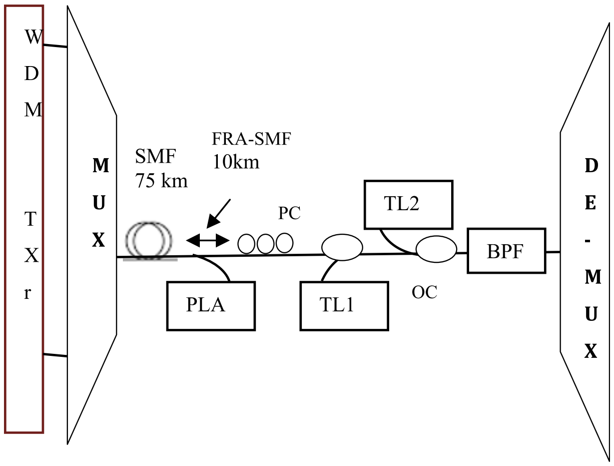

Figure 1. Schematic of the experimental set up for proposed Raman–multisection FOPA hybrid SMF-Single Mode Fiber, PLA-pump laser array, TL-tunable CW laser, OC- optical circulator, PC-polarization controller, BPF-band pass filter. (The color version of this figure is included in the online version of the journal.)

3. Results and discussions

Multisection FOPA using PCF was proposed in [20] with achievable flat gain of nearly 21.54 dB over 405 nm bandwidth and gain ripple <3 dB. Marhic et al. [22] analyzed the multisection non-linear fiber (NLF) segments with periodic dispersion compensation for gain fluctuations. It was demonstrated a gain enhancement of 5 dB and increased bandwidth from 7 to 28 nm could be achieved using NLF with periodic compensation using dispersion compensated fiber.

From [20] the transfer matrix of single fiber section is

$$\psi(z) = \begin{bmatrix} \cosh(gz) + \frac{iK}{2g}\sinh(gz) & \frac{2i\gamma\sqrt{P1P2}}{g}\sinh(gz) \\ \frac{-2\gamma\sqrt{P1P2}}{g}\sinh(gz) & \cosh(gz) - \frac{iK}{2g}\sinh(gz) \end{bmatrix} \tag{1}$$

where $K = \Delta\beta + 2\gamma P_0$

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

$$\omega_c = \frac{\omega_{p1} + \omega_{p2}}{2},\ \Omega = \omega_s - \omega_c \text{ and } \omega_p = \frac{\omega_{p1} - \omega_{p2}}{2}$$

For *N*-section of HNLF in FOPA the signal and idler amplitudes are given as

$$\begin{aligned} Y_N(Z_N, \Omega) &= \prod_{k=1}^{N}\psi(z_k)XY(0,\ \Omega) \\ &= \left[F_s(z, \Omega), F_i^*(z,\ \Omega)\right]^T \end{aligned} \tag{3}$$

Where $F_s(z, \Omega)$ is signal amplitude and $F_i^*(z, \Omega)$ is the idler amplitude. $Y_N(Z_N, \Omega)$ is the sum of outputs of N fiber sections used in FOPA.

Each fiber section results in gain G given by

$$G = 1 + \left(\frac{\gamma P}{g}\sinh(gL)\right)^2 \tag{4}$$

where $g = \sqrt{(\gamma P)^2 - \left(\frac{K}{2}\right)^2}$ for single pump FOPA.

From theory of Raman scattering in optical fibers, Raman interactions are expressed by [20]:

$$\delta = -\left(\frac{3\omega_1}{8ncA_{\text{eff}}}\right)\chi_3''(\Omega) \tag{5}$$

where n is the is refractive index of the core and $\chi_3''(\Omega)$ is the imaginary part of the third-order susceptibility resulting in set of equations expressed as:

$$\frac{\partial A_3}{\partial z} = 2qA_3 + qA_4^* e^{-iKz} \tag{6a}$$

$$\frac{\partial A_4^*}{\partial z} = -2qA_4^* - qA_3 e^{iKz} \tag{6b}$$

for signal and idler, respectively. Here $q = (i\gamma + \delta)P_0$ affects the four wave mixing interaction of signal waves to vary the gain significantly due to phase modulation due to pump interactions [23]. The real part of Raman susceptibility strongly affects peak parametric gain in case of single pump FOPA [24]. Figure 2 shows the flatness of gain achieved using multisection HNLF of short fiber lengths. Here $G1$ is the gain using 200 m of fiber length with $\gamma = 20\ \text{W}^{-1}\ \text{km}^{-1}$, pump power of 500 mW and $\lambda_0 = 1550$ nm, $\lambda_p = 1558.6$ nm. This is followed by FOPA of fiber length 100 m with $\Delta\lambda_0 = 3$ nm. This gives gain $G2$ which decreases the gain ripple around zero dispersion wavelength (ZDWL) region and improves gain by nearly 2 dB. The third section has $\Delta\lambda_0 = 3$ nm for 50 m fiber length. The dispersion characteristics of each section are varied to achieve the reduced ripple around ZDWL region to approximately 1 dB and maximum gain improved from single section FOPA gain (maximum) of 11.05 to 17.88 dB.

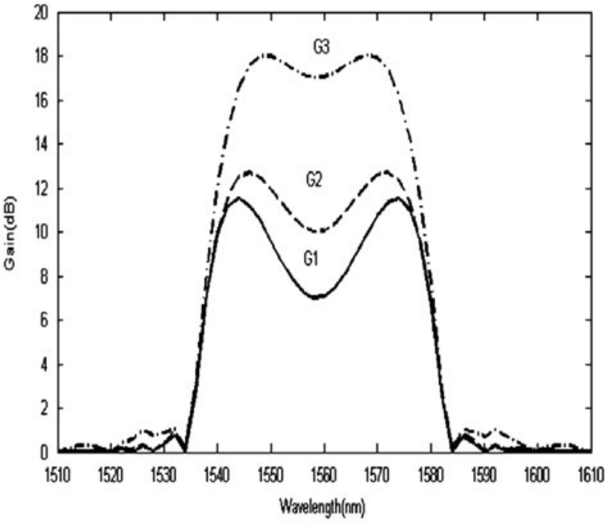

Figure 2. Gain profile for 3-section FOPA with λ_0 shifted by ±3 nm around 1550 nm λ_p at 1558.6 nm.

So, multisection parametric amplifier has been exploited in our proposed design to achieve flat gain over wide bandwidth. The broad band amplification of entire input bandwidth is achieved by tuning Raman pumps and parametric pumps in complementary regions. The lower wavelength region is amplified using Raman amplification with pumps tuned at 1405 and 1359.5 nm with 0.9 and 2.25 W pump powers respectively. Figure 3 shows Raman gain to be highest in wavelength s from 1450 to 1530 nm. The Raman amplified signal is launched into short length HNLF of 200 m for parametric amplification with pump power of 3 W coupled at 1598 nm. This amplifies the higher wavelengths ranging from 1570 to 1670 nm as seen by red curve in Figure 3(*a*). With each stage reduction in Noise figure can also be seen in Figure 3(*b*). For wavelengths amplification in middle region from 1530 to 1570 nm parametric amplified signal is launched in another short section of HNLF of 100 m with 2 W power 1558.6 nm. Due to increased crosstalk at higher wavelengths, high pump power is used for amplification. The dispersion characteristics of each HNLF have been modified with ZDWL shifted to 1609 and 1550 nm respectively with different dispersive properties for two section of HNLF. The state of polarization of pumps and ZDWL fluctuations are assumed to be uniform in our design. Figure 4 shows the gain profile of each individual amplifying component: Raman, FOPA Section 1 and FOPA Section 2. As can be seen from the gain profiles of parametric amplifier sections the ZDWL has important effect and gain is highest for perfect mismatch obtained around ZDWL

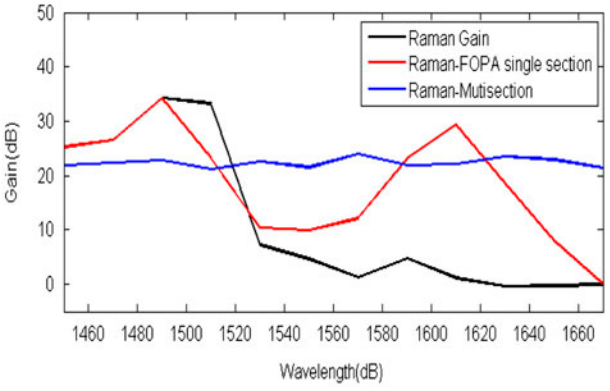

Figure 3(*a*). Gain achieved at different stages of cascade proposed. (The color version of this figure is included in the online version of the journal.)

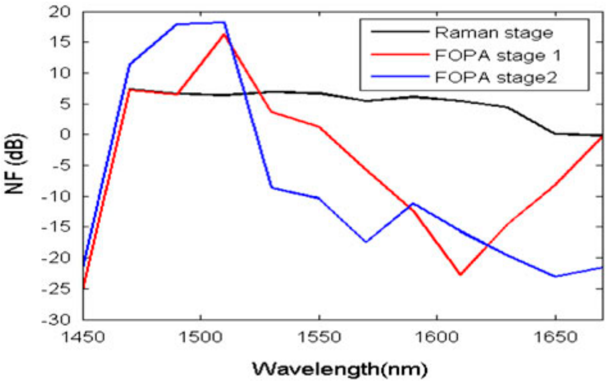

Figure 3(*b*). Noise figure variations at different stages of cascade proposed. (The color version of this figure is included in the online version of the journal.)

region. Further, λ_p is chosen in close to λ_o for flat and broad gain. Overall gain resulting from cascade of Raman amplifier with multisection FOPA gives flat gain over entire bandwidth from 1450 to 1670 nm. Red curve in Figure 4 shows the flat gain achieved using proposed Raman-FOPAconfiguration. The proposed schematic is governed by

$$G_{\mathrm{total}} = G_{\mathrm{Raman}} * G_{\mathrm{FOPA}} \tag{7}$$

where G_{Raman} and G_{FOPA} is the gain of parametric sections.

Raman gain in dB is $10.\log_{10}\left(\exp\left(\frac{g_{R.P.L_{\mathrm{eff}}}}{A_{\mathrm{eff}}} - \alpha L\right)\right)$

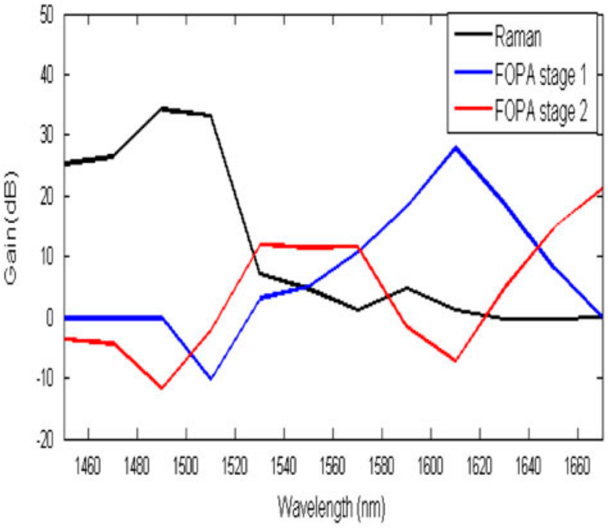

Figure 4. Gain profile of each section of proposed Raman-FOPAcascade. Each section amplifies a different region of bandwidth to achieve flat gain over entire bandwidth. (The color version of this figure is included in the online version of the journal.)

The maximum gain achieved at input of 0 dBm (1 mW) is 24.03 dB whereas minimum gain of 21.25 dB is achieved. This is the maximum gain with lowest ripple reported till date using RA–FOPA hybrid. Moreover the 100 Gbps NRZ modulated bit has been used which is expected to be future of optical communication systems [25]. Variation of gain with input power is shown in Figure 4. Parametric amplifiers have lesser sensitivity to saturation due to amplified spontaneous noise (ASE) because of unidirectional amplification [17,26,27]. Figure 5 shows increase in gain with total input power at -5 dBm where a maximum gain of 28 dB is achieved but flat gain bandwidth is narrowed by nearly 40 nm on the lower frequency band from 1450 to 1490 nm. As the input power is increased to 1 mW gain falls to 24.03 dB but peak-to-peak gain uniformity increases and a flat gain with low ripple is attained across entire bandwidth. Further increases in input power to 3 mW decrease the gain drastically to 17 dB with exception at lower frequency around 1450 nm where gain is at 21 dB. The fall in gain with increased power is expected due to gain-saturation effects as well as increased fiber non-linearities at higher input powers.

The parametric amplifiers used are single pump. Dual pump amplifiers are proved to give flat [20,26,28] gain at expense of bandwidth as shown in Figure 6. Noise figure of single pump and dual pump amplifiers is comparable [28], so much of deterioration in noise figure is not expected by use of single pump in proposed cascade. With same pump wavelengths and powers proposed Raman-FOPAcascade with two sections gives better and flat gain than Raman-dual FOPA cascade at same pump powers and wavelengths as shown in (Figure 7).

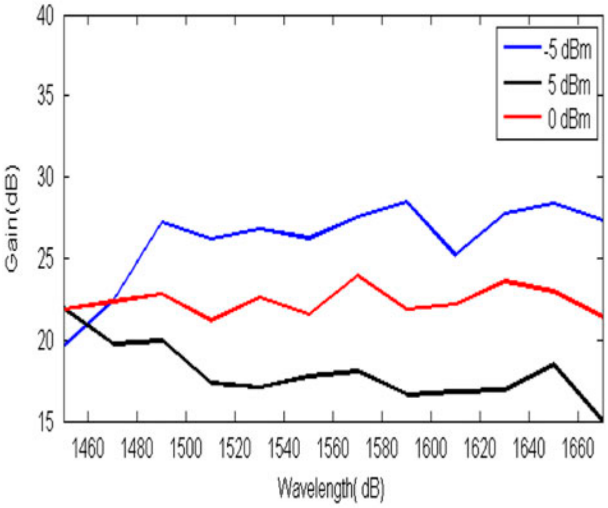

Figure 5. Gain variation of proposed Raman–multisection FOPA at different values of input power. (The color version of this figure is included in the online version of the journal.)

Additionally, in the proposed design no EDFA is used for achieving high power parametric pump signal which degrades performance due to ASE due to the presence of EDFA [23]. At high data rates of 100 Gbps BER of the order of 3.8 × 10^{-3} can be further improved using forward error correcting codes up to 10^{-15} [25]. But using our proposed design minimum bit error rate (BER) of 2.2 × 10^{-9} is achieved at per channel input power of –6 dBm at 100 Gbps and output power is of order of −22 dBm for minimum BER.

Single pump parametric amplifiers and their hybrids have proved to be potential candidates for broadband amplification in WDM systems [29,30]. Gain saturation in Raman-assisted fiber optical parametric amplifier has been proved [31,32] to enhance input saturation power over conventional FOPA by nearly 5 dB. The Raman–multisection is expected to raise the saturation limit of parametric amplifiers.

RA are known to have a negative effect on noise figure [33]. Reduced noise figure of 3.6 dB in Raman-assisted fiber optical parametric amplifier was demonstrated using a fiber Bragg grating to suppress input parametric pump noise. Reduction to noise figure close to 3 dB was further demonstrated by Wang et al. [34]. In [35], Wang et al. discussed the phase-match model used to characterize the gain of Raman-assisted parametric amplifiers. Phase matched model works best for relatively small Raman pump powers. When the Raman amplification is large, the phase matched model overestimates the peak gain because the Raman [35] pump amplifies the parametric pump and the phase matched peak gain region move away from the parametric pump wavelength (see Figure 7).

In our proposed model Raman pump power is comparable to parametric pump powers and is 0.9 and 2.25 W against parametric pump powers of 2 W and 3 W. So the phase matching condition of parametric sections does not peak at ZDWL but on the higher frequency from ZDWL at 1610 nm for first parametric section with peak gain 29.37 dB while second parametric amplifier section of HNLF peaks at 1670 nm with peak gain of 21 dB while flat gain band of nearly 11 dB is achieved from 1530 to 1570 nm. Wang et al. [36] also proposed the use of multiple Raman pumps with careful choice of pump wavelengths to achieve flat gain over wide bandwidth. Use of 5 Raman pumps at wavelengths from 115 to 1565 nm were used for counter propagation assisting parametric pump close to ZDWL region to achieve flat gain. But bandwidth under consideration is from 40 to 80 nm, which is limiting the broadband capabilities of parametric amplifiers. Raman-assisted parametric hybrid amplifier has been demonstrated to give gain of 19.5 dB with low parametric pump power of 89 mW in HNLF [37] and 16.7 dB [38] in dispersion shifted fiber and using continuous tunable pump laser. The gain is higher than the Raman-FOPAcascade. But the cascaded Raman-FOPAcan be used for gain enhancement as well as increase in gain bandwidth by using the more than one HNLF section of parametric amplifiers in cascade. Though Wang et al. [16] proposed FOPA cascade following Raman-assisted FOPA giving peak gain enhancement of 10 dB, the major drawback of proposed

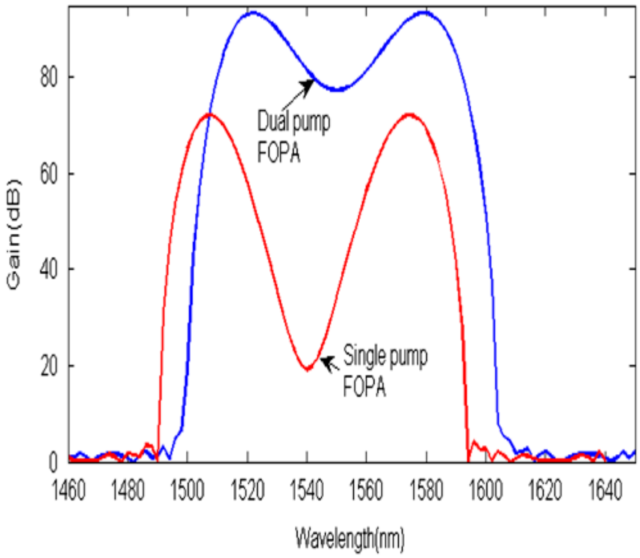

Figure 6. Single pump vs dual pump gain variation $\gamma = 18\ \mathrm{W^{-1}Km^{-1}}$, $\beta_2 = -2.2 \times\ 10^{-2}\ \mathrm{ps^2/km^2}$, $\beta_4 = 1.34 \times 10^{-4}\ \mathrm{ps^4/km^4}$, $\lambda_0 = 1550$ nm, $\lambda_p = 1540.2$ nm (single pump) and $\lambda_1\ =\ 1540.2$ nm and $\lambda_2\ =\ 1560$ nm (dual pump), at $\gamma\ =\ 11.45\ \mathrm{W^{-1}Km^{-1}}$ Raman powers pump powers of 1 W in 500 m of HNLF. (The color version of this figure is included in the online version of the journal.)

Table 1. Comparison of proposed Raman–multisection FOPA with existing Raman- parametric amplifier configurations.

Parameter	Tandem Raman-FOPA [18]	Raman-assisted FOPA pumping [19]	Proposed
Proposed novelty	Tandem configuration 1450–1510 nm *LB 1510–1610 nm *UB	Raman-assisted parametric pumping	RA–FOPA cascade with two section FOPA using HNLF
Bandwidth	170 nm (1450–1620)	7.16 nm	220 nm (1450–1700)
Channels	9	10	12
Spacing	20 nm	100 GHz	20 nm
Gain	20 dB (min)	20 dB	21.25 dB(min)
Non-linearity	11.67 W^{-1} km^{-1}	8.2 W^{-1} km^{-1}	11.45 W^{-1} km^{-1}
Pumps-Raman	1428–1.93 W	1455 nm, 5.6 W	1405 nm–0.9 W,1359.5 nm–2.25 W
FOPA-pumps	1522.6–2.5 W (UB) 2.22 W (LB)	191.57 THz, 2 W	1558.6 nm–2 W, 1598 nm–3 W
Gain ripple	<4 dB	1.9 dB	<2.8 dB
Fiber lengths	500 m HNLF–Raman 120 m HNLF–FOPA	Same HNLF 200 m for Raman and FOPA	10 km Raman; 200 m, 100 m–FOPA sections

Note: LB – lower band; UB – upper band.

design was very high ripple as gain reduced to minimum value of nearly 22 dB from its peak value of 42 dB.

The Raman–multisection hybrid proposed reduces the gain ripple to 2.78 dB which is minimum reported till date for Raman–FOPA. Also the bandwidth over which the flat gain is achieved is enhanced to 220 nm which is maximum bandwidth reported with flat gain of more than 21.25 dB reported till date with Raman-FOPAhybrid.

Our proposed hybrid has been compared with recent parametric–Raman hybrids [18,19] in Table 1. As can be seen for a comparable WDM system with nine channels in [18] at 20-nm channel spacing un-optimized minimum gain of 20 dB has achieved at a ripple of 4 dB.

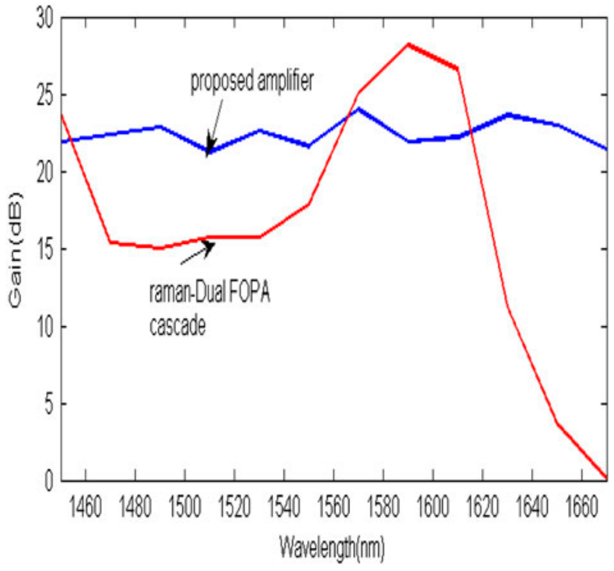

Figure 7. Gain comparison of Raman–multisection FOPA cascade vs. Raman-dual pump cascade. (The color version of this figure is included in the online version of the journal.)

In our proposed system gain of minimum 21.2 dB has been achieved lowering the ripple to 2.7 dB. This is the lowest gain ripple reported till date for 220 nm wide gain amplifier. Though ripple is as low as 1.9 dB for system proposed in [20] but the bandwidth is a narrow band of frequencies from 193.5 to 194.4 THz and gain has been limited to 20 dB. The maximum achievable gain is 24.03 dB at 1570 nm.

4. Conclusions

Flat gain of maximum 24.3 dB with minimum ripple of 2.78 dB is achieved which is the lowest ripple reported to the best of our knowledge for wide bandwidth of 220 nm using cascaded arrangement of Raman and multisection FOPA. Mostly, the previous work in Raman-FOPAhybrid has focused on Raman-assisted pumping of parametric amplifiers in same short length HNLF [15,16]. But cascade arrangement of Raman-FOPAin separate fibers gives much higher gain due to the fact that Raman gain requires long length fiber interaction unlike use of short length HNLF in parametric amplifiers. Multisection FOPA gives high and flat gain. The multisection parametric amplifiers have never been previously analyzed with Raman gain for WDM systems. It has shown improved performance over the earlier result both in gain amplitude and its uniformity over wide bandwidth. Terabit/s capacities were reported for the first time at 100 Gbit/s channel rate [39]. Electrical time-division-multiplexing transmitters of 107 Gbps NRZ modulation formats [40] and optical time division multiplexing systems at 100 Gbps [41], have already been demonstrated. Though other modulation formats as DQPSK have been suggested to give better results, the complete analysis of different modulation formats has not been included at 100 Gbps. The dispersion analysis and capacity-distance limitation at 100 Gbps could make significant enhancement to results. Inclusion of data modulation formats as DPQSK, PDM-QPSK [25,42] is expected to surely improve the performance. Minimum peak-to-peak gain uniformity of 0.04 has been achieved in said design. The results indicate feasibility of long-haul WDM systems with inline Raman–multisection FOPA amplifiers at high data rates of up to 100 Gbps. Further, polarization sensitivity of used parametric amplifiers could be optimized to maximize gain.

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