

Amplified Spontaneous Emission Noise Power in Distributed Raman Amplifiers

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Abstract— The noise accompanying an optically amplified signal plays an important role in understanding the basic properties of the gain medium. In this paper, we demonstrate an analytical formalism and a numerical integration of the amplified spontaneous emission (ASE) noise power for distributed Raman amplifier (DRA). Three types of distributed Raman amplifiers; forward, backward and bidirectional pumping configurations, are simulated and compared.

Index Terms—Distributed Raman Amplifier (DRA), Amplified Spontaneous Emission (ASE), Bidirectional Pumping, Counter Pumping.

1 INTRODUCTION

In the early 1970s, Stolen and Ippen demonstrated Raman amplification in optical fibers [1]. However, throughout the 1970s and the first half of 1980s, Raman amplifiers remained primarily laboratory curiosities. In the mid-1980s, many research papers elucidated the promise of Raman amplifiers, but much of that work was overtaken by erbium-doped fiber amplifiers (EDFAs) by the late 1980s. However, in the mid to late 1990s, there was a resurgence of interest in Raman amplification.

Rapid growth of optical amplifiers in optical communication systems enhances the channel capacities and transmission lengths and in this context, Raman amplifiers play an important role. These amplifiers are used in wavelength division multiplexed (WDM) systems. Raman amplification is based on stimulated Raman scattering (SRS) phenomena, which is a nonlinear effect in optical fibers and its result is optical signal amplification.

There are two types of Raman amplifiers: discrete Raman amplifier and distributed Raman amplifier (DRA). The distributed type utilizes a transmission optical fiber as an active medium. If the amplifier is contained in a box at the transmitter or receiver end of the system, it will be called a discrete Raman amplifier.

Raman fiber amplifiers are attractive as not only DRAs for improving the optical signal-to-noise ratio (SNR) in transmission systems but also as discrete Raman amplifiers for overcoming the EDFA bandwidth limit [2-3].

In the distributed form, Raman amplification allows a lower signal launch powers to transverse the span above the noise floor while still increasing the optical SNR (OSNR), improve the noise figure and reduce the nonlinear penalty of fiber systems, allowing for longer amplifier spans, higher bit rates, closer channel spacing, and operation near the zero-dispersion wavelength [4].

1.2 DRA Pumping Configurations

The scheme of a typical DRA which uses two pump sources is shown on Fig. 1. The pump sources marked as PS1 and PS2 are placed at both ends of the transmission span and their power are switched in the medium of the

silica fiber using optical multiplexers MX1 and MX2.

When the pump power propagates in the direction of the signal, it is called co- or forward pumping scheme, and when the pump travels in the opposite direction, it is called counter or backward pumping. If PS1 and PS2 are used in the same time, the pumping scheme is bidirectional, including both the co-pumping and counter-pumping, simultaneously.

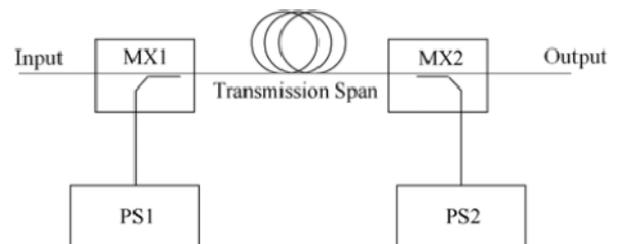


Fig. 1. Schematic of an optical communication system employing Raman amplification.

The paper is organized as follows, the mathematical model of analytical and numerical integration of DRA for different pumping configurations are presented in Sec. 2. Section 3 displays and discusses the obtained results, based on the described model. This is followed by the main conclusions in Sec. 4.

2 MATHEMATICAL MODEL

The signal power of DRA is defined as [5]:

$$P_S(L) = P_S(L) \exp (g_R P_0 L_{\text{eff}} - \alpha_S L) = G(L) P_S(0) \quad (1)$$

where P_0 is the pump power at $Z=0$, $G(L)$ is the net signal gain, L is the amplifier length and L_{eff} is its effective length defined as:

$$L_{\text{eff}}(Z) = \int_0^Z \frac{P_p(Z)}{P_p(0)} dZ = \frac{1 - \exp(-\alpha_p Z)}{\alpha_p} \quad (2)$$

and at L, it is

$$L_{\text{eff}} = \frac{(1 - \exp(-\alpha L))}{\alpha_p} \quad (3)$$

where α_s and α_p are the attenuation coefficients at the signal and pump wavelengths, respectively.

Using forward pumping, the pump power can be expressed as

$$P_p(Z) = P_p(0)\exp(-\alpha_p Z) \quad (4)$$

In the backward pumping, the pump power is

$$P_p(Z) = P_p(0)\exp(-\alpha_p(L - Z)) \quad (5)$$

where $P_p(0)$ is the value of the pump power at $Z = 0$.

In the general case, when a bidirectional pumping is used ($0.0 < S < 1.0$), the laser sources work at the same wavelength and at different pump power. Therefore, to calculate the pump power at point Z, one can use

$$P_p(Z) = S P_p(0)\exp(-\alpha_p Z) + (1 - S)P_p(0)\exp(-\alpha_p(L - Z)) \quad (6)$$

The net gain is one of the most significant parameters of the DRA. It describes the signal power increase at the end of the transmission span and presents the ratio between the amplifier accumulated gain and the signal loss. It can be simply described by [6]

$$G(Z) = \exp\left(g_R P_0 \frac{1 - \exp(-\alpha_p Z)}{\alpha_p} - \alpha_s Z\right) \quad (7)$$

$$G_{\text{NET}}(L) = \frac{P_s(L)}{P_s(0)} \quad (8)$$

2.1 Analytical Expression of ASE for Different Pump Configurations

In this case, in which the loss rate at the pump wavelength differs from the loss rate at the signal wavelength, a simple numerical integration is required to evaluate the power of amplified spontaneous emission (ASE). 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:

$$P_{\text{ASE}} = h\nu B_0 \eta T \left(G - 1 + \frac{G\alpha}{g_R P_p} \left(\exp(\alpha L) - \frac{1}{G} \right) \right) \quad (9)$$

where ηT is thermal equilibrium phonon number and B_0 is the bandwidth of the optical filter. $h\nu$ is the photon energy.

The ASE spectral density is defined by [7]

$$S_{\text{ASE}} = n_{\text{SP}} h\nu g_R G_L \int_{Z=0}^L \frac{P_p(Z)}{G(Z)} dZ \quad (10)$$

where the spontaneous scattering factor is defined as

$$n_{\text{SP}} = (1 - \exp(-h(\nu_p - \nu_{\text{ASE}})/KT))^{-1} \quad (11)$$

2.2 Numerical Integration Expression of ASE for Different Pump Configurations

The ASE power is defined through a numerical integration as [7]

$$P_{\text{ASE}} = 2 \int_{-\infty}^{\infty} S_{\text{ASE}} H_f(\nu) d\nu = 2 S_{\text{ASE}} B_0 \quad (12)$$

The factor 2 accounts for the two polarization modes of the fiber. Indeed, ASE can be reduced by 50% if a polarizer is placed after the amplifier.

3 RESULTS AND DISCUSSION

In this section, firstly we present the analytical results of the ASE noise power and the secondly numerical results. This is followed by a comparison between two methods.

3.1 Analytical Results

In Fig. 2, the simulations are accomplished with the main pumping schemes forward, backward and bidirectional versus span length.

As predicted by Eqs. (9) and (12), when ($S = 0$), P_{pf} is equal to zero and P_{pb} is equal to 100%, which gives higher ASE power. This case is the backward pumping.

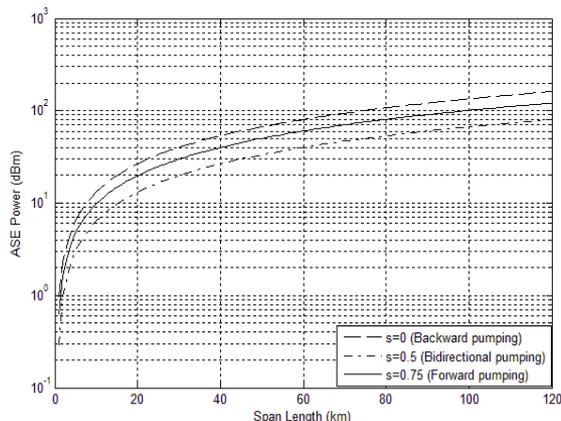


Fig. 2. ASE power versus span length in several pumping regimes.

Also, we observe that, when ($S = 0.5$), P_{pf} is equal to 50% and P_{pb} is equal to 50%, which gives a lower ASE power. This case is the bidirectional pumping.

When ($S = 0.75$) P_{pf} is equal 75% and P_{pb} is equal 25%, resulting in higher ASE power than bidirectional pumping.

Figure 3 presents the three cases of pumping within $S = 0$, $S = 0.5$ and $S = 0.65$.

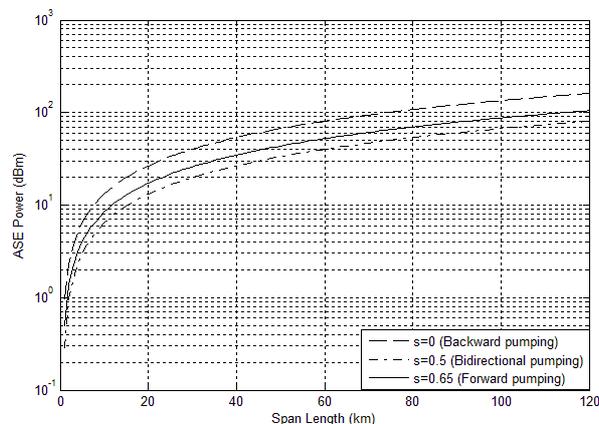


Fig. 3. ASE power versus span length in several pumping schemes.

In backward pumping, the higher ASE power occurs when ($S = 0$) and in bidirectional pumping, it occurs at ($S = 0.5$).

Based on the mathematical model, when ($S = 0$), P_{pf} equals zero and P_{pb} equals 100%, which gives a higher ASE power in the backward pumping, as shown in Fig. 4. When ($S = 0.5$, bidirectional pumping) both P_{pf} and P_{pb} equal 50%, which gives a lower ASE power than backward pumping.

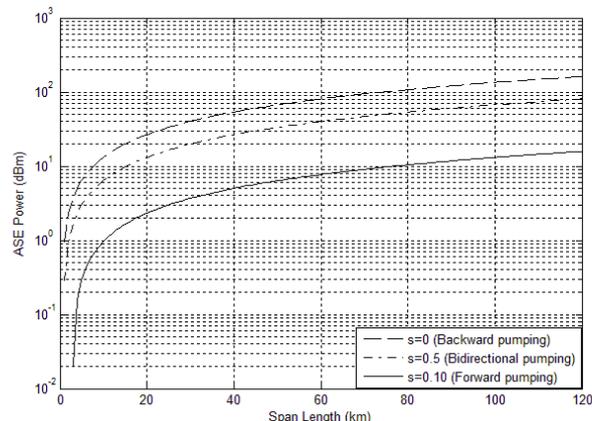


Fig. 4. ASE power versus span length for different values of S for the different pumping schemes.

When ($S = 0.10$) P_{pf} equals 10% and P_{pb} equals 90%, which gives a lower ASE power than bidirectional and backward pumping as indicated in Fig. 4.

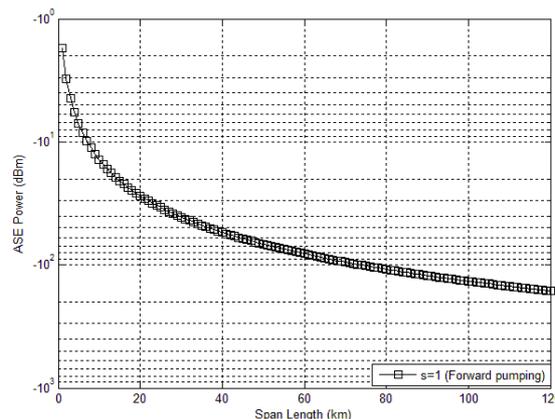


Fig. 5 ASE power versus span length forward pumping scheme.

Figure 5 shows that, ASE power for forward pumping decreases exponentially with the span length and is maximum (-1 dBm) at $L = 0.0$.

3.2 Numerical Integration Results

Figure 6 represents the three cases of pumping within $S = 0$, $S = 0.5$ and $S = 0.75$.

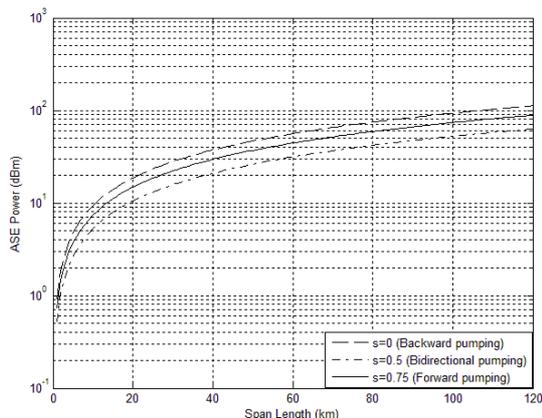


Fig. 6. ASE power versus span length in several pumping regimes.

In backward pumping, the higher ASE power occurs when $S = 0$ and in bidirectional pumping, it occurs at $S = 0.5$, which are nearly the same results obtained analytically. This Figure exhibits a good match between the analytical expressions and the numerical solutions.

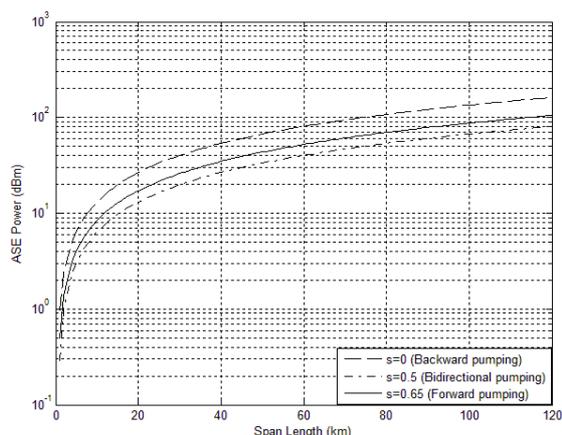


Fig. 7. ASE power versus span length in several pumping schemes.

Based on the mathematical model, when $S = 0$, P_{pf} equals zero and P_{pb} equals 100%. This gives a higher ASE power in the backward pumping, as shown in Fig. 7. When $S = 0.5$, bidirectional pumping, both P_{pf} and P_{pb} equal 50%. This gives a lower ASE power than backward pumping.

When $S = 0.65$, P_{pf} is equal 65% and P_{pb} is equal to 35%. This results in a higher ASE power than bidirectional pumping, as obtained from analytical method.

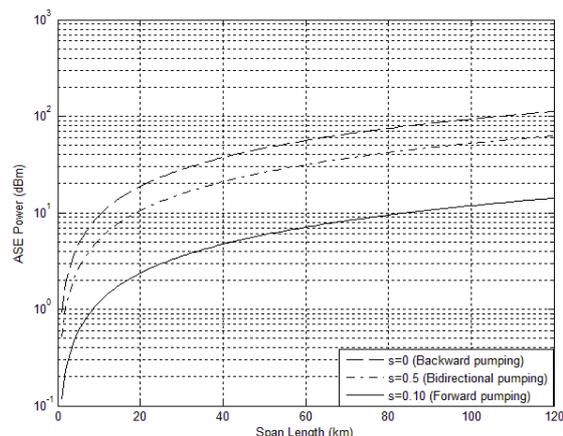


Fig. 8. ASE power versus span length for different values of S for the different pumping schemes.

Figure 8 represents the three cases of pumping within $S = 0$, $S = 0.5$ and $S = 0.10$. ASE power reaches the maximum value, respectively, 10^2 , $10^{1.6}$, and 10^1 dB, as in case of the analytical method.

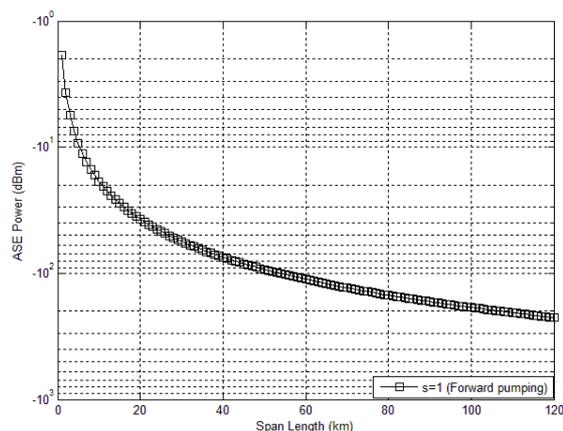


Fig. 9. ASE power versus span length forward pumping schemes.

Figure 9 shows that, ASE power for forward pumping decreases exponentially with the span length and has its maximum of -1 dB, which is approximately the same result obtained from analytical method. The graph shows a very good agreement between analytical and numerical results.

3.3 Comparison between Results of Analytical Expression and Numerical Integration:

The analytical expressions were compared to the numerical formalism of Eqs. (9) and (12) for different pumping schemes. The obtained results have shown a fair

agreement between the analytical expressions and a numerical formalism.

4 CONCLUSION

In this study, we present the ASE noise power analytically and numerically of the DRA as a function of fiber length at different pump configurations: forward pumping (co-pumping), backward pumping (counter-pumping) and bidirectional pumping.

Analytical expressions have been developed which describe accurately the power profiles of the pump, signals noises in different regimes. We also present numerical formalism. The obtained results exhibit a good match between the analytical expressions and the numerical formalism. The simulation has been done at the signal and pump wavelengths 1550 nm and 1450 nm, respectively.

We reached a lower ASE noise power in case of forward pumping, a higher lower ASE noise power in backward pumping and a medium lower ASE noise power in bidirectional pumping.

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