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RAMAN amplifier gain dynamics with ASE : Numerical analysis and simulation approach

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Abstract

Spontaneous Raman scattering add up with the amplified signal and reflect as a noise because of random phases linked with all spontaneously generated photons. The amplified spontaneous emission noise in systems with distributed Raman gain for single pump amplification is diagnosed numerically and simulated using MATLAB to obtain experimental outcome. The signal gain of Raman Amplifier as a function of fiber length and pump power is elaborated. The noise accompanying an optically amplified signal plays an important role for understanding the basic properties of the gain medium. So in this work, we demonstrate an analytical formalism and a numerical horizon of the amplified spontaneous emission (ASE) noise power for distributed Raman amplifier (DRA).

Keywords: Amplified spontaneous emission (ASE), optical noise, Raman amplification

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1. Introduction

Nonlinear effects within optical fiber provide optical amplification, this achieved by stimulated Raman scattering, stimulated Brillion scattering or stimulated four photon mixing by injecting a high power laser beam into undoped or doped optical fiber. Raman amplification hold the advantage of self phase matching between the pump and signal along with a broad gain-bandwidth or high speed response in comparison with the other nonlinear processes (Parekhan *et al*, 2009).An alternative approach to loss management for wavelength division multiplexed (WDM) optical communication systems is the optical amplifiers, that amplify the optical signal directly without requiring its conversion to the electric domain. Optical amplifiers are indispensable optical components to compensate for fiber loss in long-haul transmission system(Agarwal,2002).Several kinds of optical amplifiers were developed during the 1980s, and the usage of optical amplifiers in long-haul lightwave systems became widespread during the 1990s (Agarwal,2005). .

Raman fiber amplifier (RFA) has merit of arbitrary gain bandwidth, which were recently being recognized as an enabling technology for high capacity and long-haul density wavelength-division- multiplexing (DWDM) systems. It can be used to amplify not only the C-band, but also the S, L and other bands, depending on the usage of the pumped wavelengths (Liaw *et al*, 2006).RFA has several advantages including lower noise figure (NF), flexibility on the selection of gain medium, and wide gain bandwidth (Taylor *et al*, 2002), especially that RFA has the capability to “distribute” the gain over a long distance in the transmission fiber. The difference between maximum and minimum intensity in a span can be reduced without reducing the span length, avoiding problems of noise and nonlinearity. Distributed fiber Raman amplification entails creating a gain medium within the transmission fiber which amplifies the signal channel before they reach the optical receiver. This has been proved over time to improve greatly the signal-spontaneous beat noise performance allowing longer transmission distances (Agarwal, 2005).

Raman amplification using the transmission fiber as the gain medium is a promising technology for the optical long haul DWDM communication system. It require more pump power due to which more amplified spontaneous emission (ASE) noise and other noises generated in the amplifier, also the input signal power to the amplifier is decreased. Lower signal power implies that the

ASE noise is competing with the signal for achieving gain. So ASE plays an important role in degradation of desired output at the receiver. The variation of gain as a function of signal power at different pump configurations and fiber length were studied since the important parameters representing discrete Raman amplifiers is input power level of the signal (Agarwal, 2005).

2. Mathematical Modeling

It has been assumed that field-mode profile is nearly the same for both the pump and the Stokes. With mode profile as a Gaussian function, the coupled pump and Stokes equations are solved for predicting the performance of Raman amplifiers. The most important parameter characterizing Raman amplifiers is the Raman gain coefficient (g_R), related to the cross section of spontaneous Raman scattering (Bromage *et al*,2003).It describes how the Stokes power grows as pump power is transferred to it through SRS. Consider the simplest situation in which a single CW pump beam is launched into an optical fiber used to amplify a CW signal. The signal gain of RAMAN amplifier with and without ASE is calculated.

2.1 Gain without ASE

The power evolutions of signal and pump waves along an optical fiber for forward pumping including losses can be described using following coupled equations

$$\frac{dP_s}{dz} = -\alpha_s P_s + \frac{g_R}{A_{eff}} P_p P_s \tag{1}$$

$$\frac{dP_p}{dz} = -\alpha_p P_p + \frac{g_R}{A_{eff}} \cdot \frac{\omega_p}{\omega_s} P_p P_s \tag{2}$$

where *Ps* and *Pp* are the signal and pump powers, respectively, g_R is the Raman gain efficiency for the wavelengths of the signal and pump, ω_s and ω_p are the frequencies of signal and pump waves, respectively, and α_s and α_p are the attenuation coefficients of the optical fiber at the signal and pump wavelengths, respectively. A_{eff} is the fiber effective area. For $g_R = 0$ the pump equation can be written as

$$\frac{1}{P_p} dP_p = -\alpha_p dz$$

Integrating with respect to z over the limits 0 to L.

$$\log P_p(L) - \log P_p(0) = -\alpha_p L$$

$$P_p(L) = P_p(0) \exp(-\alpha_p L) \tag{3}$$

Similarly using equation (1)

$$P_s(L) = P_s(0) \exp(-\alpha_s L) \tag{4}$$

Using equation (3) in equation (1) for analytical solution and rewriting, we get

$$\frac{1}{P_s} dP_s = \left[-\alpha_s + \frac{g_R \mu_p(0)}{A_{eff}} \exp(-\alpha_p Z) \right] dz$$

Integrating with respect to z over the limits 0 to L.

$$\log \frac{P_s(L)}{P_s(0)} = -\alpha_s L + \frac{g_R P_p(0)}{A_{eff}} \left\{ \frac{1 - \exp(-\alpha_p L)}{\alpha_p} \right\}$$

$$P_s(L) = P_s(0) \exp\left(-\alpha_s L + \frac{g_R \mu_p(0) L_{eff}}{A_{eff}} \right)$$

Where effective amplifier length $\left(L_{eff}\right)$ is defined as

$$L_{eff} = \frac{1 - \exp(-\alpha_p L)}{\alpha_p} \tag{5}$$

So the net signal gain of the Raman Amplifier in dB can be described as

$$G_s = \frac{P_s(L)}{P_s(0)} = \left(\frac{10}{2.3025} \right) \cdot \left(-\alpha_s L + \frac{g_R P_p(0) L_{eff}}{A_{eff}} \right) \tag{6}$$

The quantity *Gs* represents the net signal gain and can be even<1 (net loss) if the Raman gain is not sufficient to overcome fiber losses. So the On–Off Raman gain is defined as

$$G_A = \frac{P_s(L) \text{ with pump on}}{P_s(0) \text{ with pump off } (g_R = 0)}$$

$$G_A = \frac{P_s(0)\exp\left(-\alpha_s L + \dfrac{g_R P_p(0) L_{eff}}{A_{eff}}\right)}{P_s(0)\exp\left(-\alpha_s L\right)}$$

$$G_A = \exp\left(\frac{g_R P_p(0) L_{eff}}{A_{eff}}\right) \tag{7}$$

$$G_A \approx \exp(g_0 L) \tag{8}$$

with

$$g_0 = \left(\frac{g_R \mu_p(0) L_{eff}}{A_{eff} L}\right) \tag{9}$$

where *L* is the physical length of the optical fiber and *P_s(L)* with pump on is assumed to be the amplified signal power without the amplified spontaneous emission (ASE) and thermal noise. Using equation (5)

$$g_0 \approx \left(\frac{g_R \mu_p(0)}{A_{eff} L_{\alpha_p}}\right) \tag{10}$$

2.2 Gain with ASE

Noise in Raman amplifiers stems from spontaneous Raman scattering. It can be included in Equation (1) by replacing P_s in the last term with $P_s + P_{sp}$, where $P_{sp} = 2 n_{sp} h \upsilon_s \Delta V_R$ is the total spontaneous Raman power over the entire Raman-gain bandwidth. The factor of 2 accounts for the two polarization directions.

$$\frac{dP_s}{dz} = -\alpha_s P_s + \frac{g_R}{A_{eff}} P_p (P_s + P_{sp}) \tag{11}$$

$$P_{sp} = 2 n_{sp} h \upsilon_s \Delta V_R \tag{12}$$

$$n_{sp} = \frac{1}{1 - \exp\left(\dfrac{-h\Omega_s}{K_B T}\right)} \tag{13}$$

$$K_B T = \text{ Thermal Energy at room tempeture } \approx 25\text{m}_e v$$

$$\frac{dP_s(z)}{dz} = -\alpha_s P_s + \frac{g_R}{A_{eff}} P_p P_s + \frac{g_R}{A_{eff}} P_p 2 n_{sp} h \upsilon_s \Delta V_R \tag{14}$$

Using equation (3), equation (4) and equation (14) and taking integration with respect to z for 0 to L, we have

$$\int_{z=0}^{z=L} \frac{1}{P_s} dP_s(z) = \int_{z=0}^{z=L} \left[-\alpha_s + \frac{g_R}{A_{eff}} P_p(0)\exp(-\alpha_s P_s(z)) + \frac{g_R}{A_{eff}} . \frac{P_p(0)\exp(-\alpha_p P_p(z))}{P_s(0)\exp(-\alpha_s P_s(z))} 2 n_{sp} h \upsilon_s \Delta V_R \right] dz \tag{15}$$

$$G_{ASE} = \exp\left(-\alpha_s L - \frac{g_R P_p(0)}{A_{eff}\alpha_p}[\exp(-\alpha_p L) - 1] + \frac{2 h \upsilon \Delta V n_{sp} g_R}{A_{eff}} . \frac{P_p(0)}{P_s(0)} . \frac{1}{\alpha_s - \alpha_p} .[\exp(\alpha_s - \alpha_p) L - 1] \right) \tag{16}$$

$$G_{ASE} = \exp\left(-\alpha_s L - \frac{g_R P_p(0) L_{eff}}{A_{eff}} - \frac{2 h \upsilon \Delta V n_{sp} g_R}{A_{eff}} . \frac{P_p(0)}{P_s(0)} . \frac{1}{\alpha_s - \alpha_p} .[1 - \exp(\alpha_s - \alpha_p) L] \right) \tag{17}$$

So the signal gain of the Raman Amplifier with ASE in dB can be described as

$$(G_{ASE}) dB = \left(\frac{10}{2.3025}\right) . \left(-\alpha_s L - \frac{g_R P_p(0) L_{eff}}{A_{eff}} - \frac{2 h \upsilon \Delta V n_{sp} g_R}{A_{eff}} . \frac{P_p(0)}{P_s(0)} . \frac{1}{\alpha_s - \alpha_p} .[1 - \exp(\alpha_s - \alpha_p) L] \right) \tag{18}$$

3. Simulation Results and Analysis

In addition to the pumping configuration, the amount of noise transferred will depend on the gain and the length of fiber used. For longer lengths of fiber, more averaging of the pump noise may occur. However, for typical transmission spans where L_{eff} is 17 km, the actual length of the span has little effect. In discrete Raman amplifiers in which the effective length is 5 km, the fiber length becomes important. So we are analyzing and simulating the variation of gain as a function of pump power and fiber length. The various parameters taken are defined with the respective specification in Table (1).

Table 1. Parameters

S.No.	PARAMETER	SYMBOL	VALUE(unit)
1	RAMAN gain Coeff	g_R	9.5*10^-14 (1/mW)
2	Initial Pump Power	Pp(0)	500mW
3	Effective Length	L_{eff}	Calculated
4	Effective Area	A_{efff}	Calculated, Πr^2
5	Length	L	0-50 km
6	Fiber losses at Stokes wavelength	αs	018dB/km
7	Fiber losses at Pump wavelength	αp	260dB/km
8	Planck's constant	h	6.6260*10^-34m2kg/s
9	BandWidth	ΔV	6THz
10	Initial Signal Power	Ps(0)	1mW
11	Signal Wavelength	λs	1550nm
12	Pump Wavelength	λp	1450nm
13	Core Diameter	d	12 μm
14	Spontaneous Scattering factor	n_{sp}	1.13

In the SRS process noise is added to the amplified signal because of random phases associated with spontaneous generated photons. The noise incurred by the spontaneous Raman scattering across the length of the fiber is accumulated and is known as amplified spontaneous emissions (ASE). Figure (1) demonstrates the Amplifier signal gain for a given pump power with respect to Amplifier length. The pump signal is taken of 1450nm with pump power of 500mW.The gain is calculated for various amplifier length from 0 to 50 km .It is apparent , from the first glance that the amplifier gain increases up to an specific length of fiber (14 Km), and then begins to decrease after a maximum signal gain of 5.8dB . The reason behind the decrease in gain is insufficient stimulated Raman scattering due to excessive pump depletion and getting higher losses than the provided gain at the signal wavelength, while the fiber attenuation plays a more important role for longer fiber length and the net gain decreases. Further the situation is analyzed in the presence of ASE. It can be observed that the gain increase for all respective fiber lengths after 2.50 Km. In this case the peak gain is 6.0dB.This increase in gain is of 0.2 dB. The difference will get accelerated when multiple amplifiers will be employed and will influence the amplification process.

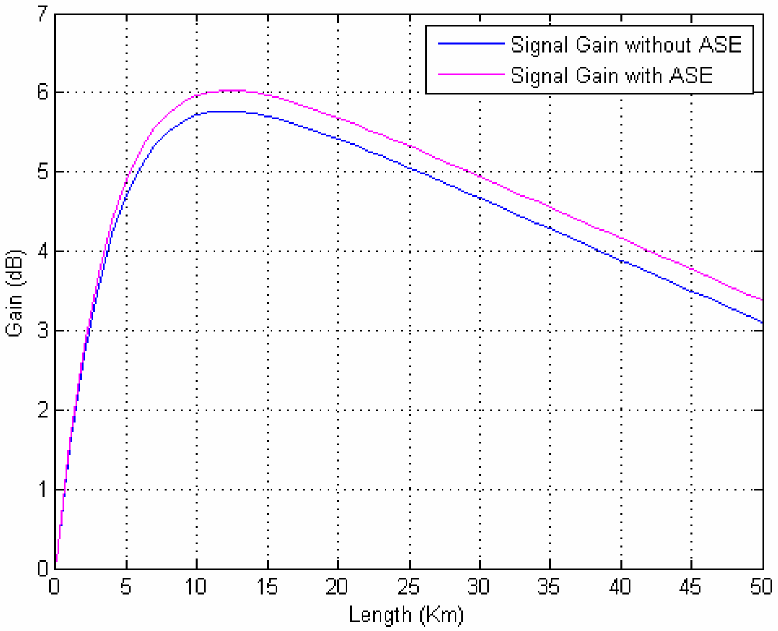

Figure 1. The Variation of Signal Gain (Gs) of Raman Amplifier with Amplifier Length (L).

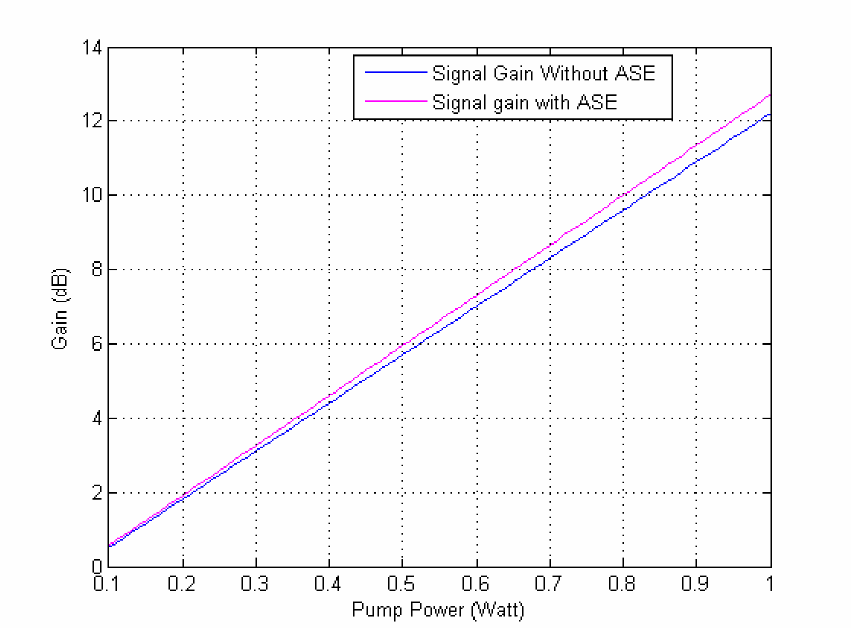

Figure 2. The Signal Gain (Gs) characteristic for varying Pump Power (Pp).

The important parameters representing discrete Raman amplifiers are (a) wavelength of the signal, (b) input power level of the signal,(c) wavelength of the pump (d) input power level of the pump, and (iii) the type and length of the gain fiber. An optimal discrete Raman amplifier is designed and found by changing these parameters for various configurations. One of the foremost optical characteristics of a discrete Raman amplifier is usually gain .For WDM signals, the dependence of the gain on pump signal should also be optimized. The case of single pump amplification is reviewed here with L=10Km. The pump power is varied from 100 mW to 1000mW and it is observed and shown in Figure (2) that the signal draw gain proportional to the pump power with loss due to the attenuation of optical fiber. As the pump power receives loss due to the energy transfer to the signal and the attenuation of optical fiber causes pump depletion. So the signal gain is proportionally get effected over the fiber length that leads to the gain saturation. It is also reflected in Figure (2) that the gain is increasing in the presence of ASE .However the ASE effect is negligible at the low pump power but get significant as the pump power increases.

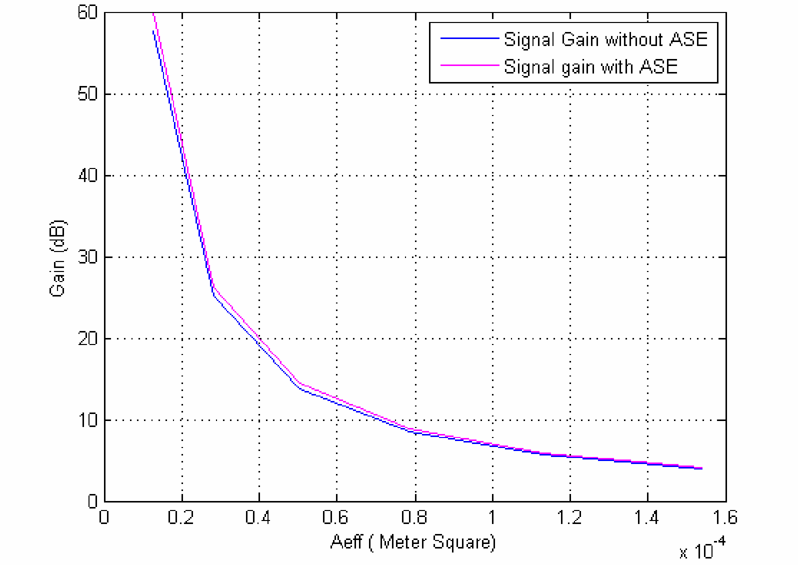

Figure 3. Evolution of Signal Gain (Gs) for different Affective Area.

Different fibers have different nonlinear strength. This is mainly due to different content of germanium and different effective areas. So effective area is an important design parameter. Large effective area (A_{eff}) fibers reduces the effects of fiber non-linearities when signal power is high. On the contrary, in the case of Raman pumping, small A_{eff} fibers increase the Raman efficiency and therefore give higher gains for a set pump power (Taylor *et al*, 2002).For the current study ,the fiber core radius is applied from 2 μ m to 10 μ m. The sole purpose of Figure (3) is to show the significant impact of the ASE generated within the Raman amplifier on amplifier gain for certain range of effective area. Figure (3) shows that the 70 μm^2 fiber will provide 5dB more Raman gain in for the same pump power than the 140 μm^2 fiber. Theoretically, the effective area and its wavelength dependence may be evaluated by assuming a Gaussian mode profile. Here using this assumption effective area is calculated as $A_{eff} = \Pi r^2$ (Agarwal, 2005).Around a signal wavelength of 1.55 μm, a typical transmission fiber has an effective area *A*eff around 75 μm^2. A very slight variation in gain is observed for a change in effective area in the presence of ASE.

4. Conclusion

In this paper, it is indicated that the desirable characteristics of a fiber are small effective area, short length of the fiber to obtain high net gain and for less effect of ASE on Raman gain. The net gain increase with increasing fiber length up to 14km, and then begins to decrease .The maximum gain obtained at 14Km fiber length is 5.8dB.However a difference of 0.2 dB occur when ASE is included. It is found that the signal receives gain proportional to the pump power. However, under the influence of ASE an increasing difference in comparison with the case of without ASE is observed in the signal gain for respective higher values of pump power. For a given pump power, the Raman gain in dBs is approximately inversely proportional to the fiber effective area. The Raman gain in a fiber with an effective area of 75 μm^2 is about 5dB more than in a 140 μm^2 fiber. Though this higher Raman gain is more effected by ASE. Therefore, an optimum length and small effective area need to be considered when selecting fiber types for Raman amplified systems to reduce the effect of ASE over the Raman gain.

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