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Comparative study of performance of EDFA/Raman hybrid optical amplifier with Raman only amplifier and EDFA only amplifier

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In this paper, comparative study of the gain and noise figure for EDFA/Raman hybrid amplifier, EDFA and Raman amplifier was done. In addition, the optical signal to noise ratio (OSNR) is calculated as a function of signal wavelength. The higher gain was 41.1 dB for EDFA/Raman hybrid amplifier at -30 dBm input signal power, 100 mW of both EDFA and Raman pump power and signal wavelength of 1530 nm and the lower noise figure was 3.8 dB for EDFA only at -30 dBm input signal power, 100 mW of EDFA pump power and signal wavelength of 1530nm. The lower values of OSNR obtained for Raman amplifier only at signal wavelength 1530 – 1600 nm with -30 dBm input signal power and 100 mW Raman pump power. The flatness of the gain profile of EDFA/Raman hybrid amplifier is higher than of both EDFA only and Raman only.

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1. Introduction

Extremely high signal gains and low noise figures can be achieved in EDFAs with modest pump powers. (For instance, in an EDFA a signal gain of a few dB per mW of pump power is obtainable, whereas only 0.06 dB of gain per mW of pump power in a Raman amplifier is achievable in typical optical transmission fibers at present) [1]. Over the last several years, we have witnessed a tremendous rebirth of the interest in Raman amplification in optical fibers. Practical, efficient, high-power pump sources have diminished the disadvantage of the relatively poor efficiency of the Raman process compared to the erbium amplification process, and Raman amplifiers do offer several very attractive advantages over EDFAs [2]. Because the important features of EDFAs, many researches and developments were done to improve the characteristics of such amplifier and the other optical amplifiers, and in the last few years, the amplification of optical signals by stimulated Raman scattering in Raman fiber were done for future telecommunications systems [3].

The use of distributed Raman amplification in transmission fibers can provide improved noise figure, signal power gain and optical signal to noise ratio (OSNR). EDFA/Raman with hybrid configuration has been extensively studied showing low noise figure and high gain for transmission systems compared to conventional EDFA [4]. Lee et al. work on experimental study of performance comparison of three different schemes of single pump dispersion-compensating fiber (DCF) – based Raman/EDFA hybrid amplifiers [5], also M. H. Abu Bakar et al. work on L- band remote EDFA/Raman hybrid amplifiers experimentally and they choose the L – band for flat gain [6]. Furthermore, Simranjit Singh et al., demonstrate a paper for investigation comparison of EDFA, Raman and semiconductor optical amplifiers (SOA) individually and the performance has been compared on the basis of transmission distance and dispersion with and without nonlinearities [7].

In this paper, we make a comparative study of the three types of optical amplifier, EDFA/Raman hybrid, Raman only and EDFA only amplifier. In this comparison, the gain and noise figure profiles (plotted as a function of signal wavelength) are calculated for different values of input signal power, EDFA pump power and RA pump powers for the three types of amplifiers, EDFA/Raman hybrid, Raman only and EDFA only amplifier.

2. Model of calculations

2.1 Raman amplification

When an input signal is introduced to an optical fiber with strong pump, it will be amplified due to the Raman interaction between the pump and signal, so the signal and pump power can be described by the following equations [8]

$$\frac{dP_s}{dz} = \frac{g_R P_p P_s}{\sigma_p} - \alpha_s P_s \qquad (1)$$

$$\frac{dP_p}{dz} = \frac{\omega_p}{\omega_s}\frac{g_R P_p P_s}{\sigma_p} - \alpha_p P_p \quad (2)$$

where P_s is the signal power, g_R is Raman gain coefficient, P_p is the pump power, σ_p is the cross section area of pump, α_s and α_p the fiber losses at signal and pump frequencies (ω_s and ω_p) respectively. The gain of Raman is [9]

$$G(dB) = 10log_{10}\left[exp\left\{\frac{g_R P_p(0)}{\sigma_p} L_{eff} - \alpha_s L\right\}\right] \quad (3)$$

with

$$L_{eff} = \frac{1-e^{-\alpha_p L}}{\alpha_p} \quad (4)$$

The Raman gain coefficient is calculated from the relation [10]:

$$g_R = \sigma(\nu)\frac{\lambda_s^3}{c^2 h(n(\nu))^2} \quad (5)$$

γ_s is the Raman cross section of the signal, λ_s is the Stokes wavelength, h Planck's constant and n(ν) is the frequency dependent refractive index.

For noise figure calculation, [11]

$$NF(dB) = 10log_{10}\left[2\exp(-\alpha_s L) + \frac{1}{G}\right] \quad (6)$$

The optical signal to noise ratio (OSNR) is given as [12]

$$SNR = \frac{P_s(0)}{h\nu\Delta\nu\left[NF - \frac{1}{G}\right]} \quad (7)$$

2.2 EDFA amplification

The absorption and emission cross sections could be calculated for EDFA using [13]

$$\sigma_a(\nu) = \frac{\lambda^2}{8\pi n^2 \tau \Delta\upsilon} g_a(\nu) \quad (8)$$

The McCumber relation states that the absorption cross section $\sigma_a(\nu)$ and the emission cross section $\sigma_e(\nu)$ spectra between a ground state (manifold of eight sublevels of energy E_{1j}) and the excited state (is a manifold of seven sublevels of energy E_{2j}) are related by [14]

$$\sigma_e(\nu) = \sigma_a(\nu)\exp(\varepsilon - \frac{h\nu}{kT}) \quad (9)$$

where k is the Boltzmann constant, T the absolute temperature, and ν the optical frequency. The parameter ε [14] is defined as:

$$\exp(\frac{\varepsilon}{kT}) = \frac{\sum_{j=1}^{8}\exp(-\frac{E_{1j}}{kT})}{\sum_{j=1}^{7}\exp(-\frac{E_{2j}}{kT})}\exp(\frac{E_o}{kT}) = R\exp(\frac{E_o}{kT}) \quad (10)$$

where $E_o = E_{21} - E_{11}$ is the energy difference between the lowest energy levels of the two manifolds [14]

where $g_{a,e}$ is the normalized absorption and emission line shape function (Gaussian line shape), Δν is the band width of the line shape, τ life time of the atoms in the meta-stable state and n is the refractive index of the medium.

Considering for simplicity the three energy levels of erbium reduced to two levels, the propagation equations for pump, signal and amplified spontaneous emission (ASE) powers can written as [15]

$$\frac{dP_p(z,t)}{dz} = -P_p\Gamma_p\left(\sigma_a^p N_1 - \sigma_e^p N_2\right) - \alpha_p P_p \quad (11)$$

$$\frac{dP_s(z,t)}{dz} = +P_s\Gamma_s(\sigma_e^s N_2 - \sigma_a^s N_1) - \alpha_s P_s \quad (12)$$

$$\frac{dP_{ASE}(z,t)}{dz} = +P_{ASE}\Gamma_s(\sigma_e^s N_2 - \sigma_a^s N_1) + 2\sigma_e^s N_2 \Gamma_s P_{ASE} - \alpha_s P_{ASE} \quad (13)$$

Here $\sigma_a^{p,s}$ is the absorption cross section for pump and signal respectively, $\sigma_e^{p,s}$ is the emission cross section for pump and signal respectively $\Gamma_{p,s}$ is the overlap factor for pump and signal respectively and α_p, α_s are the fiber loss for the pump and signal respectively.

The gain of the amplifier is the ratio of the output power P_{out}^s to the input power P_{in}^s
which is given by solving equations(11, 12 and 13) analytical result in:[8]

$$G = \exp(-\alpha_s L) \times exp\left[\frac{h\nu_s}{P_{in}^s}\left(\frac{P_p(0)-P_p(L)}{h\nu_p} + \frac{P_s(0)}{h\nu_s}(G-1) - \frac{P_{ASE}^{+}(L)}{h\nu_s}\right)\right] \quad (14)$$

The net noise figure will calculated as considering macro-bending EDFA and Raman amplifier as cascaded amplifiers, for EDFA noise figure [16]

$$NF_{EDFA} = \frac{1}{G_{EDFA}} + \frac{P_{ASE}^0(\lambda_s)}{G_{EDFA}h\nu_s} - \frac{P_{ASE}^i(\lambda_s)}{h\nu_s} \quad (15)$$

2.3 EDFA/Raman amplification

The gain of EDFA/Raman amplifier is [8]:

$$G = exp\left[L_r exp\left[\Gamma_s N_t L_e\left\{-\sigma_a^s + (\sigma_a^s + \sigma_e^s)\frac{[\omega_p+\omega_{12}]}{[\frac{1}{\tau_{sp}}+\omega_p+\omega_{12}+\omega_{21}]}\right\} - (\alpha)L_e\right] g_0 - \alpha_s exp\left[\Gamma_s N_t L_e L_r\left\{-\sigma_a^s + (\sigma_a^s + \sigma_e^s)\frac{[\omega_p+\omega_{12}]}{[\frac{1}{\tau_{sp}}+\omega_p+\omega_{12}+\omega_{21}]}\right\} - (\alpha)L_r L_e\right]\right] \quad (16)$$

where Γ_s, Γ_p are the overlap factors for signal and pump respectively for EDFA, σ_e^s, σ_a^s are the emission and absorption cross sections for the signal respectively. σ_{pae} is the absorption cross section of pump for EDFA, α, α' are the background losses and N_t the total concentration of the erbium ions, ω_p is the pump frequency, τ_{sp} is the spontaneous emission lifetime for transition from E_2 to E_1, and ω_{21} and ω_{12} are the frequencies of emission and absorption signals. g_r is Raman gain coefficient, P_{pr} is the pump power for Raman amplifier, γ_p is the cross sectional area of pump beam inside the fiber, α_s and α_p is fiber losses at signal and pump at frequencies (ω_{sr} and ω_{pr}).

with

$$g_0 = \frac{P_{ipr} - L_{eff} g_r}{\gamma_p L_r} \quad (17)$$

and

$$L_{eff} = \frac{1-e^{(-\alpha_p L_r)}}{\gamma_p} \quad (18)$$

The net noise figure for the purposed system is [16]

$$NF_{net} = NF_{EDFA} + \frac{NF_{Raman}-1}{G_{EDFA}} \quad (19)$$

The relation between net noise figure and optical signal to noise ratio is given as [17]

$$OSNR = \frac{P_{ise}}{h\nu_{sr}\Delta\nu_r(NF_{net} - \frac{1}{G_{net}})} \quad (20)$$

where P_{ise} is the input signal introduce to the EDFA amplifier (1st) amplifier.

The parameters used in our model are listed in Tables 1 and 2.

Table 1. EDFA parameters.

Symbol	Definition	Value
σ_e^s	Signal emission cross section	6.8 ×10^{-25} m^2
σ_a^s	Signal absorption cross section	8 ×10^{-25} m^2
P_{ae}	Pump absorption cross section	2.44×10^{-25} m^2
P_{ee}	Pump emission cross section	0.87×10^{-25} m^2
τ_{sp}	Life time	10.8 ms
N_t	Erbium concentration	2.4 ×10^{25} m^{-3}
λ_s	Signal wavelength	1560 nm
λ_p	Pump wavelength	980 nm
$P_{ASE}^{+}(L)$	Co propagation ASE power	0.15 mW
α	Background loss	0.5 dB/m

Table 2. RA parameters.

Symbol	Definition	Value
g_R	Raman gain coefficient	10 ×10^{-14}
$\Delta\nu_r$	Reference optical bandwidth	0.1 nm
λ_p	Pump wavelength	1450 nm
α_s	Fiber loss at signal frequency	5.76 ×10^{-5} dB/m
α_p	Fiber loss at pump frequency	5.76 ×10^{-5} dB/m
σ_s	Cross sectional area of pump beam	12.6×10^{12} m^2
σ_p	Cross sectional area of signal beam	12.6×10^{12} m^2

3. Results and discussion

Fig. 1 shows the gain of the three amplifiers as a function of signal wavelength. The RA length is 20 km, EDFA length 15 m, the input signal -30 dBm and the both EDFA and Raman pump power are 100 mW. From Fig. 1 the gain of EDFA/Raman hybrid amplifier is higher at 1530 nm and less than of EDFA only at 1560 nm and equal to the gain of EDFA only at 1580 nm. The lower gain was obtained for Raman amplifier only over the signal wavelength.

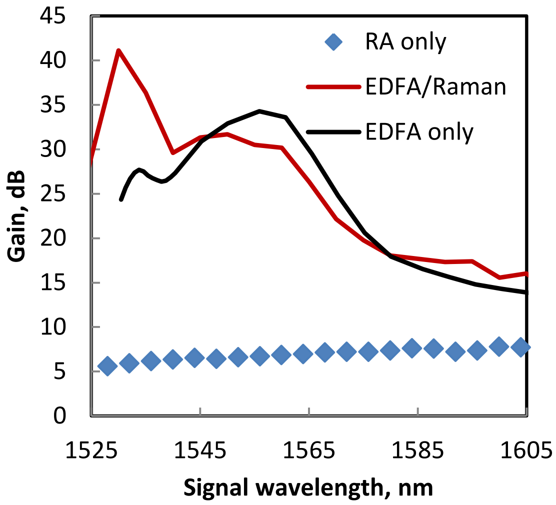

Fig. 1. Gain profile of the three amplifiers as a function of signal wavelength.

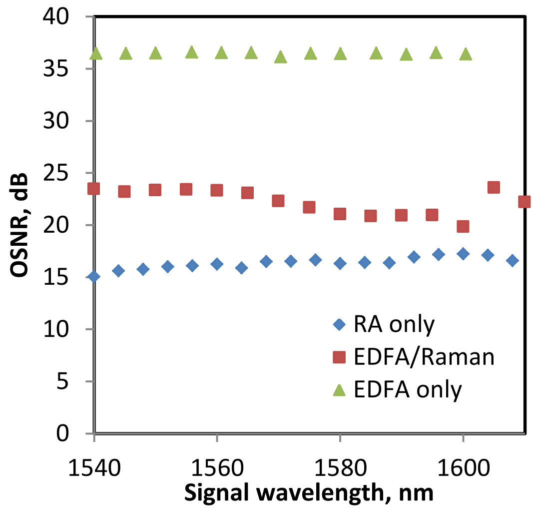

Fig. 3. Optical signal to noise ratio (OSNR) of the three amplifiers as a function of signal wavelength.

Fig. 2 shows the noise figure of the three amplifiers as a function of signal wavelength at the same input parameters of Fig. 1. The lower values of noise figure are obtained for EDFA/Raman and EDFA only and the higher values of noise figure was obtained for Raman amplifier only.

The optical signal to noise ratio (OSNR) is plotted against the signal wavelength for EDFA/Raman, EDFA and Raman amplifier at the same setting parameters of Fig. 1 in Fig. 3. The lower values of OSNR obtained for Raman amplifier only in the range of signal wavelength, which mean that the gain of Raman amplifier is low in comparison to EDFA/Raman hybrid amplifier and EDFA only.

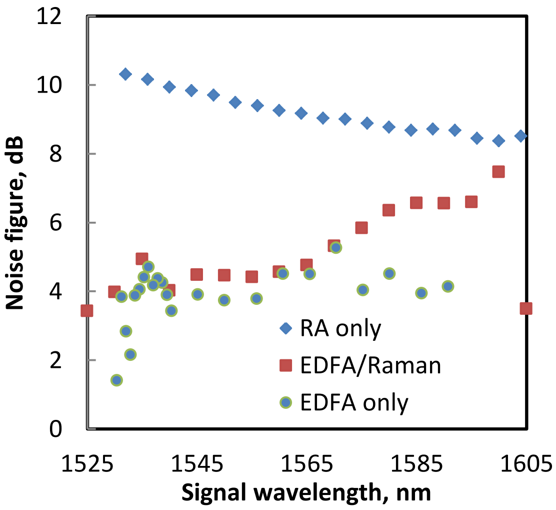

Fig. 2. Noise figure profile of the three amplifiers as a function of signal wavelength.

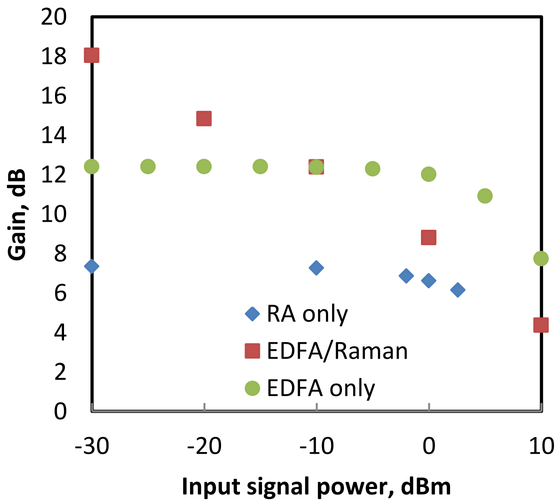

Fig. 4. Gain of the three amplifiers as a function of input signal power.

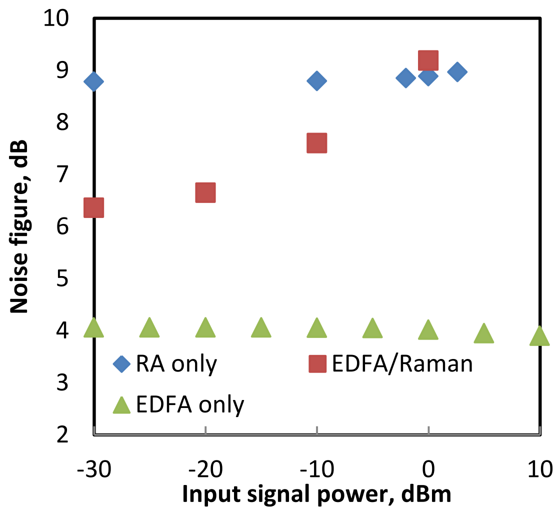

Fig. 5. Noise figure of the three amplifiers as a function of input signal power.

Fig. 4 shows the gain of the three amplifiers as a function of input signal power. The RA length is 20 km, EDFA length 15 m, the signal wavelength at 1580 nm and both EDFA and Raman pump power are 100 mW. From Fig. 4 the gain decreases as the input signal power decrease for the three types of the amplifier. At input signal -30 dBm, the gain of EDFA/Raman hybrid amplifier is 18 dB, 12.4 of EDFA only and 7.35 dB for Raman amplifier only. The flatness of the gain profile of EDFA/Raman hybrid amplifier is higher than of both EDFA only and Raman only.

Fig.5 shows the noise figure of the three amplifiers as a function of input signal power. The RA length is 20 km, EDFA length 15 m, the signal wavelength at 1580 nm and both EDFA and Raman pump power are 100 mW. The noise figure increases as the input signal power decrease for EDFA/Raman hybrid and nearly saturated for EDFA only and Raman only.

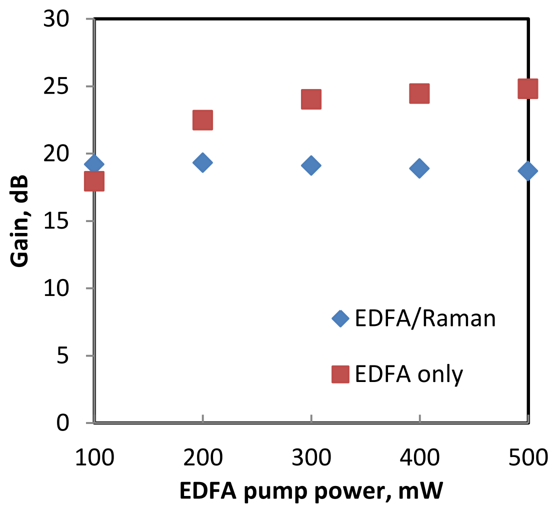

Fig. 6. Gain of EDFA/Raman HOA and EDFA only as a function of EDFA pump power.

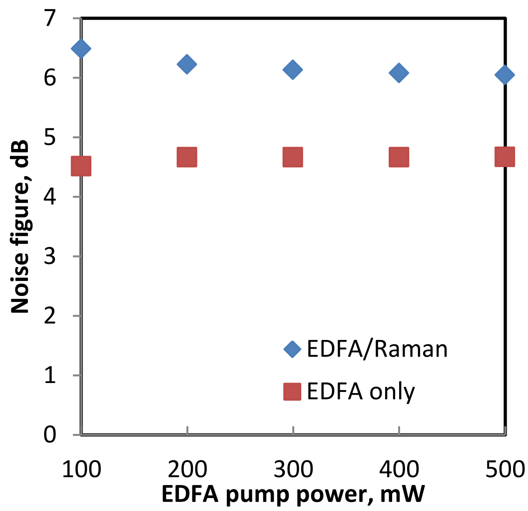

Fig. 7. Noise figure of EDFA/Raman HOA and EDFA only as a function of EDFA pump power.

The effect of EDFA pump power on the gain and noise figure of EDFA/Raman hybrid amplifier and EDFA only is illustrated in Fig. 6 and Fig. 7, for the case of EDFA/Raman hybrid amplifier, the Raman pump power is fixed to 100 mW. From the figures, the gain of EDFA/Raman hybrid amplifier is decreases with EDFA pump power increase and the values of the gain is less than EDFA only except at EDFA power 100 mW, the gain is higher than of EDFA only. Also the noise figure of EDFA/Raman hybrid amplifier is higher than of EDFA only.

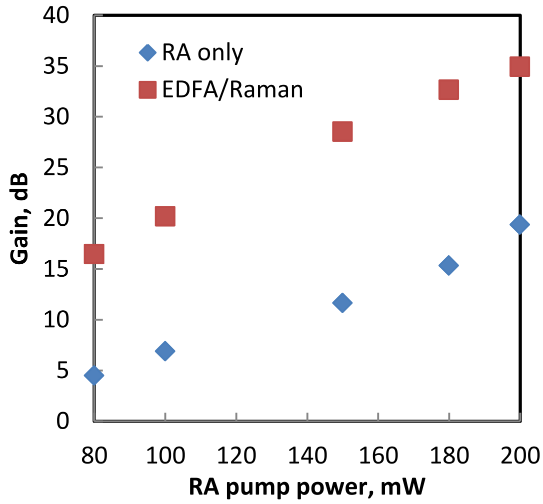

Fig. 8. Gain of EDFA/Raman HOA and RA only as a function of RA pump power.

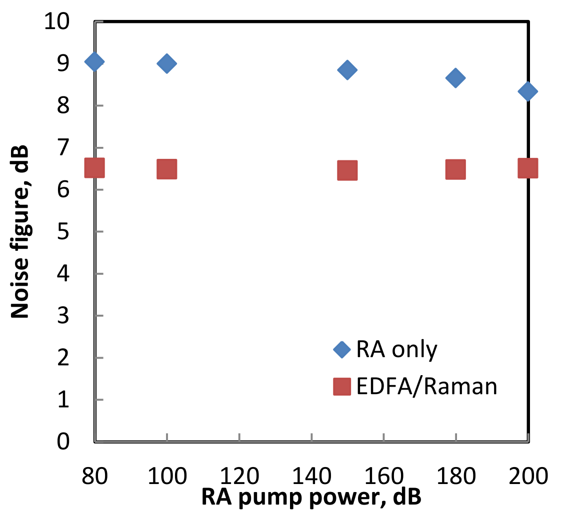

Fig. 9. Noise figure of EDFA/Raman HOA and RA only as a function of RA pump power.

The effect of Raman pump power on the gain and noise figure of EDFA/Raman hybrid amplifier and Raman only is illustrated in Fig. 8 and Fig. 9, for the case of EDFA/Raman hybrid amplifier, the EDFA pump power is fixed to 100 mW. From the figures, the gain of EDFA/Raman hybrid amplifier is increases with Raman pump power increase and the values of the gain is higher than Raman only and the noise figure of EDFA/Raman hybrid amplifier is lower than the noise of Raman only.

We can summarized the results discussed later in the given Tables.

Table 3. Gain and noise figure at 1530 nm.

Amplifier	Input signal (dBm)	Length (km)	Pump power (mW)	Gain (dB)	NF (dB)
EDFA/Raman	-30	(20, 0.015)	100, 100	41.1	3.9
EDFA only	-30	0.015	100	24.35	3.8
Raman only	-30	20	100	5.7	10.5

Table 4. Gain and noise figure at 1560 nm.

Amplifier	Input signal (dBm)	Length (km)	Pump power (mW)	Gain (dB)	NF (dB)
EDFA/Raman	-30	(20, 0.015)	100, 100	30.2	4.5
EDFA only	-30	0.015	100	33.6	4.5
Raman only	-30	20	100	6.83	9.3

Table 5. Gain and noise figure at 1580 nm.

Amplifier	Input signal (dBm)	Length (km)	Pump power (mW)	Gain (dB)	NF (dB)
EDFA/Raman	-30	(20, 0.015)	100, 100	18	6.35
EDFA only	-30	0.015	100	12.4	4.51
Raman only	-30	20	100	7.35	8.7

4. Conclusion

Our paper is a comparative study of the gain and noise figure for EDFA/Raman hybrid amplifier, EDFA and Raman amplifier was done. The parameters dependence of gain and noise figure of the three amplifiers was the pump power of both EDFA and Raman, the signal wavelength and the input signal power, the length of the three amplifier which is fixed to 20 km of Raman amplifier, 15 m of EDFA and (20 km, 15 m) of EDFA/Raman hybrid amplifier. In addition, the optical signal to noise ratio (OSNR) is calculated as a function of signal wavelength. The higher gain was 41.1 dB for EDFA/Raman hybrid amplifier at -30 dBm input signal power, 100 mW of both EDFA and Raman pump power and signal wavelength of 1530 nm and the lower noise figure was 3.8 dB for EDFA only at -30 dBm input signal power, 100 mWof EDFA pump power and signal wavelength of 1530nm. The lower values of OSNR obtained for Raman amplifier only at signal wavelength 1530 – 1600 nm with -30 dBm input signal power and 100 mW Raman pump power. The flatness of the gain profile of EDFA/Raman hybrid amplifier is higher than of both EDFA only and Raman only.

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