Characteristic Investigations of Raman/EDFA Hybrid Optical Amplifier in Multichannel Transmission System

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Abstract: In his paper, characteristics performance of Raman/EDFA hybrid fiber amplifier is investigated at 16 × 10 Gb/s in C band (1540-1552 nm) optical transmission system. The investigations are carried out in terms of hybrid gain, noise figure, gain ripple and noise figure tilt as function of Raman amplifier's length, input optical power per channel, total Raman pumping power and erbium doped fiber length. It has been reported that an average total gain 38 dB, noise figure 8 dB, gain ripple 2.6 dB and NF tilt 0.3 dB with 20 km Raman fiber length. Similarly, as the Raman length is increased 20 to 40 km, 1 dB higher total gain has been obtained with gain ripple and NF tilt deteriorate which effect the bandwidth of transmission system. Further, investigation of input optical power per channel indicate that –2 dBm optical power is suitable whereas at higher input power than it performance degradations. Moreover, it has been shown the 3 dB gain ripple and 0.32 dB NF tilt for all 12 nm gain bandwidth at 755 mW total Raman pumping power. Finally, EDFA's analysis indicate 5 m erbium doped fiber length is most suitable for the proposed hybrid fiber amplifier's set up.

Keyword: *Hybrid optical amplifier (HOA), Fiber Raman amplifier (FRA), Erbium doped fiber amplifier (EDFA), Total gain, Noise figure (NF), Gain ripple, NF tilt.*

I. INTRODUCTION

Recent developments in optical networks have enhanced their capacity with Wavelength Division Multiplexing (WDM) by large number of channels transmission at less spacing. This also led to need of improvement in bandwidth of single optical amplifiers to hybrid amplifiers (HA) which are combinations of different types of amplifiers. There are various classification of optical amplifiers such as: erbium doped fiber amplifier (EDFA), semiconductor optical amplifier (SOA) and fiber Raman amplifier (FRA) etc. which are employed in series, parallel, and series parallel hybrid configurations. In [1], Singh et. al. have reviewed and compared varius configuration of hygrid optical amplifiers in terms of gain bandwidth, gain, gain flatness, tansient efeect and cosstalk. They have reported more than 80 nm gain bandwidth of Raman-EDFA optical fiber hyrid amplifiers.

In [2], Kaler et. al., elaboarted performance evaluation of Raman- EDFA hybrid optical amplifier for long haul high cpacity links. They have achieved total link length 2070 km employing hybrid amplifier in comparison to 1794 km with EDFA single amplifier for acceptable perfmance in terms of BER and Q- factor. Ali et. al. in [3] have proposed various configurations of hybrid fiber amplifier (HFA) such as serial, parallel and combined serial-parallel. They have evaluated performance in terms of average gain level, average noise figure and flat gain bandwidth. Their results show that series–parallel configuation of hybrid amplifier exhibit a flat gain bandwidth of 65 nm, 16 dB average gain and 7 dB average noise figure. Similarly, Wason et. al. in [4] have demonstrated that Raman- EDFA configuration provides better results for the small distances up to 100 km as compared to EDFA-EDFA and SOA-EDFA configurations.

Similarly, in [5], Mohammed et. al. have analyzed design of Raman/EDFA hybrid fiber amplifer to amplifying 32 channels in L-band (1560-1600nm). They achieved overall gain ripple and noise figure tilt 38.52 ± 1.28 dB and 4.5 ± 0.7 dB respectively without using any flatting technique. However, while emplying a gain flatting technique Guassian filter between the Raman and EDFA amplifier total gain ripple improves to 38.46 ±0.55 dB. In [6] C. Kumar et. al., have proposed a Raman-Erbium doped silica fiber optical amplifier hybrid optical amplifier in super dense WDM system. They have obtained total gain 37.5 dB and noise figure of 5.4 dB. Similarly, In [7] N. Saidin et. al. have analyzed performance of multiple backward pumping Raman and bidirectional pumping EDFA hybrid amplifier configuration in terms of gain, noise figure, and gain flatness. They have varied input siganl power, pumping power and fiber length parameters of Raman to get the optimum result. Furthermore, EDFA peformance in terms of such as erbium ion density, input signal power, fiber length parametrs are varied to obtain the results.

In [8], Sharma et al., have obtained total gain 2.7 dB and noise figure 6.86 dB with optimized pump wavelength and power for EDFA/Raman hybrid amplifier. In [9], Singh et. al. have invesigated fiber Raman amplifier for gain, gain bandwidth and gain ripple with one, two and seven number of backward pump waves in WDM system. They have eloborated,, when number of pump waves increase one to seven, Raman gain bandwidth increse 45.3 to 97.6 nm whereas gain ripple improves from 0.82 to 0.47 dB. In [10], Gupta et. al. 2016, have designed a hybrid optical amplifier confihurations, Raman-EDFA, Raman-SOA, and EDFA-EDFA and r compared their performance in terms of Q-Factor and transmission distance. They have recommended, that Raman- EDFA hybrid amplifier shows better results as compared to other configurations. To conitinue it further, there is still need of investgations in gain flatness and noise figue tilt of Raman/EDFA fiber hybrid optical amplifers in WDM transmission systems.

To conitinue it further, there is still scope of gain flatness and noise figue tilt improvement of Raman/EDFA fiber hybrid optical amplifers in WDM transmission systems. In this paper we have evaluated performance of Raman/EDFA hybrid fiber optical inline amplifier configuration for 16 channels WDM optical transmission link. The characteristics parameters total gain, gain flatness, noise figure, noise figure tilt by varing Raman fiber length, input optical power launched in each channel, total Raman pumping power and erbuim doped fiber length. These parameteric investigated observations are compared with the literature.

The paper comprises fiver sections, its first section elaborate basic inroduction and literature survey, second section presents a theoretical model of hybrid fiber amplifier, third section describes a block diagram of system set-up. The set up investigations are elaborated in section four with various results and their discussions. In last section, conclusions are drawned and future scope is recommended.

II. THEORETICAL MODEL

Fiber Raman Amplifier (FRA) is based on principle of stimulated Raman scattering (SRS) a fiber nonlearity, according to which when a high intensity pump wave while propagating in the fiber with along a signal wave either in forward, backward or bidirectional get stroke shifted and amplify signal wave. This amplification ocurs efficiently when pump wave have the wavelength about 100 nm less than the propagating signals , typically a pump wave must be 1450 nm to amplify the signal wavelength at 1550 nm. This interaction between pump and signal wave propagating in a optical fiber can be described analytically by following FRA's coupled equations as in [11].

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

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

Where P_s is the signal wave, g_R is Raman gain coefficient, P_p is the pump wave, σ_p is the cross-sectional area, α_s and α_p are fiber loss at signal and pump frequencies (ω_s and ω_p) respectively. The Raman gain can be expresed as:

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

Where

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

The noise figure of Raman can be calculated:

$$NF\,(dB) = 10\, log_{10}\left[2\exp(-\alpha_s L) - \frac{1}{G}\right] (5)$$

erbium doped fiber amplifier's gain can be expressed as

$$G = \exp(-\alpha_s L) \times exp\left[\frac{h\upsilon_s}{P_{in}^s}\left(\frac{\left(P_p(0) - P_p(L)\right)}{h\upsilon_p} + \frac{P_s(0)}{h\upsilon_s}(G-1) + \frac{P_{ASE}^{+}(L)}{h\upsilon_s}\right)\right] 6)$$

The net noise figure of EDFA as:

$$NF_{EDFA} = \frac{1}{G_{EDFA}} + \frac{P_{ASE}^{0}(\lambda_s)}{h\upsilon_s} - \frac{P_{ASE}^{i}(\lambda_s)}{h\upsilon_s} \quad (7)$$

$$G_{total} = G_{Raman} + G_{EDFA} \quad (8)$$

The FRA model is applicable in WDM transmission scenario for multiple number of signal wave's amplification in the fiber with multiple pump waves.

III. SYSTEM SET-UP

Fiber Raman amplifier (FRA) amplifies optical signals by SRS effect with the suitable choice of pumping parameters such as pump wavelengths and their powers. Broad bandwidth of Raman amplifier can be achieved by employing multiple pump waves with their optimum choice of wavelength and power levels. It have been observed that a hybrid fiber Amplifier configuration increases gain bandwidth of WDM optical system with less gain and noise figure variations over the signal channels [9].

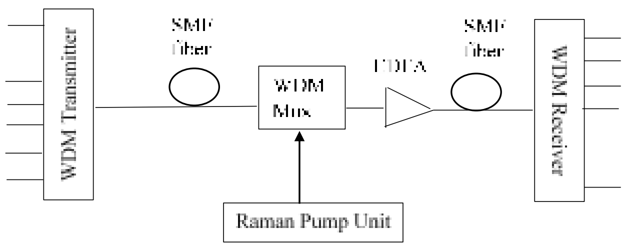

Fig. 1 Raman/EDFA hybrid fiber optical amplifier in 16 channel optical transmission system

Fig. 1 shows a proposed schematic diagram of Raman/EDFA hybrid fiber optical amplifier for 16 channel WDM optical transmission system. The optical transmitter consists of PRBS (pseudo random bit sequence) data sources which generate a NRZ (non-return to zero) pulses which are modulated externally by optical modulators on optical laser light. The channel waves are selected from ITU grid C band, in range of 1540 -1552 nm wavelength with 0.8 nm spacing. They are multiplexed by WDM ideal MUX with zero insertion loss. The multiplexed channels are launched into 20 km standard single mode fiber (SMF) with -10 dBm optical power per channel. The SMF fiber parameters are: core diameter 80 μm^2, attenuation effect 0.2 dB/km and dispersion 16 ps/km/nm. The channels are amplified by a hybrid optical amplifier consisting of backward multiple pumped fiber Raman amplifier and in series with it a bidirectional pumped EFDA. The amplified signals are further transmitted further on 40 km SMF down the fiber. At the optical receiver side 16 channel are de-multiplexed by ideal DEMUX and each is optically detected by PIN photodiode and further signal condition is carried out.

Table 1 Raman amplifier selected parameters

S No.	Parameter	Value	Backward Pumping Unit, (Pump wavelength and their power)		
1.	Raman gain peak	1×10^{-13} m/W	Pumping Parameters		
			No.	Wavelength (nm)	Power (mW
2.	Raman fiber length	25 km	1.	1442	200
3.	Core diameter	75 μm^2	2.	1445	175
4.	Attenuation	0.2 dB/km	3.	1450	195
5.	Dispersion	16.75 ps/km/nm	4.	1455	185
6.	Rayleigh Back scattering Coefficient	5×10^5 1/km	Total Pump Power		755

The Raman/EDFA hybrid optical amplifiers characteristic parameters are selected such that, to obtain a flat gain bandwidth over the transmitted signal band with minimum noise figure at each channel. Raman amplifier comprises of standard single mode fiber of 25 km length, core diameter 75 μm^2 and its other parameters are shown in Table 1. The Raman backward pumping module have four pump waves and their wavelength and power parameters are selected best suitable as in [9, 12]. To get a hybrid gain down the span EDFA amplifier is connected in tandem to FRA, as shown in Fig. 1. It consists of 5 m Er^{3+} doped fiber with core doping radius 2.2 μm^2. The numerical aperture is 0.24 and Er^{3+} ion density is 1×10^{25}. It is bidirectional pumped by 980 nm forward pump and 1480 nm backward pump waves each having power 100 mW. Table 2 shows selected parameters of EDFA amplifier.

Table 2. Raman amplifier selected parameters

S. No.	Parameter	Value
1.	EDF Fiber Length	5 m
2.	EDF fiber core radius	2.2 μm
3.	Er3+ core radius	2.2 μm
4.	EDFA forward and backward Pump Wavelength/Power (nm/mW)	980/100 1480 nm /100

IV. RESULTS AND DISCUSSION

The proposed hybrid amplifier's set up is numerically computed for total gain and noise figure by varying Raman amplifier fiber's length from 20 to 60 km for all channels. Fig. 2(a) shows plot of total gain at each transmitted channel wavelengths for versus the fiber length. It is observed, at higher transmitted wavelength channels in 1540 to 1552 nm range are amplified more compared to the lower channels. It have been observed that, total gain is decreasing (curves are shifting down) for fiber length from 20 to 60 km. As shown in Fig.2(a), at minimum 20 km fiber length we obtain 39.50 dB Raman gain peak with 2.75 dB gain ripple whereas at maximum fiber length 60 km the gain is 39 dB with 4.25 dB gain ripple. Clearly, as fiber length is varied 20 to 60 km total gain decreases and gain ripple deteriorates. These results are in agreement with [13].

Noise figure is also computed and plotted in fig. 2(b). It increases from 8 to 12 dB with Raman fibre length increase from 20 to 60 km. This effect occurs due to power attenuation, gain fluctuations and amplifier's ASE (amplified spontaneous emission) noise phenomenon dominant due to spontaneous Raman scattering. Further, total gain ripple (gain flatness) and noise figure tilt are important in long haul optical transmission links in which large number of cascading optical amplifiers are employed. Consequently, Fig. 2 (c) present gain ripple and NF tilt parameters by varying FRA length from 20 to 100 km. It has been observed, gain ripple and NF tilt parameters degrade 2.2 to 4.25 dB and 0.20 to 0.43 dB respectively with fiber length 20 to 60 km and beyond 60 to 100 km length, gain ripple shows an improvement of 0.45 dB.

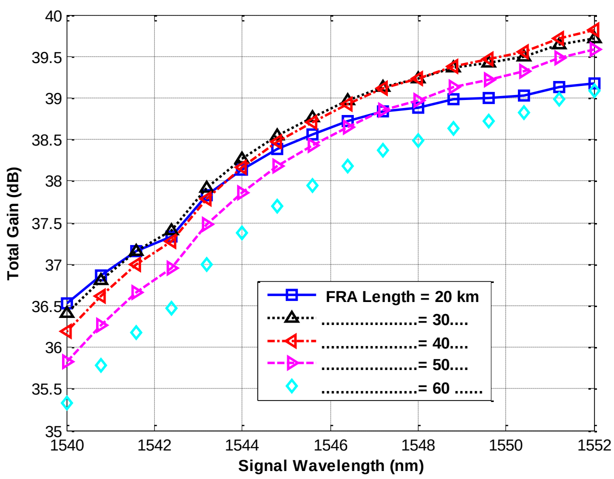

Fig. 2. (a) Total gain versus FRA length.

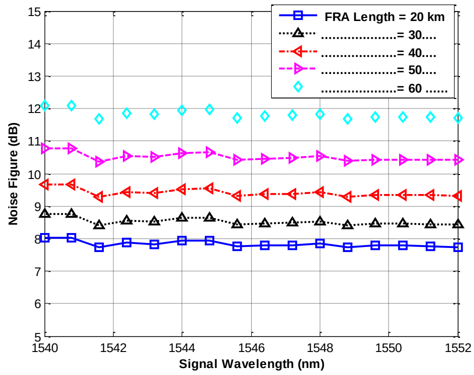

Fig.2. (b) Noise figure versus FRA length.

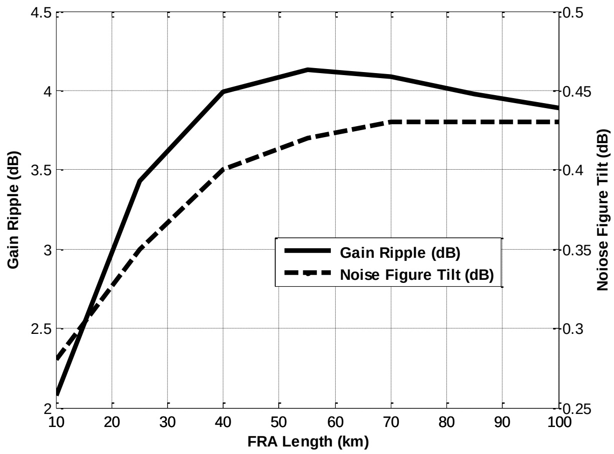

Fig. 2. (c) Gain ripple & NF tilt versus FRA length.

Mahran et. al. in [14], have studied performance of WDM system with input optical power in terms of gain and noise figure of hybrid optical amplifier because at higher power levels in the fiber, nonlinear effects start dominating. Apparently, in the our proposed set up, we have changed input optical power per channel in a range of -10 to 10 dBm observed the resulting total gain, noise figure, gain ripple and noise figure tilt as shown in Fig. 3(a)-(b)-(c) respectively. It is evident from these results, as input power increases in the indicated range the total gain decreases from 35 to 20 dB whereas noise figure deteriorates from 8.4 to 8.1 dB. Moreover, these plots show that within the transmission band from 1540 to 1552 nm total gain improve and NF deteriorates. These changes are elaborated as gain ripple and NF tilt in Fig. 3(c) which show that as input optical power level increase in the investigating range, gain ripple and NF tilt deteriorate 4.1 to 5.4 dB and 0.4 to 0.6 dB respectively. This deterioration is due to pump to pump, pump to signal and signal and signal interactions at high power levels. Analysis these of these interactions are not considered in this work. Further, it is illustrated that, maximum optical power – 2 dBm, is suitable value for the lower interaction effects.

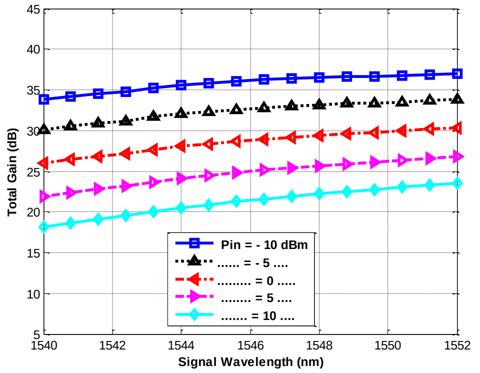

Fig. 3. (a) Total gain versus input optical power.s

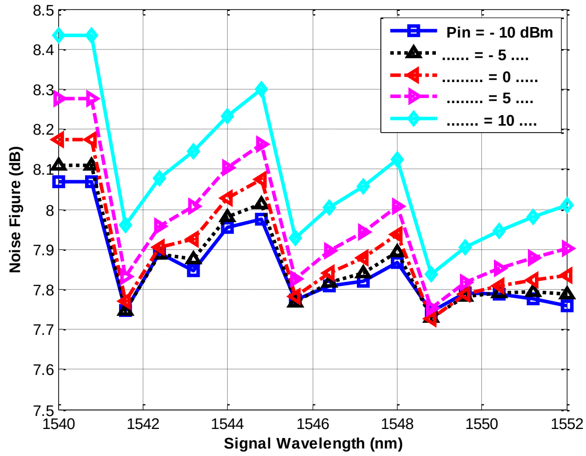

Fig.3. (b) Noise figure versus input optical power.

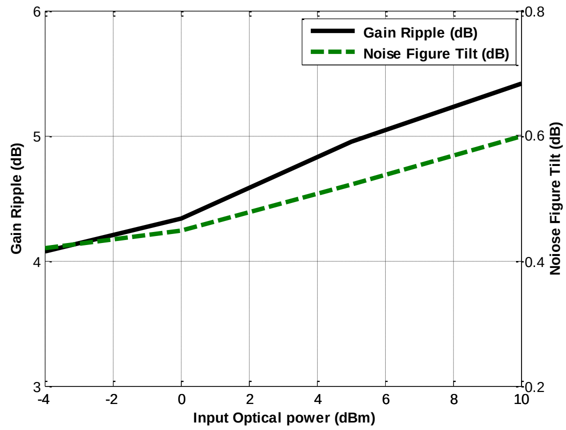

Fig. 3. (c) Gain ripple and NF tilt versus input optical power.

Table 3 Raman amplifier Gain and NF with Raman Total Pump Power (mW)

Four Pump Waves and their wavelengths		**Case No. 1**	**2**	**3**	**4**	**5**
Pump Wave No.	Pump Wavelength (nm)	Pump Powers (mW)				
1.	1442	105	130	155	200	225
2.	1445	110	135	160	175	200
3.	1450	125	150	175	195	220
4.	1455	115	140	165	185	210
Total Pump Power		455	555	655	755	855

Similarly, the proposed system is also evaluated for the total backward pumping power of distributed fiber Raman amplifier. Fig. 4 (a) – (b) show when total pumping power is increased from 455 to 855 mW, the total gain increases whereas noise figure decreases as shown from the selected eight signal channels. Moreover, has been observed that, within the 1540 to 1552 nm band higher wavelength channels are amplified more (Higher total gain) compared to lower wavelength channels. However, noise figure has been improved in the channel wavelength range. This phenomenon is due to Raman amplifier gain gets saturated at higher pump power levels. Fig. 4 (c) show that, gain ripple and NF tilt deteriorate from 2 to 3.5 dB and from 0.30 to 0.36 dB respectively with increase of total Raman pump power. Raman amplifier pumping power is changed as shown Table 3. Show the five cases of individual pump powers within the total Raman pumping power unit.

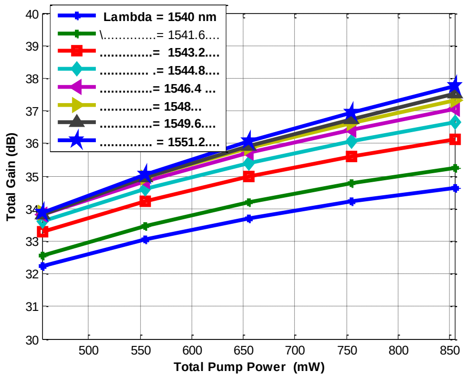

Fig. 4. (a) Total gain versus total Raman pump power.

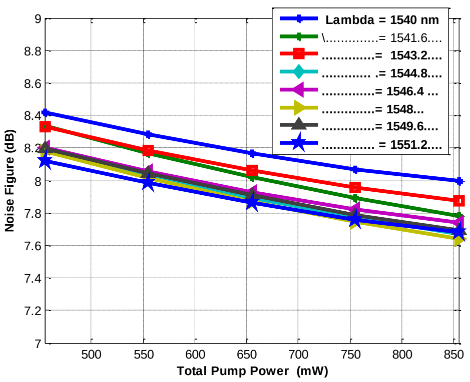

Fig.4. (b) Noise figure versus total Raman pump power.

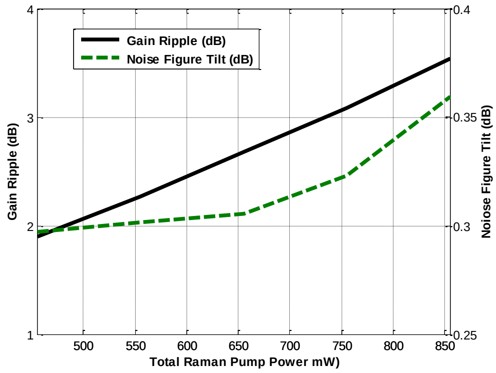

Fig.4(c) Gain ripple and NF tilt versus total Raman pump power.

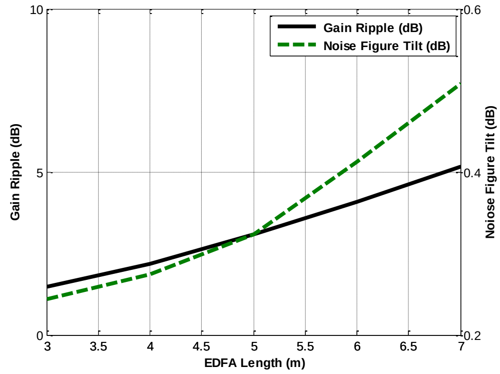

Fig. 5 Gain ripple and NF tilt versus EDF length.

Fig. 5 show that, gain ripple and NF tilt increase from 2 to 5 dB and from 0.3 to 0.5 dB respectively with EDF length increase from 3 to 7 m. It is clear that 3 m length of EDFA is optimal selected value to control gain ripple and NF tilt high values. Furthermore, performance of hybrid fiber amplifier can be explored with advance pumping schemes. It have been elaborated in [15-17], fiber Raman amplifier with higher order pumping scenario, gain profile characteristics improvements with considerable noise effect. Similarly, as in [18], EDFA/Raman hybrid fiber amplifier configuration have evaluated for gain profile parameter with minimum gain ripple employing recycling residual pumping.

V. CONCLUSION

It is concluded that, the proposed Raman/EDFA hybrid fiber amplifier presents the average total gain 38 dB gain, noise figure 8 dB, gain ripple 2.6 dB and NF tilt of 0.3 dB at minimum 20 km FRA length. However, when the fiber length is increased longer than 20 km the total gain increases but gain ripple and NF tilt parameters deteriorate which affect the gain bandwidth performance of the transmission system. Similarly, –2 dBm optical power level in each channel is observed most suitable, because it results the acceptable performance metrics. Further, as shown in results, total Raman backward pumping power of 755 mW is optimum power level in all four pump waves [Case4, Table 3] which generates 3 dB gain ripple, 0.32 dB NF tilt and maximum 12 nm gain bandwidth. Furthermore, it have been observed, that EDFA's erbium fiber length of 5 m value, give a suitable performance characteristics. Future scope of the work is, it can be extended for high capacity transmission systems with the Raman/EDFA hybrid fiber amplifier employing advanced Raman pumping schemes with their noise analysis.

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