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Performance Analysis of Hybrid Optical Amplifier in C and L Band over EDFA and RFA

Soniya N. Padwal[1] and Manisha Chattopaddhyay[2]
Electronics and Telecommunication Department
Vivekanand Education Society's Institute of Technology
Mumbai , India

Abstract— **The authors consider hybrid amplifiers consisting of a distributed Raman fibre amplifier (RFA) and Erbium Doped Fiber Amplifier(EDFA) using only one pump laser. The pump and signal beams co-propagate in the forward-pumping configuration. We have analyzed the performance of EDFA and Raman Amplifier in C and L band. In this paper we have concluded that best results are obtained using the Hybrid amplifier, i.e. EDFA in C-band and Raman in L-Band. The gain spectra of C+L band are flattened by optimally dividing the pump power ratio of 1:29 for EDFA/RFA. In this paper we determined the average gain for hybrid amplifier is 50.5dB with the flatness of ±1.5dB over the bandwidth of more than 100nm.**

***Index Terms*-- EDFA, Gain, Hybrid amplifier, Noise Figure, Pump Power, Raman fiber amplifier.**

I. Introduction

The growing demand for higher transmission capacity in wavelength division multiplexing(WDM) systems causes need for upgrading channel speed, number of channels and spectral efficiency [1]. To overcome these problems hybrid amplifiers are playing an important role. The characterization of the Raman+EDFA hybrid amplifier has been performed in terms of global gain, ripple, and noise figure.

In this paper we have investigated a hybrid C+L band EDFA and RFA by sharing common 1480 nm pump source. EDFA is suitable to operate at the conventional (C) band from about 1530 to 1565 nm [2] since the entire C band of EDFA is fully utilized. EDFA has a lower gain in the L-band and larger noise figure (NF) than in C-band. To extend the optical bandwidth and increase the number of WDM channels, L-band optical amplifiers are used [3]. The long (L) band optical amplifiers are used to operate in longer wavelength from about 1565 to 1625 nm. The disadvantage of L band EDFA can be overcome using L band RFA. The overall performance, in C and L band, can be enhanced by using both EDFA and RFA in hybrid configuration. In this paper we analyzed the best results of hybrid amplifier compared with the results of individual amplifier.

II. Erbium Doped Fiber Amplifier

An EDFA is a doped fiber amplifier, functional in the C band and the dopant used is Erbium ions. In EDFA the core of a silica fiber is doped with trivalent Erbium ions and can be efficiently pumped with a laser at a wavelength of 980 nm or 1480 nm, and exhibits gain in the 1550 nm region [4], [5]. In principle, a doped fiber amplifiers such as EDFA depicts three energy levels.

A. *EDFA Amplification*

Amplification is achieved by stimulated emission of photons from dopant ions in the doped fiber. A relatively high-powered beam of light is mixed with the input signal using a wavelength selective coupler. At the signal wavelength, the pump laser excites ions into a higher energy from where they can decay via stimulated emission of a photon back to a lower energy level. The excited ions can also decay spontaneously (spontaneous emission) or even through nonradiative processes. The erbium atoms give up some of their energy to the signal and return to their lower-energy state. A significant point is that the erbium gives up its energy in the form of additional photons which are exactly in the same phase and direction as the signal being amplified [6]. So the signal is amplified along its direction of travel only.

B. *Equations of EDFA*

The gain of EDFA is given as [3],[7]:

$$G_{EDFA} = \frac{\sigma . n_t . (W_p - \Gamma)}{2 . \sigma \, c . p + \Gamma + W_p} \quad (1)$$

Where σ, c, Γ, n_t, and p are the cross section for induced emission, velocity of light, reciprocal of lifetime of charge carrier, total population density of Er ions and photon density respectively. Wp is the pump rate of particles which is the product of the probability that a particle passes from state 1 to state 3 and the transition from 3 to 2 in three level system. Amplification occurs only when the pump rate is larger than the rate of spontaneous emission. This is achievable when the life time τ_s is very large.

Noise figure (NF) of EDFA is defined as in [5]:

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$$NF = \frac{P_{ASE}}{h.\nu.\Delta\nu.G} + \frac{1}{G} \qquad (2)$$

Where G is the EDFA gain, h is the Planck's constant, ν is the frequency of light, $\Delta\nu$ is the bandwidth and P_{ASE} is the amplified spontaneous emission power. The noise figure (NF) can be very simply written in terms of amplified spontaneous emission power (P_{ASE}) exiting the fiber in a bandwidth $\Delta\nu$. Since the noise power is given by [5],

$$P_{ASE} = 2n_{sp}.h.\nu h.\nu .(G-1)$$

Where n_{sp} is the inversion factor which depends on the energy levels of erbium ions.

C. *Results of EDFA in C-band*

Fig. 1 and Fig. 2 show the gain and NF Vs. wavelength of EDFA for different values of pump powers, P_p= 10mW, 11 mW, 12mW and 13mW. We find the optimized gain at

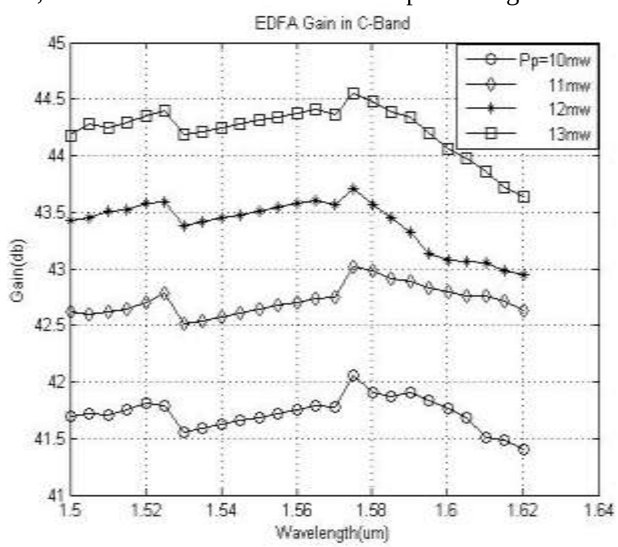

Figure 1. C-band EDFA Gain versus Wavelength

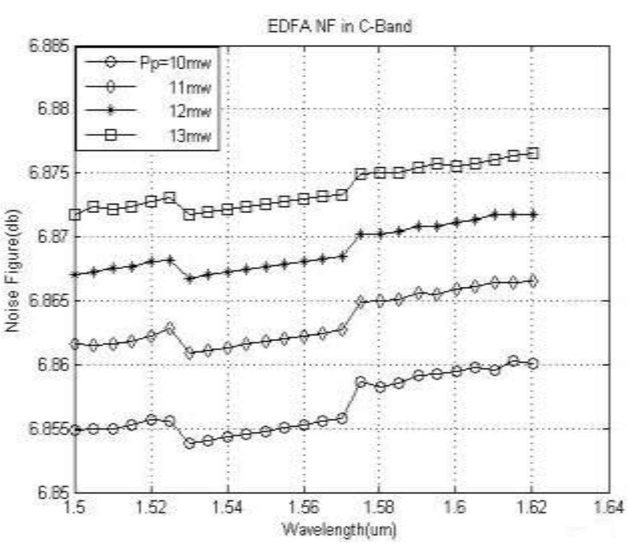

Figure 2. C-band EDFA Noise Figure versus Wavelength

1560nm is 44.4dB and the NF is 6.873dB, for the pump power 13mW (11.14dBm) and the signal power 1μW (-30dBm). As per the analysis we find the gain in C-band, from 1530 to 1570nm, is in the range of 44.2 to 44.5dB, i.e. the average gain is 44.35dB with a flatness of ±0.15dB over the bandwidth of 40nm by using 1480nm pump laser. Beyond this wavelength, in L band, the gain starts to decrease and the NF starts to increase, due to low gain efficiency [8]. According to our results, the gain and NF were obtained as functions of or were strongly dependent on the pumping power, signal input power and erbium ion density.

III. RAMAN FIBER AMPLIFIER

Unlike in EDFA, in RFA an amplification effect is achieved by a nonlinear interaction between the signal and a pump laser within an optical fiber. A distributed Raman amplifier is one in which the transmission fiber is utilized as the gain medium by multiplexing a pump wavelength with signal wavelength. Stimulated Raman scattering (SRS) is a type of inelastic scattering that results in broadband amplification of optical channels [9]. The amplifiers resulting from this effect are called *Raman amplifiers* and have a distinct feature of amplification in a large waveband.

A. *Raman Amplification*

During Raman scattering, light incident on a medium is converted to a lower frequency. A pump photon, excites a molecule up to a virtual level (nonresonant state). The molecule quickly decays to a lower energy level emitting a signal photon in the process. The difference in energy between the pump and signal photons is dissipated by the molecular vibrations of the host material. These vibrational levels determine the frequency shift and shape of the Raman gain curve. For high enough pump powers, the scattered light can grow rapidly with most of the pump energy converted into scattered light. This process is called SRS, and it is the gain mechanism in Raman amplification [10].

B. *Equations of RFA*

One of the most important parameters for Raman amplification in any applications is the Raman effective gain coefficient [11]. It depends not only on the Raman gain coefficients (g_R) itself but also on the effective area of the fiber (A_{eff}). Thus gain of RFA (G_R) is given by [12],

$$G_R = \exp\left(\frac{g_R P_0 L_{eff}}{A_{eff}}\right) \qquad (3)$$

Where P_0 is the input pump power at L = 0 and L_{eff} is an effective length of optical fiber. The noise figure may be simply estimated by measuring the Raman gain G_R and the amplified spontaneous emission power, P_{ASE} [13]. Thus the NF is expressed as:

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$$NF = \frac{1}{G_R} + \frac{2P_{ASE}}{G_R h\nu B_0} \quad (4)$$

Where h=Planck's constant, ν = frequency of light and B_0 = bandwidth of the optical filter. Spontaneous Raman scattering adds to the amplified signal and appears as a noise because of random phases associated with all spontaneously generated photons. However, when the loss rates at the pump, α_p and signal, α_s are equal ($\alpha = \alpha_s = \alpha_p$), the ASE noise power will be evaluated analytically as [10], [14],

$$P_{ASE} = h\nu B_0 \eta_T \{G_R - 1 + \frac{G_R \alpha}{g_R P_p}(\exp(\alpha L) - \frac{1}{G_R})\}$$

where η_T is thermal equilibrium photon number.

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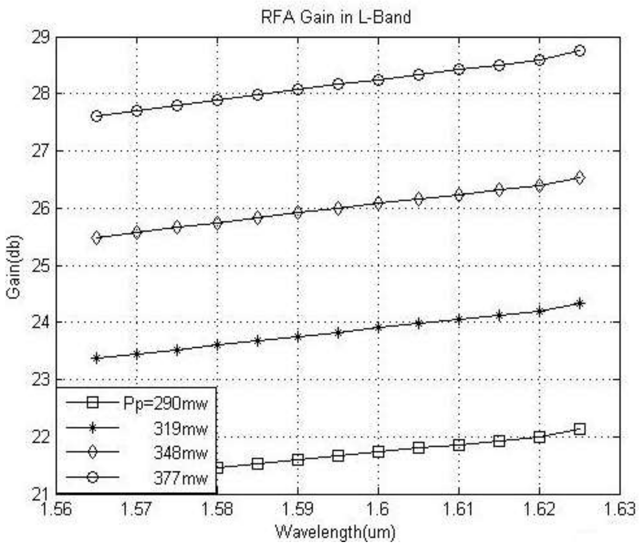

Figure 3. L-band RFA Gain versus Wavelength

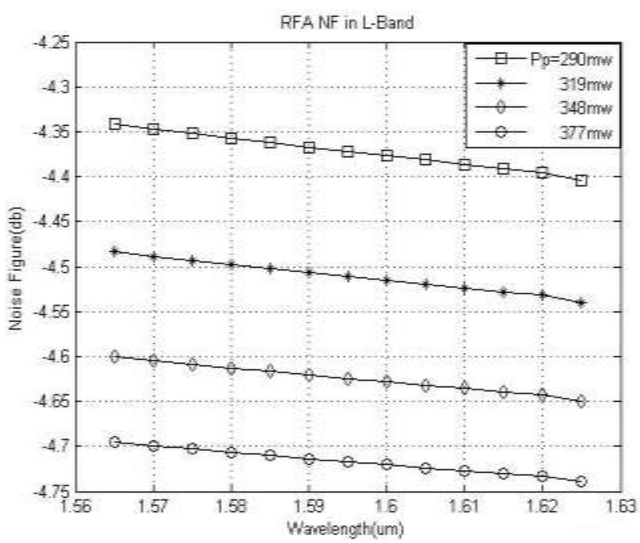

Figure 4. L-band RFA Noise Figure versus Wavelength

C. Results of RFA in L-band

We find the optimum gain at 1625nm is 28.9dB (Fig. 3) and the NF is -4.74 dB(Fig. 4), for the pump power 377mW. As per the analysis the average gain in RFA is 28.35 dB with a flatness of ±0.55dB over the bandwidth of 60 nm, using 1480nm pump laser in L-band. For the L band RFA we find the optimized gain is in the range of 27.8 dB to 28.6 dB, and the noise figure is below -4.7 dB for the pump power Pp=377mW(27.76dBm). Hence from the results the gain of RFA is very stable or flattened.

IV. Hybrid Amplifier

One of the effective ways to extend the gain bandwidth of the optical amplifiers is to use a hybrid amplifier that combines several amplifiers with different gain bandwidths. Connecting two or more different amplifiers in parallel or in series are some of the methods used to achieve a wide-band amplifier. The configuration of the hybrid amplifier proposed in this paper considers a EDFA connected parallel with a distributed Raman amplifier.

A. Hybrid Amplification

The low noise, broad bandwidth of Raman, and low pump power requirements of EDFAs can be combined into one hybrid amplifier to solve amplification issues in long-haul and ultra long-haul networks. Raman amplifiers provide a gain across a large bandwidth, even though the gain provided might not be high. In contrast, EDFAs provide a substantial gain but across a relatively small band. By using both forms in tandem providing one Raman and one or more EDFAs (depending on the bandwidth to be amplified) the amplification achieved is much better and cleaner than individual configuration [9].

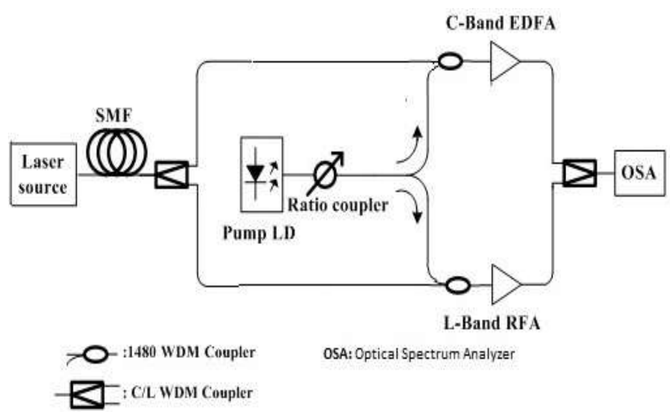

Figure 5. The proposed Hybrid C+L band EDFA/RFA to share the same pump.

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B. Configuration of the Hybrid Amplifier

Fig. 5. shows the concept of using only one pumping laser for simultaneous C-EDFA and L-RFA amplifications using forward pumping configuration. With only a pump wavelength of 1480 nm, the C-band EDFA is based on three-level amplification mechanism in erbium ions, while the L-band RFA is based on Raman shift amplification mechanism. At the input of the optical amplifier, a C/L-band WDM coupler is used to separate the WDM signals to C and L bands. The C-band signals are amplified by an EDFA and the L-band signals are amplified by a RFA. They share the same pump source, 1480 nm, which is splitted by a variable-ratio coupler to equalize the gain of C and L bands. The splitting ratio of the pump laser between the C-band EDFA and L-band RFA is optimized based on their gain characteristics such as physical properties of EDF and dispersion compensation fiber (DCF), as well as the pumping efficiency [2]. In order to provide a polarization-diversified pump, the polarization beam combiner (PBC) can combine two pump diodes with the same wavelength in an orthogonal polarization state. The gain spectra of C+L band are flattened by optimally dividing the pump power ratio of 1:29 for EDFA/RFA [2].

V. PERFORMANCE OF THE HYBRID AMPLIFIER IN C AND L BAND

Fig. 6 shows the measured overall gain spectra for the hybrid C+L band EDFA/RFA under various pump splitting ratios. If the insertion loss of PBC is neglectable, the pump power is divided into 13 mW for the C-band EDFA and 377 mW for the L-band RFA, that corresponds to a pump power shared ratio of 1:29.

Fig. 6 and Fig. 7 show the gain and NF Vs. wavelength of hybrid amplifier for different values of pump powers, P_p= 10mW-290mW, 11mW-319mW, 12mW-348mW and 13mW-377mW. The gain profiles for different pump powers of hybrid amplifier are better than the gain profiles of individual EDFA or RFA. We find the gain in C band is in the range of 49.5dB to 50dB and noise figure is below -5.06dB while in case of L band the gain is in the range of 50dB to 52.2dB and NF is below -5.07dB. Hence hybrid amplifier gives a wide gain bandwidth of about 135nm and more flat gain profile.

In this study, Hybrid optical amplifier (EDFA + RFA) has been optimized. It is shown that when the optimized parameters such as NF, pump wavelength, pump power, signal input power, erbium ion density, Raman fiber length, Raman effective gain coefficient etc. are used then the lesser noise is induced and better quality of the signal is produced.

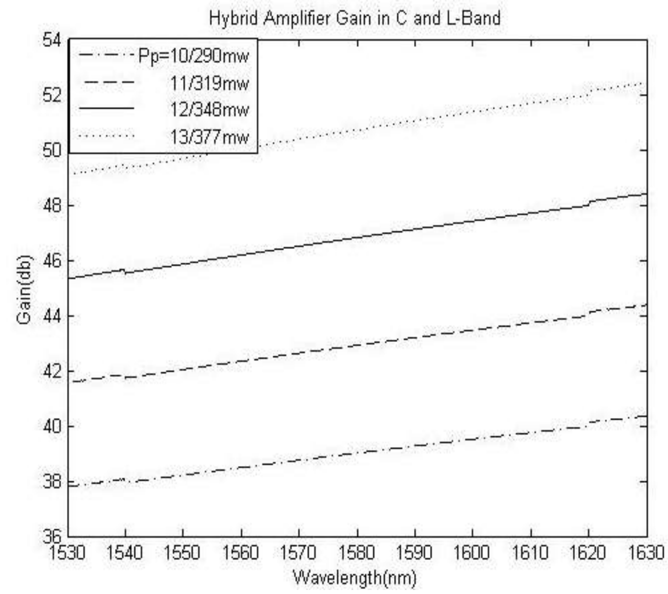

Figure 6. Hybrid Amplifier Gain versus Wavelength

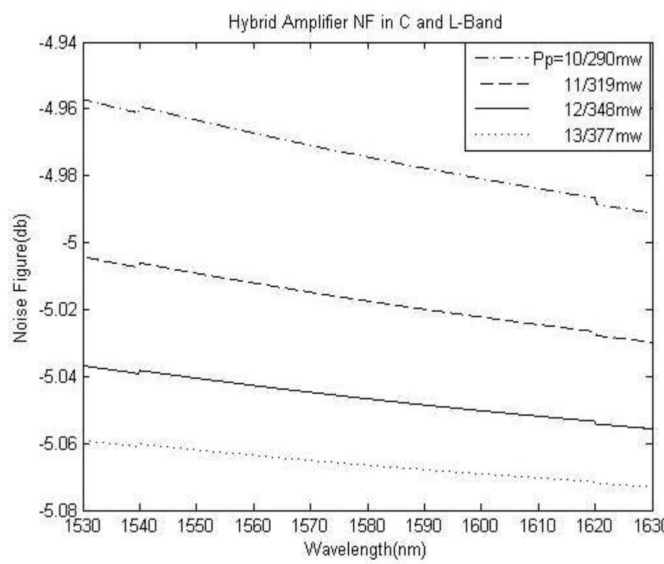

Figure 7. Hybrid Amplifier Noise Figure versus Wavelength

VI. CONCLUSION

Our study examined the characteristics of the RFA and EDFA in order to achieve the optimum design for hybrid optical amplifiers. Hybrid amplification is an effective technique for optical regeneration; it has a low NF as compared to individual fiber amplifiers. The gain profile is also much flatter, so they are able to accommodate more channels. The hybrid C+L band EDFA/RFA, with features of wide bandwidth, flattened gain and low NF, may find vast applications in WDM system and light wave transmission [2]. Therefore, this study establishes that the use of optimized optical amplifiers in the optical communication networks results in revolutionary growth of

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internet traffic for large number of users and long transmission distance.

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