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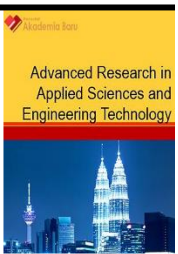

Carrier-to-Noise Ratio for Distributed Raman Amplifiers with Different Pumping Configurations

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ABSTRACT

Distributed Raman amplifiers (DRAs) achieve higher bit rate, low noise figure, a decreased nonlinear penalty, long-haul transmission, small channel spacing and operating near zero dispersion wavelength. In this paper, a model is derived for the DRA carrier-to-noise ratio (CNR) caused by amplified spontaneous emission (ASE) using different pumping configurations: co-pumping, counter and bidirectional-pumping. The bit error rate (BER) is evaluated in the S-band from optical signal to noise ratio (OSNR). The simulation results show that, at 100 km fiber length, the CNR reaches its minimum value of 40 and 41 and 42 dB, in counter and bidirectional pumping, and 42 dB in co-pumping scheme. Moreover, the co-pumping provides the lowest BER in contrast to the counter pumping which achieves the highest BER among the three pumping schemes.

Keywords:
Distributed Raman Amplifier (DRA), Carrier-to-Noise Ratio (CNR), Bit Error Rate (BER), Amplified Spontaneous Emission (ASE), Copumping, Counter and Bidirectional Pumping

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1. Introduction

Raman amplifiers are employed recently in long-haul optical fiber systems. They are widely used in optical communication systems. Raman amplifiers are distributed amplifiers (DRAs) [1]. The amplification is achieved inside the fiber core itself without the need of dopant materials like that used in lumped elements amplifiers. The amplification process is based on stimulated Raman scattering [2].

One of the great challenges for DRAs is the presence of randomly distributed noises, such as ASE noise, Rayleigh backscattering noise and relative intensity noise transferred between the pump and input signals [3, 4]. DRAs could be pumped with different configurations as shown in Fig. 1; namely, forward (copumping), backward (counter-pumping), and bidirectional pumping. They offer significant improvement of CNR, OSNR and noise figure (NF) as compared with lumped EDFAs.

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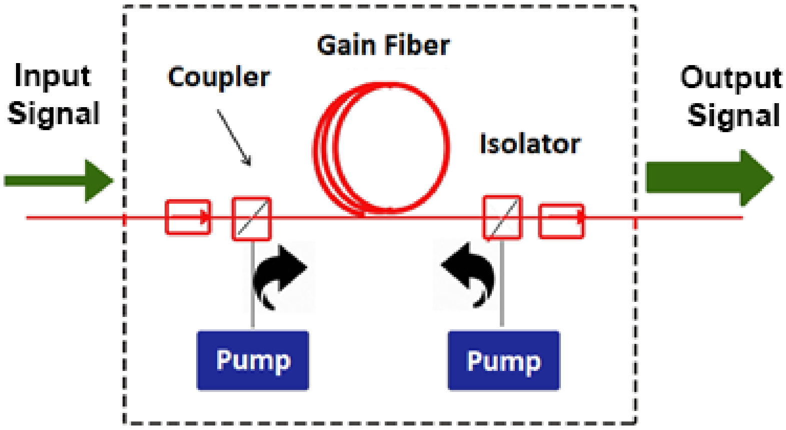

Fig. 1. Pumping schemes of distributed Raman amplifier

Cadena *et al*. proposed a hybrid system including hyperspectral and multiplex detection to study coherent Raman scattering microscopy [5]. The analysis of a single fiber transmission using wavelength division multiplexing (WDM) with a DRA is illustrated by Tithi *et al*. [6] to study how the bit error rate (BER) is affected by the amplifier induced crosstalk.

Moreover, a new approach of OSNR and NF for DRA is introduced by Beshr *et al*. in the S-band [7, 8]. In this paper, we present the analysis the CNR in DRA caused by ASE noise at different pumping schemes. We also evaluate the BER with input signal power through its OSNR. Analysis for both CNR and BER is illustrated in Sec. 2, depending on the noise power (P_{ASE}) of ASE in DRA, for the three pumping configurations. Section 3 displays and discusses the obtained results. The main conclusions of this work are summarized in Sec. 4.

2. Model and Analysis

Now, the analysis of CNR and BER caused ASE noise power is explained. The DRA signal power, P_S, is defined as [1]

$$P_S(L) = P_S(L)\exp\left(g_R P_0\, L_{eff} - \alpha_S\, L\right) = G(L)\, P_S(0) \tag{1}$$

Here, P_0 denotes the pump power at Z= 0, g_R is the Raman gain coefficient and α_s is the attenuation coefficient at the signal wavelength.

The pump power in copumping and in counter-pumping cases, respectively, could be defined by [1]

$$P_P(Z) = P_P(0)\exp(-\alpha_P Z) \tag{2}$$

$$P_P(Z) = P_P(0)\exp\big(-\alpha_P(L - Z)\big) \tag{3}$$

where α_p is the attenuation coefficient at the pumping wavelength and $P_P(0)$ is the pumping power at Z=0.

A new parameter, S, is defined as the ratio between counter pumping power to the copumping power [9]. For the bidirectional pumping, the parameter S has a value in the range 0 - 1. At a distance Z, the pump power could be obtained by the following relation [1]

$$\mathrm{P_P(Z) = S\,P_P(0)exp(-\alpha_P Z) + (1-S)P_P(0)exp\big(-\alpha_P(L-Z)\big)} \tag{4}$$

The fiber gain, G(Z), of DRA is considered as one of the most important parameters, relating cumulative gain and signal loss at any distance Z. It could be obtained using Eq. (1) as

$$\mathrm{G(Z) = exp\left(g_R P_0 \frac{1-exp(-\alpha_P Z)}{\alpha_P} - \alpha_S Z\right)} \tag{5}$$

The DRA spectral density of ASE is defined by [1]

$$\mathrm{S_{ASE} = n_{SP}\, h\upsilon\, g_R\, G_L \int_{Z=0}^{L} \frac{P_P(Z)}{G(Z)}\, dZ} \tag{6}$$

where h is Planck’s constant, n_{SP} is the spontaneous scattering factor, $P_P(z)$ and G_L are the pumping power and amplifier gain.

Based on the work of Binh *et al*. [10], the ASE noise power can be obtained by

$$\mathrm{P_{ASE} = 2\int_{-\infty}^{\infty} S_{ASE}\, H_f(\nu)d\nu = 2\, S_{ASE}\, B_{opt}} \tag{7}$$

Here, B_{opt} is the optical filter bandwidth.

The received signal quality can be indicated by the CNR, which is defined by the ratio of carrier power to the total noise power. The CNR caused by ASE is defined as [10]

$$\mathrm{CNR_{ASE} = \frac{m^2\, P_S\, \Delta\upsilon}{2\, P_{ASE}\, B_{opt}}} \tag{8}$$

where Δυ is the optical wave band and m the optical modulation depth.

Substituting Eq. (7) in Eq. (8) yields

$$\mathrm{CNR_{ASE} = \frac{m^2\, P_S\, \Delta\upsilon}{4\, {B_{opt}}^2\, S_{ASE}}} \tag{9}$$

Substituting Eq. (6) in Eq. (9) gives

$$\mathrm{CNR_{ASE} = \frac{m^2\, P_S\, \Delta\upsilon}{4\, {B_{opt}}^2\ h\upsilon\, n_{SP}\, g_R\, G_L\ \int_{Z=0}^{L} \frac{P_P(Z)}{G(Z)} dZ}} \tag{10}$$

2.1 CNR in Copumping Scheme

In the copumping case, both signal and pump propagate from Z=0 to L. The copumping CNR can be derived by substituting Eqs. (2) and (5) in Eq. (10)

$$\mathrm{CNR = \frac{m^2\, P_S\, \Delta\upsilon}{4\, {B_{opt}}^2\ h\upsilon\, n_{SP}\, g_R\, G_L} \times \frac{1}{\int_{Z=0}^{L} \frac{P_P(0)exp(-\alpha_P Z)}{exp\left(g_R P_0 \frac{1-exp(-\alpha_P Z)}{\alpha_P} - \alpha_S Z\right)} dZ}} \tag{11}$$

Then

$$\mathrm{CNR = \frac{m^2\, P_S\, \Delta\upsilon}{4\, {B_{opt}}^2\ h\upsilon\, n_{SP}\, g_R\, G_L\ \ P_P(0)\, exp\left(-\frac{g_R P_0}{\alpha_P}\right)} \times \frac{1}{\int_{Z=0}^{L} exp(\alpha_S - \alpha_P)Z\, exp\left(\left(\frac{g_R P_0}{\alpha_P}\right) exp(-\alpha_P Z)\right) dZ}} \tag{12}$$

2.2 CNR in Counter-pumping Scheme:

In the counter-pumping case, the pump signal propagates from Z=L to Z=0 in (-Z) direction. In this case, using Eqs. (3) and (5) in Eq. (10) yields

$$\mathrm{CNR} = \frac{m^2\, P_s\, \Delta\upsilon}{4\, B_{opt}{}^2\;\; h\upsilon\, n_{SP}\, g_R\, G_L\;\; P_P(0)\exp\left(-(\alpha_P L)-\left(\frac{g_R P_0}{\alpha_P}\right)\right)} \times \frac{1}{\int_{Z=0}^{L} \exp\left(\left(\frac{g_R P_0}{\alpha_P}\right)\exp(-\alpha_P Z)\right)\exp(\alpha_P+\alpha_S)Z\, dZ} \tag{13}$$

2.3 CNR in Bidirectional Pumping Scheme:

The bidirectional pumping includes both types: copumping and counter-pumping, simultaneously. In this case, using Eqs. (4) and (5) in Eq. (10), results in

$$\mathrm{CNR} = \frac{m^2\, P_s\, \Delta\upsilon}{4\, B_{opt}{}^2\;\; n_{SP}\, g_R\, G_L} \times \frac{1}{\times\int_{Z=0}^{L} \frac{S\, P_P(0)\exp(-\alpha_P Z)+(1-S)P_P(0)\exp\left(-\alpha_P(L-Z)\right)}{\exp\left(g_R P_0 \frac{1-\exp(-\alpha_P Z)}{\alpha_P}-\alpha_S Z\right)}\, dZ} \tag{14}$$

2.4 BER for Different Pumping Schemes:

In this section, the BER is evaluated for DRA in the presence of ASE. The BER is defined as the number of received error bits to total number of transmitted bits of a data stream over a communication channel which may be altered because of interference, distortion, or noise [1]. Through the OSNR, the BER is evaluated as [11, 12]

$$\mathrm{BER} = 0.5\left(1-\mathrm{erf}\left(\frac{\sqrt{\mathrm{OSNR}}}{2\sqrt{2}}\right)\right) \tag{15}$$

Here, erf(.) denotes the error function.

The ONSR of the amplified signal can be calculated as [1, 7]

$$\mathrm{SNR}_O = \frac{P_S\,(L)}{P_{ASE}} \tag{16}$$

where $P_s(L)$ is the signal power at L, the amplifier length.

3. Results and Discussion

The described model is executed by MATLAB ver. 9 to calculate the CNR, for the three different pumping schemes, in S-band,. The affecting parameters include fiber length, input and pumping powers.

3.1 Impact of Fiber Length on CNR

Figure 2 shows the CNR at the three pumping configurations, where S = 0, 0.5 and 1.

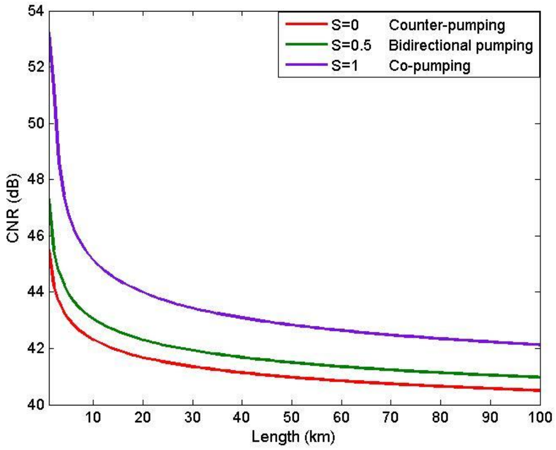

Fig. 2. CNR vs. fiber length for the three pumping configurations

At S = 0 (counter-pumping scheme), P_{pf} and P_{pb}, respectively, equal to 0% and 100%, yielding lowest CNR. Clearly, CNR decreases with amplifier length to a minimum value of 40 dB at L=100 km. From Fig. 2 also, the highest CNR is obtained at the copumping configuration (S = 1), where P_{pb} and P_{pf} are, respectively, equal to 0% and 1000%.

3.2 Effect of Signal Power on CNR

The CNR is drawn in Fig. 3 against input signal power, for the three pumping configurations, using a 20 km fiber. The value of input signal power lies within 1-10 mW and the pumping power is 200 mW, with a 0.68 $W^{-1}.km^{-1}$ Raman gain coefficient and a bandwidth of 3 MHz for the optical filter.

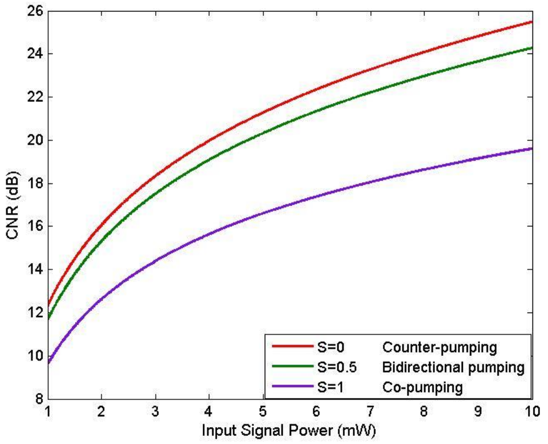

Fig. 3. CNR vs. input signal power at different pumping configurations

Obviously, from Fig. 3, the CNR increases with the input signal power at the three different pumping configurations. The lowest CNR occurs at the copumping scheme. It increases with input signal power to a maximum value of 20 dB at 10 mW input signal power. In counter-pumping configuration (S = 0), the CNR reaches its minimum value of 26 dB and provides a moderate value, 24 dB) at bidirectional pumping.

3.3 Effect of Pump Power on CNR

In a similar way to the mentioned procedure, CNR is calculated with pump power. The obtained

CNR values are found having slight differences. Hence, Table 1 is drawn to present the variation of CNR with pumping power for three pumping schemes, using a fiber of 20 km length. The pumping power is assigned values within 200-1000 mW, and the input signal power is set at 1 mW. The parameters used in calculations are $h\upsilon_0$= 0.8 eV, α_s and α_p are, respectively, 0.21 and 0.26 dB/km.

Table 1
CNR vs. pumping power at different pumping schemes (S=0.0, 0.5, 1.0)

Pumping Power (mW)	CNR (dB) at S=0	CNR (dB) at S=0.5	CNR (dB) at S=1
200	37.59	40.76	51.71
500	37.61	40.78	51.72
1000	37.63	40.80	51.75

From Table, the highest value of CNR is achieved at the copumping scheme (S=1). The counter pumping (S = 0) gives the lowest CNR and the bidirectional pumping (S = 0.5) achieves a moderate value of CNR.

3.4 Effect of Input Signal Power on BER

The BER versus signal power (in the range -30 dBm to -20 dBm) for different values of pumping ratio, S, in the presence of presence of ASE noise power (P_{ASE}) is displayed in Fig. 4. Figure 4 depicts that the counter-pumping (S = 0), where P_{pf} and P_{pb} are 0% and 100%, achieves highest BER. While the lowest BER is obtained when S = 0.75, and P_{pf} and P_{pb} are equal to 0.75% and 25%, respectively, in the bidirectional configuration.

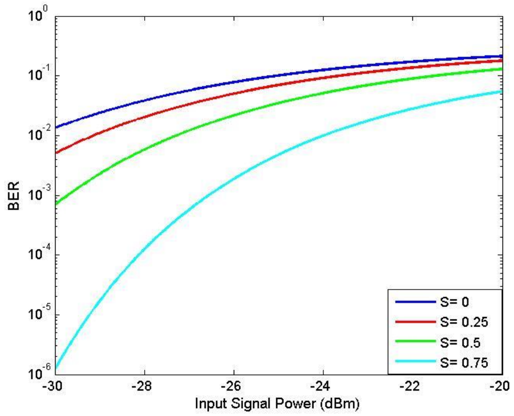

Fig. 4. BER vs. input signal power

Figure 5 shows the copumping BER dependence on the input signal power at (S = 1) where P_{pf} equals 100% and P_{pb} equals 0%. The BER increases with input signal power having 10^{-25} and 10^{-5} minimum and maximum values, at -30 dBm and -20 dBm input signal power of, respectively.

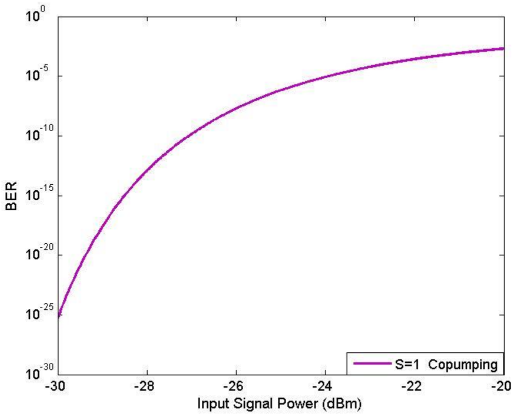

Fig. 5. Copumping BER vs. input signal power

4. CONCLUSION

In this paper, the carrier-to-noise ratio (CNR) for DRAs, caused by, is investigated at different pumping schemes. The affecting parameters, including pumping power, fiber length and power of input signal, and their impact on CNR for DRAs is demonstrated at different pumping configurations. The OSNR is utilized to evaluate the BER of DRA. For different pumping configurations, the obtained results reveal that the CNR decreases with length of fiber. The counter pumping scheme yields the lowest value, 40 dB, of CNR, at 100 km length. The copumping achieves the highest value, 42 dB, at 100 km and the bidirectional scheme yields a moderate value of CNR. Furthermore, the impact of power of input signal on CNR is investigated within 1-10 mW for the three configurations in a 100 km fiber. It is found that CNR increases drastically with power of input signal. In addition, the effect of pumping power on CNR is studied within 200-1000 mW for the three different pumping configurations, leading to a maximum value of 51.75 dB at S =1. At S =0, the lowest value, 37.63 dB, of CNR is obtained and moderate values are obtained at S= 0.5. The BER is also evaluated versus power of input signal, taking into consideration the noise caused by ASE. The copumping achieves the lowest BER, while the counter-pumping achieves the highest BER.

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