Carrier suppressed parametric pump for Flat Gain Raman Parametric Cascade amplifier in Dense Wave Multiplexed systems

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We demonstrate improved performance of Raman parametric hybrid amplifier for L-band amplification in Dense Wave division Multiplexed (DWDM) systems using novel parametric pump modulation. Results have been evaluated in 16 × 10 Gbps using CSRZ (Carrier suppressed Return to Zero) modulation of parametric pump in terms of gain flatness, OSNR (Optical Signal to noise ratio), Bit Error Ratio (BER), eye diagrams and Q factor. Gain ripple is improved by nearly 11 dB while OSNR has improved by 2.5 dB. Q-factor at high parametric pump powers increases by factor of 1.33 resulting in significant BER improvement when using CSRZ modulated FOPA pump. Hybrid modulation of parametric pump has been proposed to suppress the high power idlers by controlling the shape of the pump signal using hybrid modules. Due to Four Wave Mixing (FWM) the parametric gain falls near the pump vicinity. Higher the pump power more severe is the fall in the gain. This sudden fall of gain around pump region defeats the use of parametric amplifier for flat gain. Though Raman-parametric hybrid is able to improve the gain flatness by tuning Raman amplifiers in the region of parametric gain fall but gain ripple is still significant. So we propose a CSRZ modulation of the parametric pump which helps achieve a peak gain of 40.45 dB with maximum gain ripple of 2.63 dB. The peak to peak gain variation of less than 1.2 dB has been achieved using CSRZ modulated parametric pump. Due to phase dependence of FWM, phase modulated pump show much better results confirming effective suppressing of FWM generated idlers using pump modulation. The variation of proposed system parameters with increase in data rate, change is parametric pump phase and with Raman pump frequencies and power have also been analyzed.

1. Introduction

Optical amplifiers are significant in long haul optical transmission systems primarily because of their ability to remove electronic bottleneck by elimination O-E-O conversions for signal amplification. In context of evolving WDM systems, parametric amplifiers based on non-linear phenomenon of FWM are slowly gaining attention as high gain, low-noise, broad band optical amplifiers [1-3]. Courtney et al introduced a quasi-phase-matched, electric-field-induced, pressurized xenon-filled hollow-core photonic crystal fiber (HC-PCF) based optical parametric amplifier [4] to establish FOPA as potential candidate for low loss gain. A comparative study of polarization independent FOPA, Raman fiber amplifier and an erbium-doped fiber amplifier (EDFA) demonstrated improvement received power by more than 3dB using FOPA. In their work [6] authors presented WDM inline-amplified transmission using FOPA. The implemented system demonstrated 5.125THz amplification bandwidth and gain > 15 dB, and noise figure <5.1-dB. The parametric amplification has been numerically investigated and have been claimed to achieve nearly 75% pump to signal conversion efficiency using collinear amplification [7].

Another class of optical amplifiers characterized with capability of providing polarization-independent gain across a wide bandwidth are Fiber Raman amplifiers [8-9]. Amiri et al in their work [10] investigated single stage and multistage EDFA and Raman Amplifiers. Of all compared configurations, multistage Raman Amplifiers have shown maximum Quality factor of 218.392 for distance of 250 km.

Since both use fiber as inherent gain medium hybrid parametric amplifiers combining Raman and parametric (RA-FOPA)in different configurations have assumed popularity as wide band amplifiers. The conventional Raman assisted parametric amplification used forward travelling parametric pump within same short length HNLF augmented by a backward travelling Raman pump [11]. Supe et al. [12] demonstrated the Raman assisted fiber optical parametric amplification in a 16-channel 40 Gbps/channel WDM system. In comparison to single pump FOPA the proposed system had the 3 dB gain bandwidth 0.2 THz wider with 1.9 dB difference gain maxima and minima over the entire bandwidth. Though gain achieved is higher than sum of their individual gains but gain ripple was high [11,13]. It has been known long fiber length is required to maximize the Raman gain, but at the same time parametric amplifier used short length HNLF[14]. So, Raman assisted FOPAs do not fully exploit

the wideband capabilities of parametric amplifiers. Wang et al. [15] proposed an extended configuration comprising of RA-FOPA followed by another FOPA. If 1 km of HNLF is used for parametric amplification with high pump power maximum small signal gain of 70 dB using the proposed configuration has been achieved in 8 channel WDM systems. Ummyet al. [16] demonstrated gain of 15 B with gain ripple of 5 dB, using combined Raman assisted FOPA. Peiris et al. [17] demonstrated peak gain >20 dB over extended gain bandwidth of 170 nm and gain ripple <4 dB using hybrid Raman-Optical Parametric amplifier (HROPA) in Tandem configuration. In [18] improved performance with RA-FOPA for WDM system has been achieved with net gain of 20 dB and gain ripple of 1.9 dB in 10 × 100 GHz system employing DFB (distributed Feedback) lasers. Flexibility of tuning across any band adds to the credibility of Raman-FOPA hybrids as wide band amplifiers. Both Raman amplifiers [19] as well as FOPAs [3,20] can be tuned across any band. Akaska et al. [22] demonstrated S-band amplification and wavelength conversion using RA-FOPA. Freitas et al. [22] demonstrated 10 dB gain enhancement in S-band and S/C band wavelength conversion by simultaneous Raman amplification with parametric amplification in HNLF. Kaur et al. [23] proposed novel hybrid amplifier comprising of Raman and cascade of two-section FOPA.A flat gain of 24.3 dB has been demonstrated over bandwidth of 220 nm the proposed hybrid. Yeo et al. [24] has recently established tunable parametric oscillator cross C and L bands. We have demonstrated gain of more than 14 dB in L-band with ripple of less than 1.4 dB with RA-

FOPA cascade using gain flattening filter [25]. In their recent work Mahmoud et al. too have proposed the cascade of FOPA with Raman Amplifiers for long distance transmission [26].

In this paper we analyze a Raman-FOPA cascade hybrid amplifier for achieving flat gain in L-band, DWDM system with narrow channel spacing without any gain flattening/compensating technique. The RA-FOPA cascade has been chosen over RA assisted FOPA to fully exploit the flexibilities to tune Raman and FOPA pumps such that gain is provided in separate regions of bandwidth. To achieve flat gain, we propose to use FWM suppression at parametric pumps using CSRZ pump modulation.

2. Set up for analysis

The set up consists of 16 DWDM channels spaced 25 GHz apart covering L-band frequencies from 187 THz to 187.475 THz as shown in Fig. 1a. The proposed system equally spaced 16 DWDM channels. After traversing 50 km signals are amplified by proposed Raman FOPA cascade hybrid amplifier. The dispersion of traversed signal is compensated by 10 km fiber used as Raman amplification fiber medium with dispersion (D) = -90 ps/km/nm, A_{eff} = 32 μm^2 and attenuation= 0.5 dB/km. Raman amplified signal is then launched into 200m of short piece of HNLF serving as medium for parametric amplification.
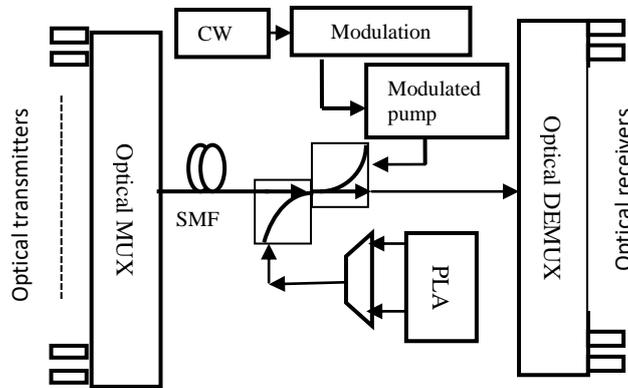

Fig. 1a. Set up for Raman-FOPA with hybrid modulator for FWM suppression. PLA –Pump Laser Array, CW-Continuous Wave Laser
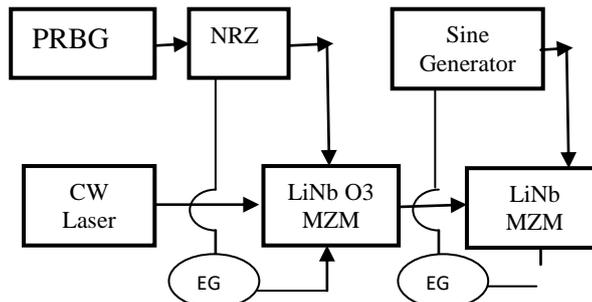

Fig. 1b. CSRZ generation set up, MZM- Mach Zender Modulator, PRBG- Pseudo Random Bit Generator, NRZ- Non Return to Zero, EG =Electrical Gain

The uniqueness of the proposed design lies in using a modulated parametric pump. This concept has never been proposed before in particularly for a Raman- FOPA hybrid amplifier. Pump signal is a CSRZ modulated signal. The CSRZ signal is generated using set up shown in Fig. 1b. It uses LiNbO$_3$ MZM which suppresses peak and retains the sidebands This CSRZ modulated pump signal is coupled along with signal to be transmitted in HNLF for parametric amplification. Single pump FOPA of length 'L' gives gain 'G' as [27]:

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

where $g=\sqrt{(\gamma P)^2 - \left(\frac{K}{2}\right)^2}$ and $K= \Delta\beta + 2\gamma P$

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

$$\Omega = \omega_s - \omega_p$$

Both Raman scattering and FWM are non-linear effects originating at high input powers. Raman interactions maybe expressed as function of susceptibility [26]:

$$\delta= -\left(\frac{3\omega_1}{8ncAeff}\right)\chi_3^{''}(\Omega) \qquad (3)$$

where 'n' is the is refractive index of the core, Ω is the frequency deviation from pump frequency and $\chi_3^{''}(\Omega)$ is the imaginary part of the third-order susceptibility. Any signal 'A' traversing due under the effect of Raman scattering as well as FWM effect may be expressed using NLSE (non-Linear Schrodinger equations) as:

$$\frac{\partial A_3}{\partial z} = 2qA_3 + qA_4^* e^{-iKz} \qquad (4a)$$

$$\frac{\partial A_4^*}{\partial z} = -2qA_4^* - qA_3 e^{iKz} \qquad (4b)$$

for signal and idler, respectively.

Here the factor $q=(i\gamma + \delta)P_0$ is strongly affected by parametric gain resulting from pump interaction of the signal [28]. This suggests the shape of parametric pump signal will affect the generated signal as well as idler. The real part of Raman susceptibility too strongly affects peak parametric gain in case of single pump FOPA [28] in particular for dispersion shifted fibers. Golovchenkoet al. [29] theoretically derived the dependence of parametric gain on the real part of the complex Raman susceptibility. Use of tunable NRZ signals has been suggested in research for reduced susceptibility of gain saturation in Raman-FOPA hybrid [30]. Rather in conventional Raman assisted parametric gain, Raman gain may cause significant spectral distortions [31]. But due to use of HNLF effect of Raman susceptibility on parametric gain is assumed to be relatively. But the proposed design assumes both Raman gain and parametric gain in separate fibers. In proposed 16 channel system single Raman pump at high power of 450

mW has been used at λ=1501.6 nm. The Raman pump is so tuned to provide gain in the lower wavelength band under consideration around 1599 nm while for higher wavelengths parametric pump is used at 1600.4 nm with 10 mW. The pump difference of at least 70 nm is maintained between Raman pump and parametric pump to keep pump-pump FWM crosstalk to minimum. Moreover peak gain regions of both Raman and FOPA fall at different band of frequencies in the output spectrum.

Considering both Raman gain and FOPA gain in dB the proposed schematic is governed by

$$G_{total}=G_{Raman} + G_{FOPA} \qquad (5)$$

where, G_{Raman} and G_{FOPA} is the gain of parametric sections. Raman gain in dB is [32]:

$$10.\log_{10}\left(exp\left(\frac{g_{R}.P.L_{eff}}{A_{eff}} - \alpha L\right)\right).$$

The parameters used for Raman fiber mediumas dispersion compensation fiber and parameters of HNLF used for parametric amplifier have been listed in Table 1.

Table 1. Values of parameters used for HNLF –parametric amplifier and DCF in Raman amplifier

Parameter	Value
DCF length	10 km
Dispersion (DCF)	-90 ps/km/nm
DCF attenuation	0.5 dB/km
Effective area	32 μm^2
HNLF length	0.2 km
HNLF effective area	11 μm^2
Dispersion (HNLF)	2 ps/km/nm
Non-linear coefficient (γ)	11.45
HNLF attenuation	0.8 dB/km

3. Results and discussions

In this work RA-FOPA cascade amplifier has been proposed for flat gain achieved by FWM idler suppression using novel pump modulation scheme. Use of single pump FOPA has been reported previously for broadband amplification. But as the number of channels increases in DWDM systems, high pump powers are required to overcome the crosstalk due to FOPA amplification [14]. But as the pump power is increased in narrow spaced multi-channel system, achievement of flat gain becomes difficult. Due to relatively high pump power the frequencies in immediate vicinity of pump frequency tend to have much higher gain than frequencies at the extremities of the band. This gives high ripple to amplifier gain. To make the gain flat around high powered pump we propose to modulate the parametric pump. The modulation of pump signal transforms the pump signal to gradually sloping signal than a sharp peak signal. Due to modulation the high power pump pulse spreads across band of

frequencies centered on the pump frequency. Use of modulated parametric pump helps suppress FWM generated idlers, in particular for Phase modulated pump signals. This results in flat gain when compared to similar system employing un-modulated CW parametric pump.
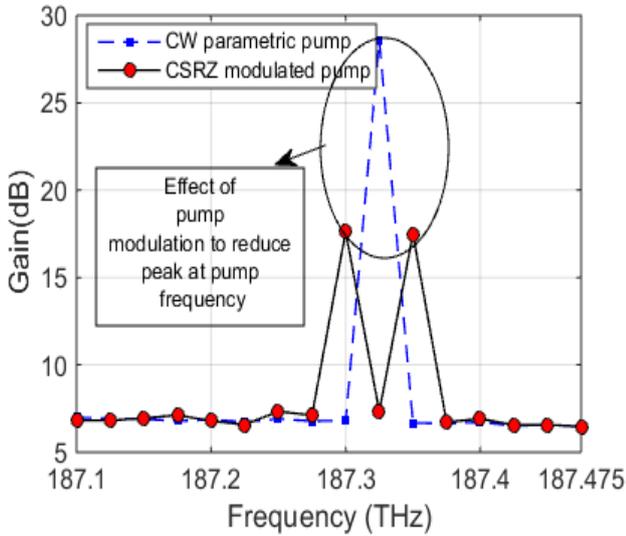

Fig. 2a. Gain comparison for 16 channels RA-FOPA at 10 Gbps with hybrid modulated parametric pump Vs un-modulated CW parametric pump (color online)
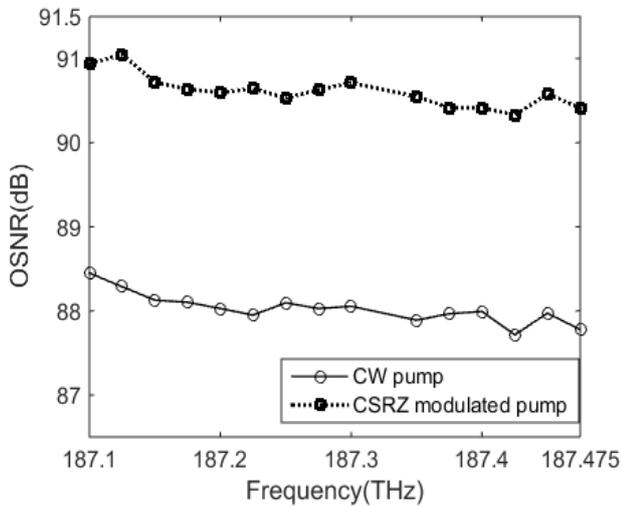

Fig. 2b. OSNR comparison for 16 channels RA-FOPA at 10 Gbps with hybrid modulated parametric pumping schemes Vs un-modulated CW parametric pump

Results of the implemented system using MZM-PM hybrid modulated pump have been previously investigated for a nearly flat gain in [33]. Though the MZM-PM modulation resulted in significant improvement but maximum power is centered at the pump signal only. In the current research CSRZ pump modulation has been proposed for the parametric pump. It can be well observed from gain results in Fig. 2a that when CSRZ modulated parametric pump is used the peak gain is decreased and low gain regions slightly raised which helps reduce the gain extremes. Results in Fig. 2a show a peak gain of

28.58 dB for CW parametric pump at 10 mW while the minimum gain falls to 6.46 dB. When using modulated parametric pump, the peak gain reduces to 17.5 dB peaking at two frequencies of 187.3 THz and 187. 35 THz around the pump signal at 187.323 THz. Due to FWM and ZDWL at 1600.4 nm (187.323 THz) gain falls to 7.33 dB at 187.325 THz giving at dip in gain at ZDWL. So the gain ripple is reduced from 22.12 dB to 11.45 dB using the modulated pump signal. The reduction of peak amplification in the vicinity of high power signal causes gain ripple to be high. The gain spectrum of Raman-FOPA can otherwise be made flat by careful tuning of Raman as well as parametric pump and optimizing their powers. But for high power pump signals gain rises sharply at frequencies around the pump signal in single pump FOPAs. Observation of OSNR in Fig. 2b shows a significant increase when using modulated parametric pump is used. So, modulation of the pump signals is proposed to reduce this abrupt peak thereby making achievement of the flat gain using Raman-FOPA hybrid possible.
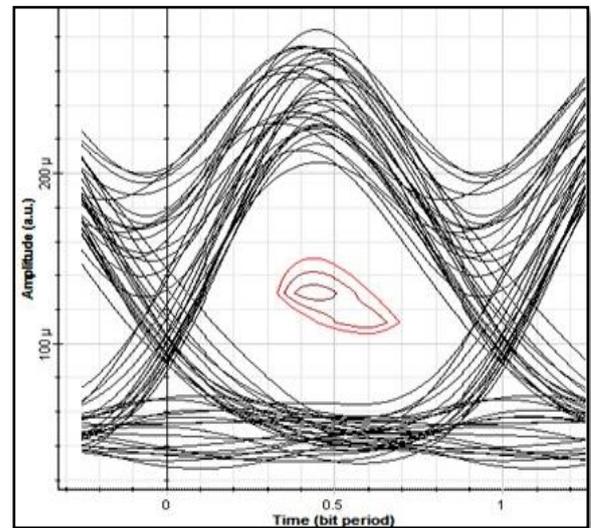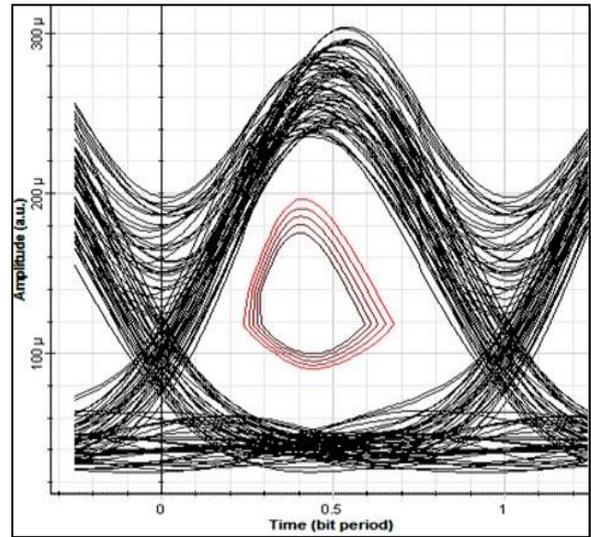

Fig. 3(a) and 3(b). Eye diagram for WDM system with CSRZ pumping scheme and Eye diagrams for WDM system with un-modulated pump

Eye diagrams in Figs. 3(a) and (b) compare the eye openings for CSRZ modulated parametric pump, and CW FOPA pump signal. Eye opening in the Fig. 3a is more wide and clear when CSRZ modulated pump signal is used in comparison to the eye opening for the un-modulated parametric pump used in Raman-FOPA hybrid. Results establish better performance using modulated parametric pump over conventional parametric pumped FOPA. For the CSRZ modulated pump the eye opening is 1.56×10^{-4} while for the un-modulated pump the maximum eye opening 1.33×10^{-4} at 0 dBm of total input power. Q-factor analysis in Fig. 4 shows a maximum increase in Q-factor of 3.22 at 4 dBm of input power. Overall maximum Q-factor achieved is 10.6 at 0 dBm input using modulated parametric pump while the highest Q-factor of 10.01 is achieved at -4 dBm using CW parametric pump.
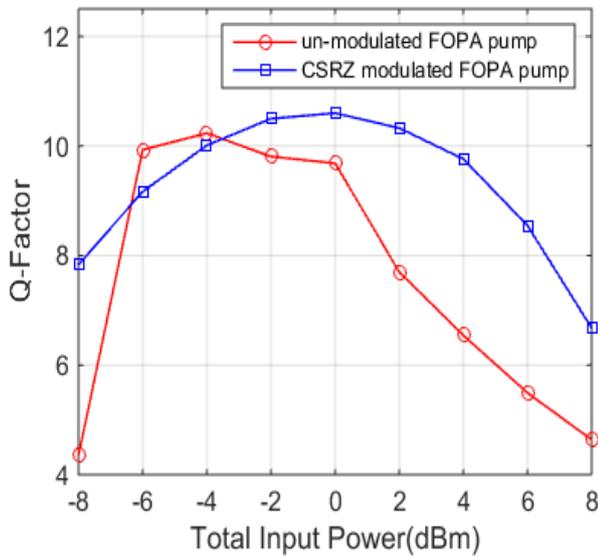

Fig. 6(a). Q Factor comparison for CSRZ and previous work on MZM-PM pump modulation [33] (color online)

Fig. 4. Q-Factor of CSRZ modulated system Vs system employing un-modulated parametric pump (color online)

Fig. 6(b). Eye diagram for WDM system with MZM-PM pumping [33]
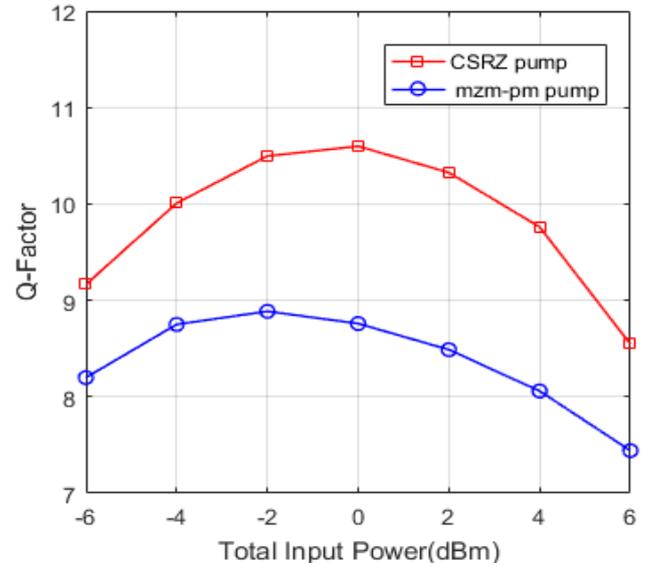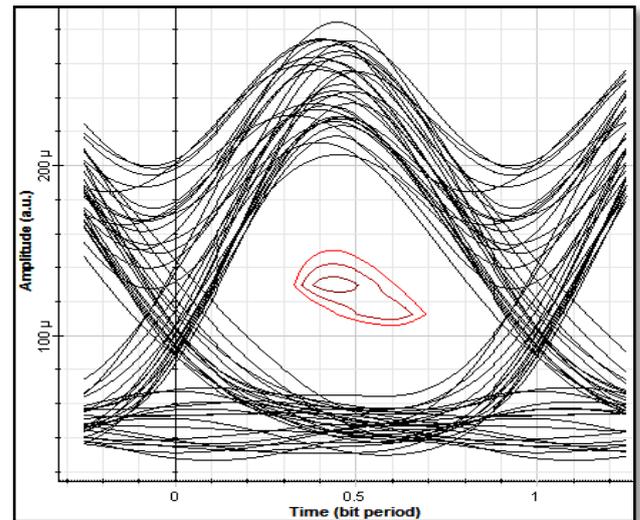

Fig. 5. BER of CSRZ modulated system Vs system employing un-modulated parametric pump (color online)

BER analysis in Fig. 5 shows at input power of 0 dBm minimum BER of order of 10^{-26} is achieved while at same input power using conventional high power pump signal BER is of the order of 10^{-22} is obtained. At high input power of 8 dBm BER for CSRZ modulated pump is 1.07×10^{-11} while for CW pump at 8 dBm minimum BER is 1.64×10^{-6}. When pump signal with high power is used, there is sharp gain at channel frequencies close to pump due to FWM while gain diminishes towards the high and low extremes of the bandwidth due to idler crosstalk. Eye opening in Fig. 3(a) when compared with eye opening in Fig. 6(c) for the MZM-PM modulated pump [33] too exhibits better results with wider and clear eye opening.

To overcome this CSRZ modulation of pump signal is proposed such that the peak is suppressed and pump power is contained in sidebands. This definitely gives better FWM idler suppression and helps achieve a flat gain amplifier. This lowering of peak power in vicinity of parametric pump results in lesser of gain ripple between highest and lowest gain achieved across the entire bandwidth.

As the data rate is increased the effect of FWM dominates [34]. To study this effect the proposed CSRZ modulated system at 40 Gbps has been implemented and results compared with 10 Gbps implementation.

The results of comparison have been presented in Figs. 7(a) and 7(b). In Fig. 7(a) the decrease in Q factor for CW pump system and CSRZ pump modulated system has been presented for single channel at 187.1 THz. The enhancement in Q-factor achieved using CSRZ modulated pump over CW parametric pump at total input power of 4dBm in 16 X10 Gbps system is 3.22 dB at 10 Gbps while at 40 Gbps the enhancement is 0.0.49 dB. Overall Q-factor drops by 3.92 dB in CW parametric system and drop is 6.44 dB in CSRZ pump modulated system as data rate is increased from 10 Gbps to 40 Gbps. Analyzing the input and output signal powers at 10 Gbps and 40 Gbps from result shown in Fig. 7(b) it may be observed that at 10 Gbps average input signal power is around -18.6 dBm which drops to -19.7 dBm at 40 Gbps. At the output for 10 Gbps CSRZ pump modulated system average output power is -8 dBm while for 40 Gbps its around -12 dBm. The average of the net gain at 10 Gbps is 10.92 dB while at 40 Gbps average net gain is 8.8 dB. The results clearly establish and confirm the dominance of FWM as data rate is increased and leads to degradation in signal quality.
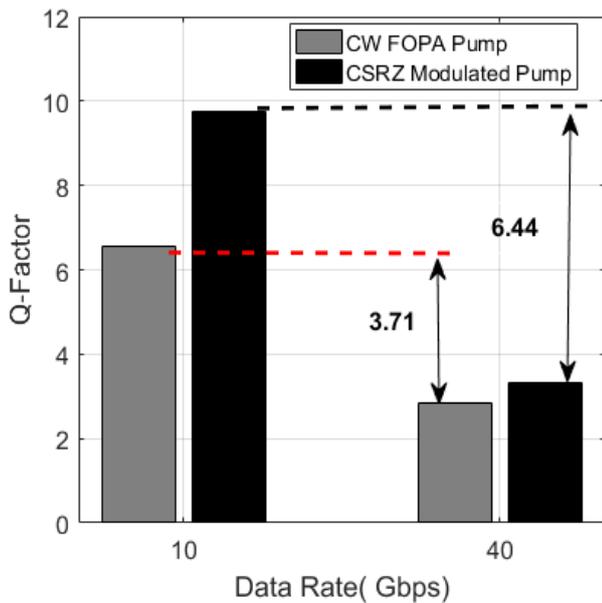

Fig. 7(a). Q-factor comparison for CW parametric pump and CSRZ modulated pump at channel frequency of 187.1 THz at 10 Gbps and 40 Gbps (color online)
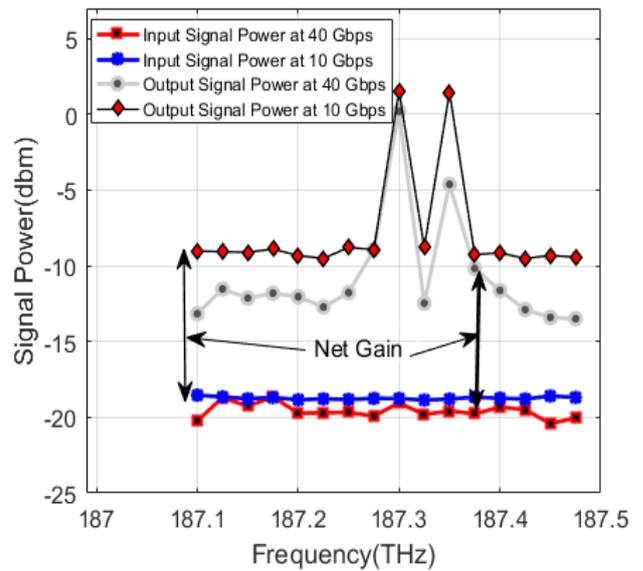

Fig. 7(b). Input and Output signal power CSRZ modulated pump at 10 Gbps and 40 Gbps for 16 channel system (color online)
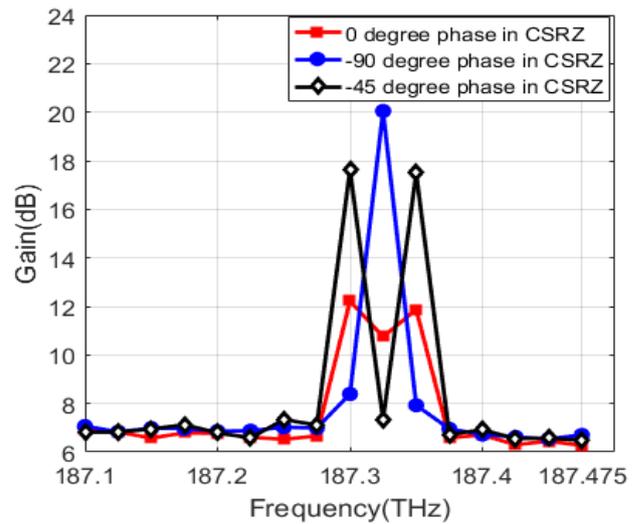

Fig. 7(c). Variation of Gain Profile with change in phase of the Pump used in CSRZ (color online)

Since the CSRZ helps FWM suppression exploiting the phase dependence of FWM, an effort has been made to study the effect of phase change in CSRZ pump. The results have been presented in Fig. 7(c). At no phase introduced in CSRZ pump, the average gain achieved is 7,55 dB with gain peaks at 12.22 dB and 11.86 dB around the pump vicinity as shown in red curve in Fig. 7(c) . If phase of -45 degree is introduced the average gain is 8.2 dB with gain peaks of 17.65 dB and 17.5 dB around pump vicinity. If phase change in azimuth is -90 degree the single gain peak of 20.01 dB is obtained with average gain 7.85 dB. So introduction of the phase change in CSRZ pump has significant impact on gain in the vicinity of the pump. More is the phase change introduced sharper the effect on gain around the pump frequency can be observed.

Based on the improved results a 100 channels DWDM system with uniformly spaced channels at 25 GHz has been implemented. The transmission fiber distance is maintained at 50 km compensated by Raman fiber medium of length 10 km. Dispersion characteristics of Raman fiber are same as in Table 1. Raman amplifier is back pumped using array of 7 pumps distributed between 1472 nm to 1510 nm with powers are shown in Fig. 8. All pumps are tuned at powers between 200 mW to 400 mW. Raman pumps are so distributed to provide Gain across longer wavelengths whereas parametric pump is tuned at 1583.98 nm at 190 mW. The FOPA pump frequency is chosen to maintain at least difference of 70 nm from Raman pumps to keep pump to FOPA pump crosstalk at minimum. Secondly it is tuned towards shorter wavelengths region which are scantly amplified using Raman amplifier. So both Raman pumps and FOPA pump work in complimentary bands.

The flat gain achieved using the proposed configuration in 100×10 Gbps system is shown in Fig. 9. From Fig. 9 it is observed that at -26 dBm of input power peak gain of 43.5 dB is achieved but gain decreases monotonically toward the shorter wavelength to below 36 dB. This gives high gain ripple of nearly dB. The gain curve at is dominated by Raman amplifier with parametric pump providing little amplification at smaller wavelengths. As the input power is increased to -10 dBm effect of parametric amplification is dominant showing significant gain towards lower wavelengths. Also due to idler crosstalk Raman gain too decreases at higher wavelengths as ZDWL of HNLF has been maintained at 1609 nm. This definitely decreases the peak gain but improves the gain flatness. As input power is further increased to 1mW optimum amplification of Raman as well parametric amplifiers is achieved giving gain of 40.45 dB as maximum and 37.82 dB minimum gain reducing the gain ripple to 2.63 dB. So as the input power increases nonlinearities, in particular FWM dominates leading to parametric amplification of signals but as channels are closely spaced idler crosstalk does affect all the frequencies lying between pump signal frequency and ZDWL.
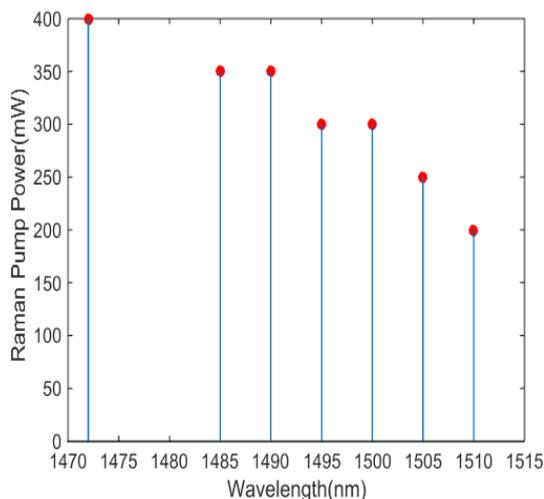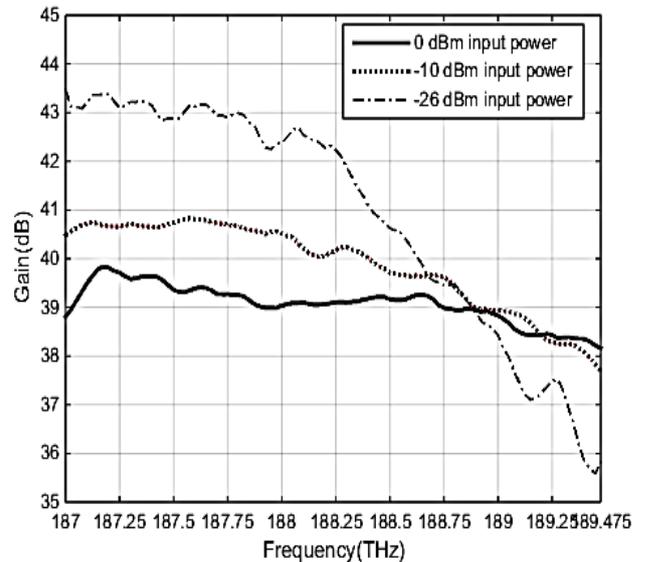

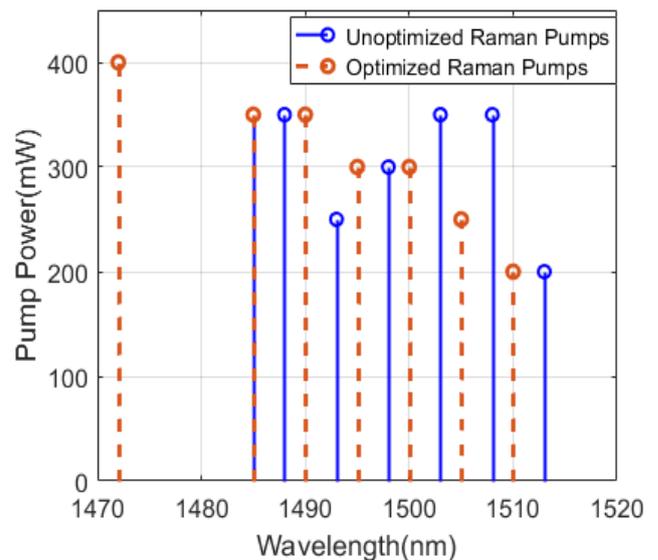*Fig. 9. Gain analysis for 100X10 DWDM system using proposed set up*

Fig. 10(a). Two different configurations of Raman pumps. The red dotted lines represents optimized configuration while blue stems represents unoptimized configuration (color online)

The choice of pump frequencies and pump powers is critical to the performance of the proposed system. This requires an optimization of the Raman pumps frequencies and their powers as well as that of parametric pump individually. To optimize the Raman pumps powers parametric pump has been set to a smaller value of 190 mW at frequency of 189.263 THz. Two different configurations of Raman pumps have been presented in Fig. 10(a). Using the two configurations the output signal power variations for 100×10 Gbps system have been presented in Fig. 10(b). The stem lines in Fig. 10(a) represent the un optimized Raman pump frequencies and correspondingly its output signal power has been presented using blue curve in Fig. 10(b). The peak output

Fig. 8. Raman pump power distribution

signal achieved is 28.18 dBm at 187.2 THz channel while the minimum value is 21.1 dBm at 189.3 THz. The stem lines in Fig. 10(a) presented in red represent the optimized pump values and the corresponding output signal variation is shown by red curve in Fig. 10(b). The peak output signal power for optimized Raman pumps is 25.3 dBm while the minimum value is 21.5 dBm. The gain ripple has been reduced from 7.08 to 3.8 using the optimized Raman pump frequencies and powers.
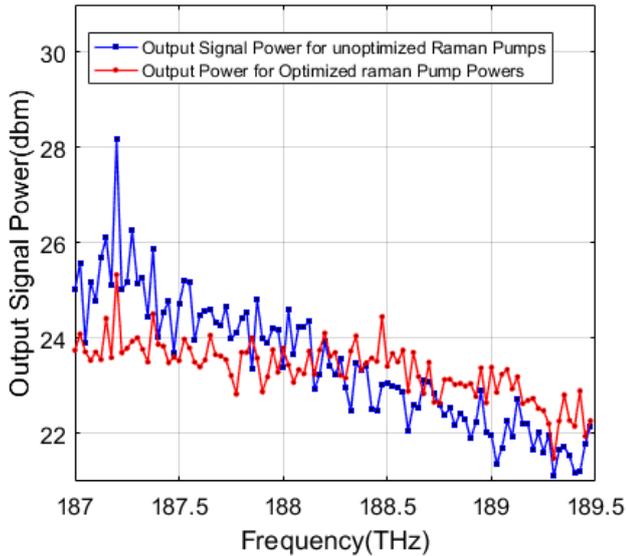

Fig. 10(b). The Output signal power of 100 X10 Gbps system for two different configurations of Raman pumps (color online)

Here pump power used for FOPA is moderately low for a 100 channels system at 190 mW. For amplifying signal using parametric amplification pump power should be high but for 100 channels single pump is not sufficient even at high powers of the order of 2W. This is well observed from the results in Fig. 11. At the low input power of -26 dBm even if FOPA pump power is increased from 190 mW to 1.5 W no significant gain is achieved except around the pump frequencies. So, the single frequency peak pump signal makes amplification limited to signals in immediate vicinity of the pump only. Hence, it is proposed to use a hybrid amplifier for a large channel DWDM system with pump signal modulated using CSRZ. The proposed configuration allows optimization of the Raman pumps as well as the parametric pump powers to give flat gain across a wide band of channels without using costly very high pump powers or any gain equalization equipment.

Hybrid Amplifiers have attained a significant attention in recent research in Optical amplification [33][35-36]. The most recent hybrid amplifier combines a wavelength converter followed by HNLF Raman amplifier and a Phase sensitive amplifier (PSA). In this work hybrid amplifier has been investigated in the hybrid amplifier to achieve gain and nearly 0 dB noise figure [35]. The achievement of low noise figure close to 0 dB in the parametric amplifiers has been established by Roudsari et al. [37] as well where they suggest use of superconducting nonlinear asymmetric inductive element in three wave mixing amplification.
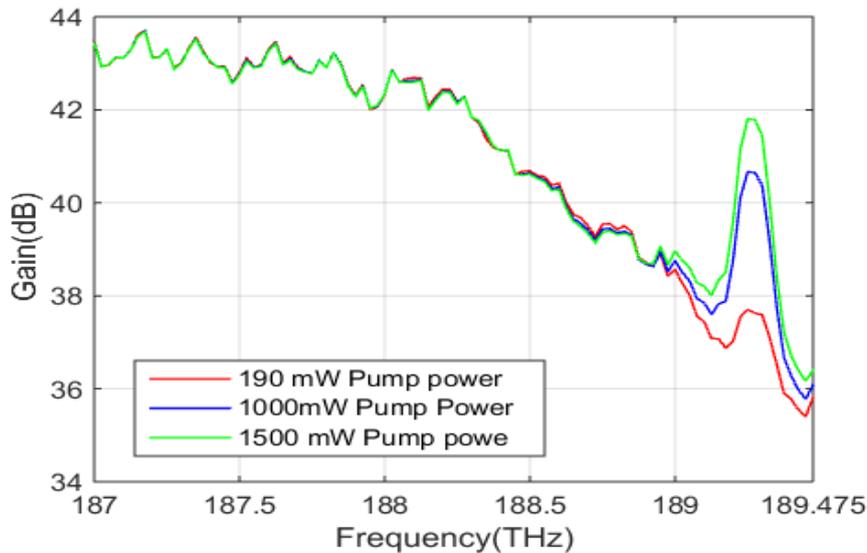

Fig. 11. Variation of Gain with Power of parametric pump (color online)

This establishes the potential of using parametric amplifier as an candidate for hybrid amplifiers in multi-channel systems. A brief comparison of the hybrid amplifiers for L-band amplification existing in the literature has been made with the proposed work in Table 2.

Table 2. Comparison of the Proposed Hybrid Amplifier with Carrier Suppressed Pump with existing L-Band Hybrid Amplifier configurations

Parameter	L Band Raman-EDFA HOA[38] (2011)	L Band Raman-EDFA-DCF[39] (2013)	Parametric Wavelength Conversion+Raman+ PSA(2022)[35]	Proposed System
System	DWDM	DWDM	DWDM	DWDM
Band	L(186.7-190.95)THz	L (187Thz-190.975Thz)	L(187.72THz-191.07THz)	L(187THz-189.475THz)
Bandwidth	35 nm	24 nm	25 nm	20.95 nm
Channels	35	160	29	100
Gain	>12 dB	>10 dB	Net Gain. 20 dB	>38.1 dB
..Ripple	~1.2dB	<4.5dB		1.7 dB
Channel spacing	125 GHz	25GHz	125GHz	25 GHz
Input Power	0.001mW-0.01mW per channel	3mW	-	1 mW
Hybrid amplifier used	Raman-EDFA	DRA + EDFA+DCF	Parametric WC+Raman+PSA	Carrier Suppressed Pump + RAMAN+FOPA
Data rate	10Gbps	10Gbps	-	10 Gbps

The results show the proposed system using carrier suppressed Pump helps have more uniform and higher gain with minimum gain of 38.1 dB over the hybrid in [35]. The maximum gain for the proposed amplifier has been maximum and offers minimum gain ripple in comparison to the existing configurations of Hybrid amplifiers in L-Band amplification.

4. Conclusion

A novel configuration of RA-FOPA hybrid used as inline amplifier has been proposed employing CSRZ modulation of parametric pump. The results have been investigated for narrow spaced DWDM system. The transmission fiber is compensated by combining dispersion compensation in Raman amplifier fiber medium making it more economical and compact. Without using any gain flattening/optimization technique highest gain of 40.45 dB with ripple of 2.63 dB has been best reported in L-band amplification at narrow channel spacing of 25 GHz spacing. Recently FWM suppression based on hybrid modules for dispersion compensation as well as using hybrid modulators have been proposed. But use of hybrid modulators to transmitters for FWM suppression adds significantly to size and cost of system. Instead, we propose modulation of parametric pump to change the pump signal shape from being single peaked signal to gradually decaying signal. This helps in reduction of idler crosstalk due to FWM resulting is relatively flat gain. At the same time suppressed peak carrier ensures absence of a sharp peaked signal around pump. This helps to reduce the gain ripple by controlling the high power peak signal gain.

This has never been done previously. Results achieved are best reported till date for L-band DWDM amplification. Parametric amplifiers and their hybrids have been widely accepted as wideband, low noise amplifiers. The ability to tune across any band makes Raman and FOPA hybrid an attractive choice for broadband amplification. Exploring the possibilities of using proposed RA-FOPA with modulated parametric pump may help identify a truly broadband, flat amplifier tunable across any communication band.

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