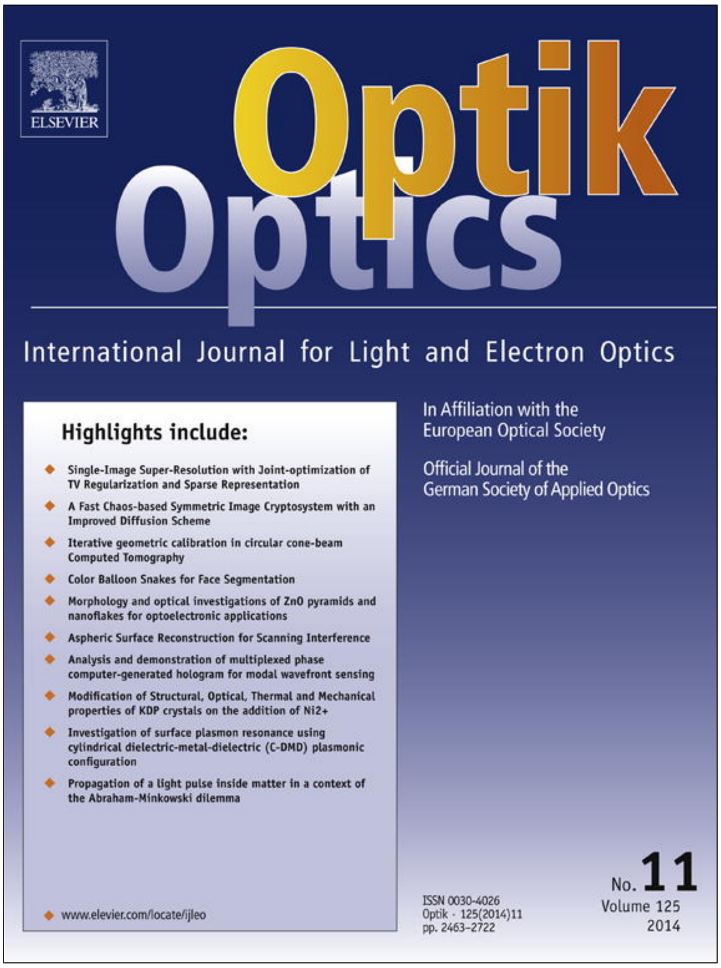

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New trend for optical signal-to-noise ratio of disturbed Raman fiber amplifier

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ABSTRACT

In a distributed Raman fiber amplifier (DRFA), Raman amplification allows a lower signal launch powers to transverse the span above the noise floor while still increasing the optical signal-to-noise ratio (OSNR). It improves the noise figure and reduces the nonlinear penalty of fiber systems. In this paper, we demonstrate a new trend of OSNR at different pump configurations: forward, backward and bidirectional pumping for DRFAs as a function of fiber length. We also present the variation of OSNR with both input pump power and input signal power. It is found that forward pumping provides the highest OSNR, reaching its maximum value of 37 dB. However, backward pumping provides the smallest OSNR that has its maximum of 22 dB and the bidirectional pumping provides the moderate OSNR between the others having its peak of 26 dB.

1. Introduction

There are mainly three reasons for the recent renewed interest in Raman amplification. One is the capability to provide distributed amplification, the second is the possibility to provide gain at any wavelength by selecting appropriate pump wavelengths, and the third is the fact that the amplification bandwidth may be broadened simply by adding more pump wavelengths.

To describe recent developments in Raman amplifiers, amplifiers may be categorized into distributed and discrete or lumped amplifiers. There are also hybrid amplifiers that can be a combination of the two mentioned categories. The term distributed amplification refers to the method of cancelation of the intrinsic fiber loss. As opposed to discrete amplification, the loss in distributed amplifiers is counterbalanced at every point along the transmission fiber in an ideal distributed amplifier. The transmission fiber is, in itself, turned into an amplifier.

Distributed Raman amplification can be achieved by optical pumping at either end of the fiber. In the co-pumped Raman configuration, the pump is launched at the front end and co-propagates with the optical signal along the transmission span. In the counter-pumped architecture that is widely deployed, the optical pump and signal launch at the opposite ends. Finally, Raman pumping at both ends of the transmission span characterizes the bidirectional scheme [1,2].

One of the more advantages of DRFAs is the capability to improve noise performance by using distributed amplification that was demonstrated in discrete erbium doped fiber amplifiers (EDFAs) in the early nineties [3–5] and more recently in the above mentioned system demonstrations using distributed Raman amplification. In both of these distributed amplification schemes, the transmission fiber is itself, turned into an amplifier.

The distributed Raman fiber amplifier (DRFA) is an amplifier where the pump power extends into the transmission line fiber. As shown in Fig. 1, the DRFA utilizes the transmission fiber in the network as the Raman gain medium to obtain amplification. Typically, high-powered counter-propagating Raman pumps are deployed in conjunction with discrete amplifiers, such as EDFAs.

Recently, Beshr et al. studied Raman amplifier concerning pumping and noise [6,7]. In this paper, we demonstrate a new trend to calculate the OSNR at different pump configurations: forward, backward and bidirectional pumping for DRFAs as a function of fiber length.

The paper is organized as follows: the mathematical model of OSNR due to the amplified spontaneous emission (ASE) noise power for DRFAs at different pumping configurations is presented in Section 2. Section 3 displays and discusses the obtained results, based on the described model. This is followed by the main conclusions in Section 4.

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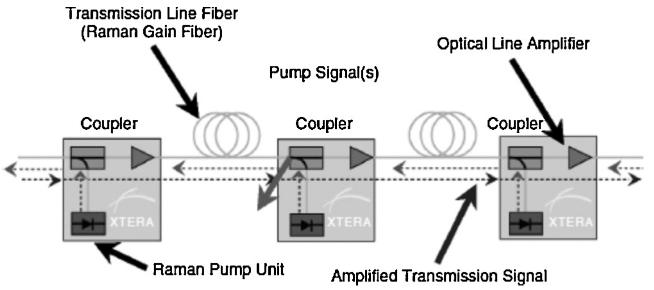

Fig. 1. DRFAs utilize the transmission fiber in the network as the Raman gain medium to obtain amplification.

2. Mathematical model

In this section, we present and demonstrate a new trend of OSNR at different pump configurations: forward, backward and bidirectional pumping for DRFAs.

The signal power of DRFA is defined as [8]

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

where g_R ($\text{W}^{-1}\,\text{m}^{-1}$) is the Raman gain coefficient of the fiber, P_0 is the pump power at $Z = 0$ and $G(L)$ is the fiber amplifier gain at L is the amplifier length. The fiber effective length, L_{eff}, is defined as

$$L_{\text{eff}} = \int_0^Z \frac{P_P(Z)}{P_P(0)}\,dZ = \frac{1-\exp(-\alpha_P Z)}{\alpha_P} \tag{2}$$

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

When using forward pumping, the pump power can be expressed as [1]

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

In the backward pumping, the pump power is [1]

$$P_P(Z) = P_P(0)\exp(-\alpha_P(L-Z)) \tag{4}$$

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

In the general case, when a bidirectional pumping is used ($0.0 < S < 1.0$) [9], the laser sources work at the same wavelength and at different pump powers. Therefore, to calculate the pump power at point Z, one can use

$$P_P(Z) = SP_P(0)\exp(-\alpha_P Z) + (1-S)P_P(0)\exp(-\alpha_P(L-Z)) \tag{5}$$

The net gain (G_{NET}) is one of the most significant parameters of the DRFA. 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 [10]

$$G_{\text{NET}}(L) = \frac{P_S(L)}{P_S(0)} \tag{6}$$

The fiber gain at any distance, Z, can be written explicitly from Eq. (1) as

$$G(Z) = \exp\left(g_R P_0 \frac{1-\exp(-\alpha_P Z)}{\alpha_P} - \alpha_S Z\right) \tag{7}$$

The ASE spectral density is defined by [1]

$$S_{\text{ASE}} = n_{\text{SP}} h\upsilon g_R G_L \int_{Z=0}^{L} \frac{P_P(Z)}{G(Z)}\,dZ \tag{8}$$

where $G(Z)$ gain of fiber span and $P_P(Z)$ is the pump power.

The spontaneous scattering factor is

$$n_{\text{SP}} = \left(1 - \exp\left(-\frac{h(\upsilon_P - \upsilon_{\text{ASE}})}{kT}\right)\right)^{-1} \tag{9}$$

where T is the absolute temperature of amplifiers, k is the Boltzmann constant and υ_P is the frequency of pump signal.

The ASE power is defined through a numerical integration as [8]

$$P_{\text{ASE}} = 2\int_{-\infty}^{\infty} S_{\text{ASE}} H_f(\nu)\,d\nu = 2S_{\text{ASE}}B_{\text{opt}} \tag{10}$$

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.

The OSNR of the amplified signal is defined by

$$\text{SNR}_{\text{O}} = \frac{P_S(L)}{P_{\text{ASE}}} = \frac{G(L)P_{\text{in}}}{P_{\text{ASE}}} \tag{11}$$

It is evident from Eq. (11) that both P_{ASE} and OSNR depend on the pumping scheme through pump power variations $P_P(Z)$ occurring inside the Raman amplifier.

Assuming that 1 mW input signal power is amplified by a 120 km fiber length, the other parameters were chosen to be $\alpha_S = 0.21$ dB/km, $\alpha_P = 0.26$ dB/km and $h\upsilon_0 = 0.8$ eV. Substituting from Eq. (10) into Eq. (11), one gets

$$\text{SNR}_{\text{O}} = \frac{G(L)P_{\text{in}}}{2\int_{-\infty}^{\infty} S_{\text{ASE}} H_f(\nu)\,d\nu} \tag{12}$$

$$\text{SNR}_{\text{O}} = \frac{G(L)P_{\text{in}}}{2S_{\text{ASE}}B_{\text{opt}}} \tag{13}$$

where S_{ASE} is the ASE spectral density, B_{opt} is the filter bandwidth and P_{in} is the input signal power.

Substituting Eq. (8) in Eq. (13) yields

$$\text{SNR}_{\text{O}} = \frac{G(L)P_{\text{in}}}{2n_{\text{SP}} h\upsilon_0 g_R G_L B_{\text{opt}} \int_{Z=0}^{L} (P_P(Z)/G(Z))\,dZ} \tag{14}$$

Then

$$\text{SNR}_{\text{O}} = \frac{P_{\text{in}}}{2n_{\text{SP}} h\upsilon_0 g_R B_{\text{opt}} \int_{Z=0}^{L} (P_P(Z)/G(Z))\,dZ} \tag{15}$$

2.1. OSNR in forward pumping

Using Eqs. (3) and (6) in Eq. (15) results in

$$\text{SNR}_{\text{O}} = \frac{P_{\text{in}}}{2n_{\text{SP}} h\upsilon_0 g_R B_{\text{opt}}} \times \frac{1}{\int_{Z=0}^{L} (P_P(0)\exp(-\alpha_P Z)/\exp(g_R P_0((1-\exp(-\alpha_P Z))/\alpha_P) - \alpha_S Z))\,dZ} \tag{16}$$

Then

$$\text{SNR}_{\text{O}} = \frac{P_{\text{in}}}{2n_{\text{SP}}\, h\upsilon_0\; g_R\, B_{\text{opt}}\, P_P(0)\exp(-(g_R P_0/\alpha_P))} \times \frac{1}{\int_{Z=0}^{L} \exp(\alpha_S - \alpha_P)Z\;\exp((g_R P_0/\alpha_P)\exp(-\alpha_P Z))\,dZ} \tag{17}$$

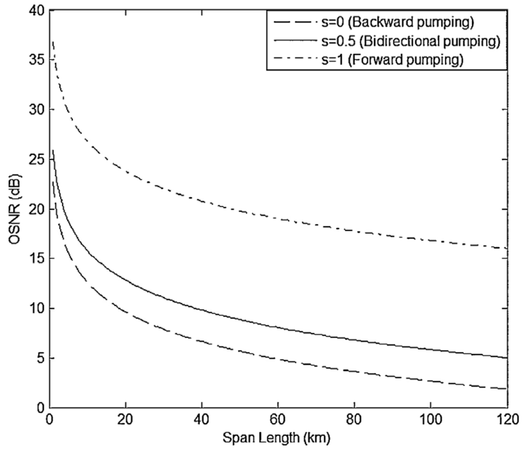

Fig. 2. OSNR versus span length in several pumping schemes.

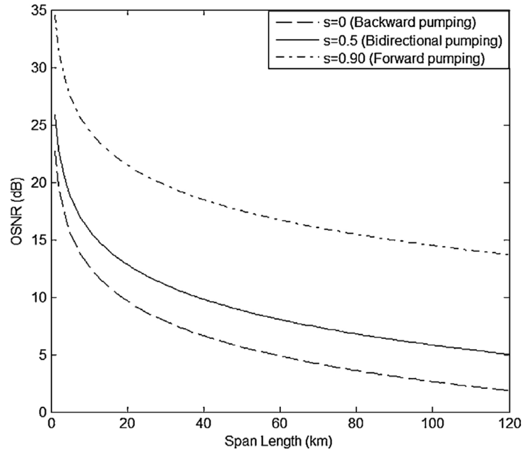

Fig. 3. OSNR versus span length in several pumping schemes.

2.2. *OSNR in backward pumping*

In the same manner, using Eqs. (4) and (6) in Eq. (15) yields

$$\mathrm{SNR_O} = \frac{P_{\mathrm{in}}}{2n_{\mathrm{SP}}h\upsilon_0 g_R B_{\mathrm{opt}} P_P(0)\exp(-(\alpha_P L)-(g_R P_0/\alpha_P))\int_{Z=0}^{L}\exp((g_R P_0/\alpha_P)\exp(-\alpha_P Z))\exp(\alpha_P+\alpha_S)Z\,dZ} \tag{18}$$

2.3. *OSNR in bidirectional pumping*

Again, using Eqs. (5) and (6) in Eq. (15) yields

$$\mathrm{SNR_O} = \frac{P_{\mathrm{in}}}{2n_{\mathrm{SP}}\,h\upsilon_0\,g_R\,B_{\mathrm{opt}}} \times \frac{1}{\int_{Z=0}^{L}(SP_P(0)\exp(-\alpha_P Z)+(1-S)P_P(0)\exp(-\alpha_P(L-Z))/\exp(g_R P_0((1-\exp(-\alpha_P Z))/\alpha_P)-\alpha_S Z))\,dZ} \tag{19}$$

3. Results and discussion

In this section, we present the results of OSNR due to the ASE noise power for DRFAs at different pumping configurations as a function of fiber length. Also, we present the variation of OSNR versus input pump power and input signal power.

3.1. *Variation of OSNR as a function of span length*

As predicted by Eqs. (15) and (18), when $S=0$, P_{pf} equals zero and P_{pb} equals 100%, which gives highest ASE power and lowest OSNR. This is the case of backward pumping, Fig. 2. Also, we observe from Fig. 2, when $S=0.5$, P_{pf} equals 50% and P_{pb} equals 50%, which gives the highest OSNR. This case is called bidirectional pumping. When $S=1$ (forward pumping), P_{pf} equals 100% and P_{pb} equals 0%, resulting in a higher OSNR than backward pumping. Fig. 3 presents the three cases of pumping with $S=0$, $S=0.5$ and $S=0.90$.

In backward pumping, the lowest OSNR occurs when ($S=0$) which is decreasing exponentially with the span length and has a maximum value of 23 dB. The maximum value is 25 dB when $S=0.5$ and is 35 dB when $S=0.9$, in the bidirectional pumping.

Fig. 4 shows that OSNR for forward pumping decreasing exponentially with the span length, have its minimum and maximum of 17 dB and 37 dB, respectively.

3.2. *Variation of OSNR as a function of pump power*

Fig. 5 displays the variation of OSNR with input pump power for different pump configurations at a fiber length 10 km. Input pump power varies from 100 to 1000 mW, input signal power is 1 mW, Raman gain coefficient is 0.68 $\mathrm{W^{-1}/km}$ and bandwidth of optical filter is 2.4 MHz.

We observe that ONSR increases exponentially with the input pump power reaching its maximum value of 37 dB, 22 dB and 17 dB for forward, bidirectional and backward pumping, respectively, at an input pump power of 1000 mW.

When $S=0.90$, P_{pf} equals 90% and P_{pb} equals 10% which gives the highest OSNR reaching its maximum value of 33 dB at the maximum value of input pump power (1000 mW). When $S=0.5$, P_{pf} equals 50% and P_{pb} equals 50% which gives a moderate OSNR having its maximum of 22 dB at the maximum value of input pump power. When $S=0$, P_{pf} equals 0% and P_{pb} equals 100%. This gives the lowest OSNR of these cases with a maximum of 17 dB at the maximum value of input pump power, as observed from Fig. 6.

Fig. 7 shows that OSNR for forward pumping increasing exponentially with the input pump power, having its minimum and maximum values of 27 dB and 37 dB, at input pump powers of 100 mW and 1000 mW, respectively.

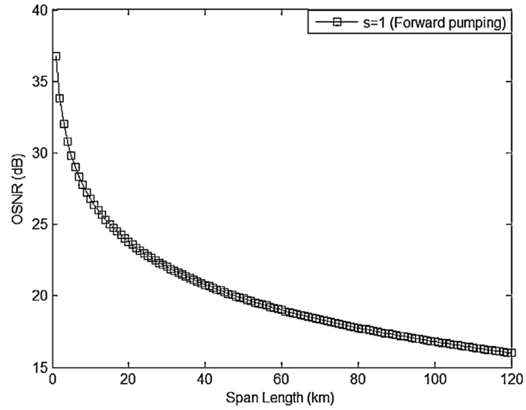

Fig. 4. OSNR versus span length forward pumping regimes.

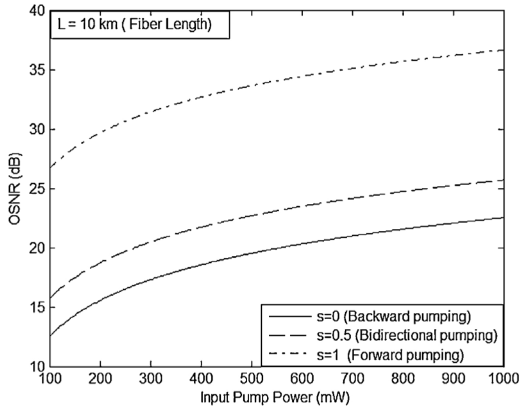

Fig. 5. Net OSNR versus input pump power for different pumping configurations in 10 km fiber.

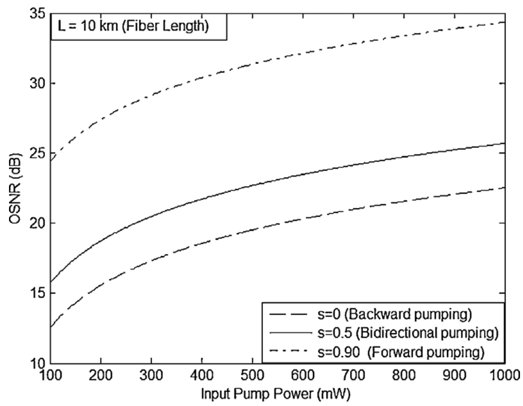

Fig. 6. OSNR versus input pump power for different pumping regimes within fiber length 10 km.

3.3. *Variation of OSNR as a function of signal power*

Fig. 8 presents the three cases of pumping with S = 0.90, 0.5 and 0.0. The input signal power varies from 1 to 10 mW. The pump power is taken 200 mW and the fiber length is 10 km. It is clear that the ONSR decreases exponentially the input signal power for different values of S. In backward pumping, the lowest OSNR occurs which is decreasing exponentially with the input signal power having a maximum value of 13 dB. While, in bidirectional pumping (S = 0.9), the highest OSNR reaches its maximum value of 24 dB.

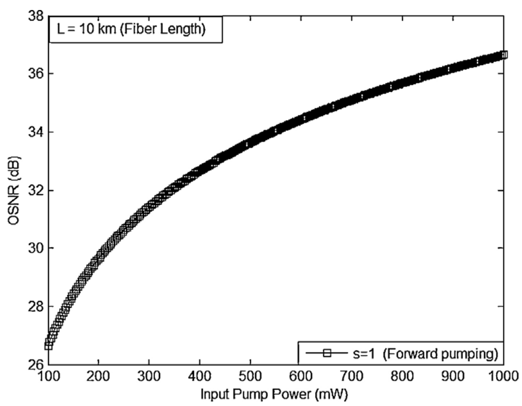

Fig. 7. OSNR versus input pump power for forward pumping scheme.

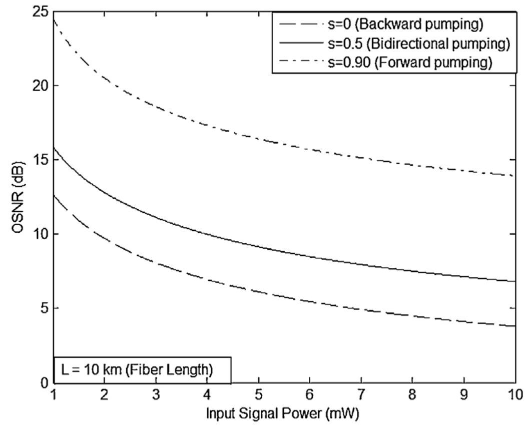

Fig. 8. OSNR versus input signal power for different values of S for the different pumping schemes.

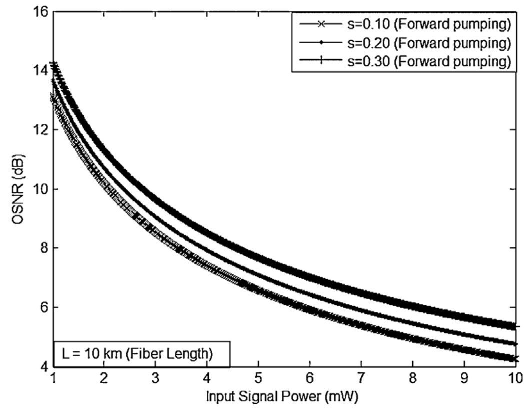

Fig. 9. OSNR versus input signal power for different pumping regimes within fiber length 10 km.

Fig. 9 displays the OSNR for forward pumping at different values of S, where ONSR decreases exponentially with the input signal power.

When S = 0.30, P_{pf} equals 30% and P_{pb} equals 70% which gives a higher ONSR that equals 15 dB. When S = 0.20, P_{pf} equals 20% and P_{pb} equals 80% which gives a moderate value of ONSR; 14 dB. The case of forward pumping was reached when S = 0.10, P_{pf} equals 10% and P_{pb} equals 90% which gives the lowest ONSR, 13 dB, than others.

4. Conclusion

In this study, we present and proposed a new trend of OSNR for DRFA as a function of fiber length. We also present the variation of OSNR with input pump power and input signal power for different pump configurations: forward, backward and bidirectional. We observe that, in all three cases of pumping, the ONSR decreases exponentially versus span length. It is found that forward pumping provides the highest OSNR, because most of the Raman gain is then concentrated toward the input end of the fiber where power levels are high reaching its maximum value of 37 dB. However, backward pumping is often employed in practice because of other considerations such as the transfer of pump noise to signal which provides the smallest OSNR that has its maximum of 22 dB. Therefore, bidirectional pumping provides the moderate OSNR between the others having its peak of 26 dB.

Also, we study the ONSR versus input pump power which varies from 100 to 1000 mW for different pumping configurations. We observe that ONSR increases exponentially with input pump power reaching its maximum value of 37 dB, 22 dB and 17 dB for forward, bidirectional and backward pumping, respectively, at an input pump power of 1000 mW.

Finally, we studied the ONSR versus input signal power in the range 1–100 mW for different pumping configurations at a fixed fiber length. We found that ONSR decreases exponentially with the input signal power.

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