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Performance Investigation of Raman- Parametric Hybrid for Broadband Amplification in L-band

Gaganpreet Kaur
Lecturer, ECED,
Thapar University, Punjab, India.
Orcid id: 0000-0002-3706-6981

Gurmeet Kaur
Prof. & Head(ECE),
Punjabi University, Punjab, India.

Sanjay Sharma
Professor(ECE)
Thapar University, Punjab, India.

Abstract

In this paper Raman-parametric amplifier has been investigated for long haul Dense Wavelength Division Multiplexed (DWDM), L-band transmission. The performance of the proposed hybrid model has been compared in terms of signal gain and OSNR with FOPA and EDFA - FOPA. Feasibility of Raman-FOPA for future long haul extended DWDM systems has been explored. Results indicate an achievable OSNR of 28 dB with gain of >10 dB, over distance of 450 km for 10 Gps, 25 GHz spacing DWDM system without using any dispersion compensation technique. The gain ripple achieved is significantly low at 4.2 dB in absence of any Application of Raman-FOPA hybrid as narrowband long haul optical amplifier has been established by the results achieved and is expected to make significant contribution to evolving DWDM systems.

Keywords: UDWDM, Four Wave Mixing, parametric amplification, gain, OSNR, RAMAN-FOPA

INTRODUCTION

With current research efforts focused on high data rates, Dense Wavelength Division Multiplexed (DWDM) systems have become the backbone of long haul communication systems. But for the long distance transmission, increased input power and number of channels limit the transmission capacity of the DWDM systems primarily due to the presence of inherent fiber nonlinearities. Of all nonlinear effects limiting the performance of high capacity DWDM systems four wave mixing (FWM) has been the most dominant and inevitable[1-3] effect. Though FWM suppression is desirable, during recent years research efforts has focused to exploit the FWM for the system performance enhancement. Number of applications such as wavelength conversion, signal regeneration, signal reshaping, logic gates implementation has attracted considerable research effort [4-5] to exploitation of FWM. Another application which has been source of potential interest is parametric amplification based on FWM [6]. When a high power pump signal interacts with low power signal due to the parametric mixing of the power from pump signal is transferred to the low power signal and in this process amplifies the signal. These parametric mixing based amplifiers are referred to as Fiber Optic Parametric Amplifiers (FOPAs).FOPAs offer the advantage of broadband and relatively low noise amplification [7]-[9]. Parametric amplification was first suggested by Stolen [10] in 1975. With availability of high power continuous wave pump sources, FOPAs have assumed significant attention in WDM systems as broadband, tunable amplifiers. Additionally, introduction of highly non-linear fibers (HNLF) has added new dimension to the design of FOPAs which can be tailored as per requirements of WDM systems [9]. Feasibility of broadband long haul DWDM transmission systems based on FOPAs has been already been experimentally proved for 50 GHz spaced DWDM systems [11] up to the distance of 750 km. But, due to the generation of the idler signals in FOPA, its gain is considerably low. Exploration of possibilities to increase the gain in FOPAs, lead to advent of hybrid FOPAs [4-6],[12]. Reduction of FWM crosstalk has also been demonstrated using FOPA-EDFA hybrid [12]. But using the booster Erbium-doped fiber amplifier (EDFA) limits the wavelength selection of parametric pump [8].Among the FOPA hybrids Raman-assisted fiber optical parametric amplifiers (RA-FOPAs) gained attention because of their flexibility in the selection of parametric pump powers [6] both in number of pumps and wavelength of pumps, which can be conveniently placed to generate boost low power regions of FOPA spectrum. In conventional Raman assisted FOPAs, most of the energy from the Raman amplifier is trapped in the parametric pump at the output end of the amplifier. Wang et al[8] proposed a hybrid fiber Raman/parametric amplifier (HFRPA) constructed by cascading a FOPA after the RA-FOPA. Wang numerically demonstrated peak gain enhancement of 34 dB compared to the conventional RA-FOPA in 8 channel DWDM system. But gain flatness has been an area of concern.

None of the hybrids of FOPAs previously have been investigated for DWDM systems with channel spacing squeezed to 25 GHz, particularly for the L-band. All the previous work of FOPAs and its hybrid variants has been focused on C-band and DWDM systems up to 50 GHz spacing. In this paper Raman –FOPA hybrid has been experimentally investigated for L-band amplification in Ultra DWDM system.

PRINCIPLE OF OPERATION

We have made an attempt to increase FOPA gain by cascading FOPA with Raman Amplifier. In the Raman-FOPA signal is amplified by back propagated pump, Raman amplifier and then directly amplified using co-propagating parametric pump in FOPA as shown in the schematic in Fig.1:

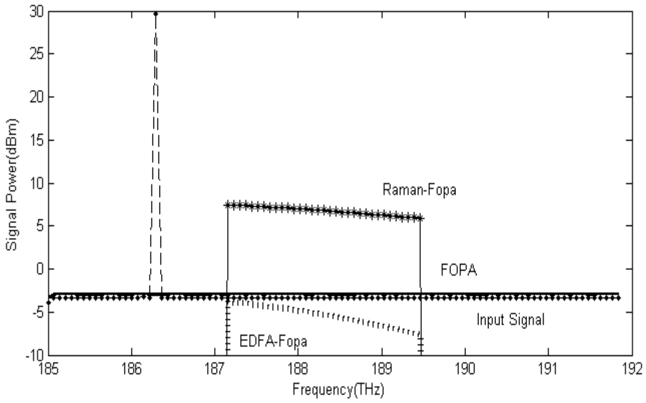

Figure 1. Signal power of FOPA, FOPA-EDFA and RAMAN –FOPA compared with input to the fiber

Gain in Raman amplifier is governed by [13]:

$$G_{Raman}= 10 \log_{10}(\exp(g_R P L_{eff}/A_{eff}) - \alpha L) \quad (1)$$

Where g_R is Raman gain coefficient, P is pump power, L_{eff} is effective fiber length in Raman amplifier, A_{eff} is effective fiber area and α is fiber attenuation.

Gain of FOPA for dual pump is given as[12] :

$$G_{fopa} = 1+\{2\gamma \frac{\sqrt{P1P2}}{g} \sinh(gL) \}^2 \quad (2)$$

Where γ is non-linear coeffiecient,P_1 P_2 are pump powers, g is parametric gain coefficient, L is length of fiber given as:

$$g= \sqrt{4\gamma^2 P_1 P_2 - (\frac{k+\delta k}{2})^2} \quad (3)$$

where k is phase mismatch and given by:

$$k=\beta_2\omega_c(\Delta\omega_s^2-\Delta\omega_p^2) +\frac{1}{12}\beta_4\omega_c(\Delta\omega_s^4-\Delta\omega_p^4) + \gamma(P_1 +P_2) \quad (4)$$

$\omega_c= \frac{1}{2} (\omega_1 + \omega_2)$ for 2 pumps at P_1 and P_2 .

The gain expected of Raman-FOPA hybrid is[15]:

$$G_{Hybrid}=G_{Raman} \text{ X } G_{FOPA} \quad (5)$$

Where G_{Hybis} gain of proposed Raman- FOPA, G_{Raman} gain of Raman amplifier and G_{FOPA} gain of FOPA.

When Raman amplified signal is launched in FOPA, it is expected to give better amplification in FOPA due to increased FWM with higher input power. The nonlinear coefficient of HNLF used is $5.11 W^{-1} km^{-1}$ which is 2-3 times than that of SMF so the higher gain is expected through parametric amplification.

EXPERIMENTAL SET UP

To investigate the performance of Raman-FOPA for L-band, a DWDM system with 93 channels equally spaced 25 GHz apart in L-band from 187.075THz to 189.375 THz with NRZ 10 Gbps modulated signal has been simulated to analyze the performance of Raman-FOPA.

Table 1. Parameters Used For Raman and FOPA

Parameter	Value
Pump frequency(Raman)	1460 THz-1530 THz
Pump Frequency(FOPA)	1609.3 THz
HNLF dispersion slope	0.02 ps/nm^2km
HNLF coefficient	10 $(W\text{-}km)^{-1}$
HNLF Length	500 m
HNLF attenuation	0.8 dB/km

The choice of L-band frequencies from 187.075 THz to 189.375 THz has been made on the basis of investigation of parametric amplifier and its two possible hybrids. For entire L-band the gain and OSNR comparison of three FOPA amplifier configurations – FOPA, EDFA-FOPA and RAMAN-FOPA has been made. The results show in Fig. 1 show Raman-FOPA hybrid shows best amplification result in range of frequencies between 187.1 THz to 189.4 THz. As can be observed from the results in Fig. 1, FOPA practically provides no amplification with single pump for 93 channel DWDM system. So FOPA hybrids have been explored for effective amplification in L-band DWDM systems, that is, Raman-FOPA and EDFA-FOPA. RAMAN-FOPA gives highest gain of nearly 7 dB though limited to band of frequencies from 187.088 THz to 189.392 THz. All these comparisons have been made without any optimizations of pump power, polarization or fiber length.

RESULTS & DISCUSSIONS

Following this finding, experimental set up for Raman-FOPA hybrid for long distance DWDM system in L-band has been used as shown in Fig. 2.

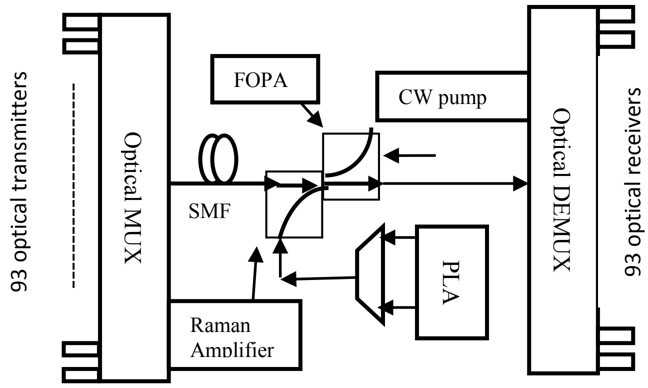

Figure 2. DWDM Schematic for setup of FOPA and RAMAN-FOPA analysis

This system has been investigated for different channel input powers at different input powers up to distance of 450 km with fiber span of 75 km each. FOPA used is single pump with pump power of 27 dBm and Raman amplifier has 15 pumps with 70 mW power. Gain of more than 10 dB with ripple of 4.2 dB has been achieved in single stage without any dispersion compensation technique or gain flattening technique.

If we attempt to increase the gain by increasing Raman pump powers up to 100 mW, maximum achievable gain increases to 18.48 dB but ripple too increase significantly to 6.66 dB as seen from the Fig. 3a. This is due to non-uniform Raman gain which falls at higher frequencies (shorter wavelengths). As the pump power of Raman pumps is increased the Raman gain increases. But as the Raman pump powers is increased noise too increases as is evident from Fig. 3b showing increased noise figure at 100 mW pump powers. Use of high pump powers is preferable for increased gain but use of multiple pumps and their powers has to be optimized to avoid pump–pump interaction noise [16]. For increase in Raman pump powers by 14.77 dB (from 70 mW to 100 mW), OSNR increases by 14 dB as indicated by blue and black curves in Fig. 4a as the number of amplification stages increase.

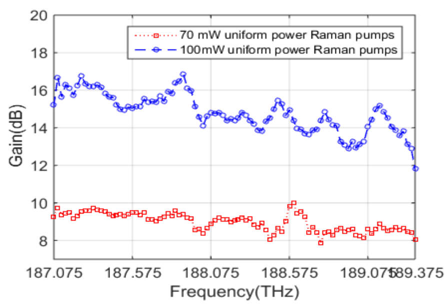

Figure 3a: Gain variations for Raman-FOPA hybrid with Raman fiber length 10 km and FOPA length 0.5 km. at different Raman pump powers.

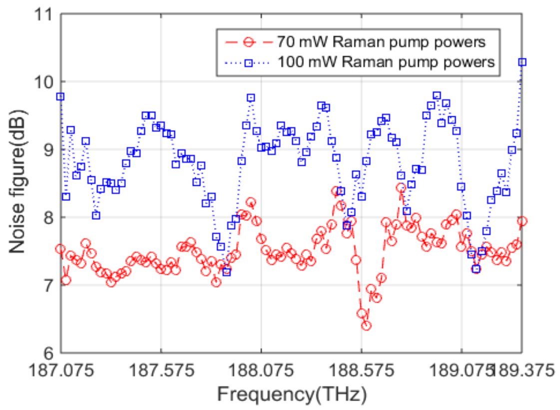

Figure 3b: Noise Fig. variations for Raman-FOPA hybrid with Raman fiber length 10 km and FOPA length 0.5 km. at different Raman pump powers.

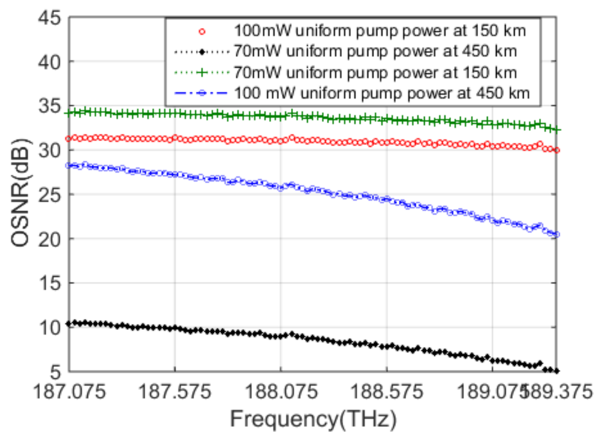

Figure 4a: OSNR comparison for RAMAN-FOPA with varying pump power of Raman amplifier at 70mWand 100 mW over distance of 450 km at P_{in} of 3mW

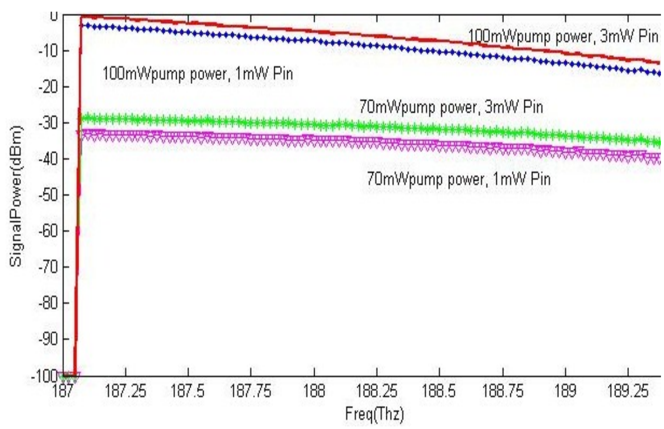

Figure 4b: Signal Power comparison for RAMAN-FOPA with Varying pump power of Raman amplifier at 70mWand 100mW over distance of 450km with each fiber span of 75km at P_{in} of 3mWand 1mW.

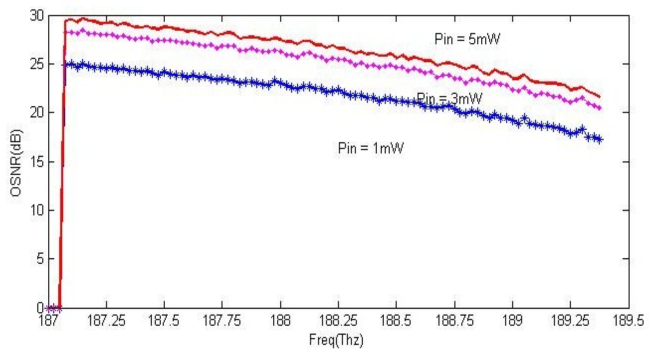

Figure 5: OSNR Variations for different Input powers

For over short single span length with single stage amplification even though pump powers are increased OSNR falls as shown by green and red curves in Fig. 4a.The output signal power significantly improves with increase in pump powers of Raman amplifier. Signal gain of 30 dB is achieved at input power of 1mW for increase in pump powers from70 mW to 100 mW whereas gain of 21dB is achieved at input power of 3mW for same pump power increase which can be confirmed from signal power variations in Fig. 4b. But OSNR falls at short distances due to increased pump-pimp interaction noise. This clearly establishes increased crosstalk due to non-linear effects at high pump powers. The non-linear effect of FWM responsible for parametric amplification too has variations in gain and signal power but in the proposed single pump FOPA has been used. As the number of channels increases single pump parametric amplification fails to dominate and hence has been excluded from study for pump power variation. Fig 5 shows OSNR variation of Raman-FOPA with input powers. As input power is increased, OSNR increases. For increase in input power per channel by 2mW from 1mW to 3mW, 4 dB increase in OSNR is achieved but for increase in input power from 3mW to 5mW gives maximum OSNR gain of 1.2 dB only which confirms signal degradation at high input powers with increased crosstalk contributed to by FWM as well as pump interactions.

It is observed from results that OSNR of Raman-FOPA significantly improves with cascaded stages with increase in pump power. In previously proposed systems employing Raman-FOPA hybrids [17] gain enhancement over conventional FOPA is achieved primarily due to FWM crosstalk reduction but as spacing will be reduced, gain is expected to fall as FWM crosstalk increases and dominates narrow-spaced systems. But our proposed system has achieved gain of > 10 dB for 25 GHz spacing, 96 channel system. For a distance of 450 km and six cascaded stages maximum OSNR improvement of nearly 18 dB is achieved. But as the pump power is increased OSNR falls at higher frequencies. So use of higher number of Raman pumps with low pump power and uniform distribution across the entire bandwidth has been proposed to maintain gain flatness.

CONCLUSION

From the results achieved it can be concluded that long haul UDWDM systems using RAMAN-FOPA amplifiers are feasible in near future. Feasibility of RA-FOPA for high capacity systems at more than 80 Gbps may be explored for direct detection systems. Though advanced formats have been proposed for high data rate systems [18-19] but they require coherent detection. Wen et al has experimentally investigated 53.2 Gbps, NRZ direct detection Ethernet system for short distance communication [20]. This motivates us to explore in future 40 Gbps DWDM systems using our proposed Raman-FOPA hybrid. Singh and Kaler [21] proposed a novel SOA-EYDWA amplifier for 0.2 nm channels spacing system with gain > 14 dB which is comparable to our proposed hybrid amplifier. Rather in the proposed amplifier channel spacing is reduced to nearly 0.1nm and gain is more than 10 dB up over distance of 450 km against the single span performance in [21]. The novelty of the propose hybrid amplifier to use Raman-FOPA cascade over conventional Raman-assisted achieves improved performance as:

1. It allows Raman and FOPA pumps to be independently tuned in complementary regions which helps reduce the gain ripple.
2. Raman Fiber requires long fiber lengths while parametric amplifiers use short length HNLFs. Our proposed design well exploits amplifying capabilities of each Raman and FOPA using separate fibers.
3. The amplified output of Raman amplifier serves as input to FOPA. This increased signal power at its input helps achieve better FWM efficiency responsible for parametric amplification.

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