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

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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 \cite{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 \cite{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 (DFA) is an amplifier where the pump power extends into the transmission line fiber. As shown in Fig. 1, the DFA 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 \cite{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 the 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.
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

$$ P_s(L) = P_s(0) \exp(g_s P_{P0} - \alpha_s L) = G(L)P_s(0) $$

(1)

where $g_s$ (W$^{-1}$m$^{-1}$) is the Raman gain coefficient of the fiber, $P_s(0)$ 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

$$ L_{eff} = \int_0^L P_s(Z) dZ = \frac{1}{\alpha_p} - \exp(-\alpha_p Z) $$

(2)

where $\alpha_s$ and $\alpha_p$ are the attenuation coefficients at the signal and pump wavelengths, respectively.

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

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

(3)

In the backward pumping, the pump power is

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

(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

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

(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

$$ G_{NET}(L) = \frac{P_s(L)}{P_{s}(0)} $$

(6)

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

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

(7)

The ASE spectral density is defined by

$$ S_{ASE} = n_{ASE} hv g_s G_s \int_{Z=0}^{L} \frac{P_s(Z)}{G(Z)} dZ $$

(8)

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

The spontaneous scattering factor is

$$ n_{sp} = \left(1 - \exp \left( \frac{-h \nu_p - v_{ASE}}{kT} \right) \right)^{-1} $$

(9)

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

The ASE power is defined through a numerical integration as

$$ P_{ASE} = 2 \int_{-\infty}^{\infty} S_{ASE} \nu dv = 2S_{ASE}B_{opt} $$

(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

$$ SNR_0 = \frac{P_{opt} G(L)P_0}{2 \int_{-\infty}^{\infty} S_{ASE} \nu dv} $$

(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 $h \nu_0 = 0.8$ eV. Substituting from Eq. (10) into Eq. (11), one gets

$$ SNR_0 = \frac{G(L)P_0}{2 \int_{-\infty}^{\infty} S_{ASE} \nu dv} $$

(12)

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

$$ SNR_0 = \frac{G(L)P_0}{2 \int_{Z=0}^{L} (P_s(Z)/G(Z)) dZ} $$

(14)

Then

$$ SNR_0 = \frac{P_{opt}}{2 \int_{Z=0}^{L} (P_s(Z)/G(Z)) dZ} $$

(15)

2.1. OSNR in forward pumping

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

$$ SNR_0 = \frac{P_{in}}{2 \int_{Z=0}^{L} \left( \frac{P_s(0) \exp(-\alpha_p Z)}{g_s P_0 (1 - \exp(-\alpha_p Z)/\alpha_p) - \alpha_s Z} \right) dZ} $$

(16)

Then

$$ SNR_0 = \frac{P_{in}}{2 \int_{Z=0}^{L} \frac{P_s(0) \exp(-\alpha_p Z)}{g_s P_0 (1 - \exp(-\alpha_p Z)/\alpha_p)} \exp(-\alpha_p Z) dZ} $$

(17)
2.2. OSNR in backward pumping

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

\[
\text{SNRO} = \frac{P_{\text{in}}}{2N_{\text{sp}} h \nu_0 g_0 B_{\text{opt}} P_f(0) \exp(-\alpha P L - (g_k P_0/\alpha_p) \int_{L=0}^{L} \exp((g_k P_0/\alpha_p) \exp(-\alpha P Z)) \exp(\alpha P + \alpha_k Z) dZ}
\]

2.3. OSNR in bidirectional pumping

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

\[
\text{SNRO} = \frac{1}{2N_{\text{sp}} h \nu_0 g_0 B_{\text{opt}} P_f(0) \exp(-\alpha P L - (1 - S)P_f(0) \exp(-\alpha P (1 - Z)) \exp(g_k P_0((1 - \exp(-\alpha P Z))/\alpha_p - \alpha_k Z) dZ}
\]

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 \( S = 0 \), \( P_{\text{pf}} \) equals zero and \( P_{\text{pb}} \) 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 \( S = 0.5 \), \( P_{\text{pf}} \) equals 50% and \( P_{\text{pb}} \) equals 50%, which gives the highest OSNR. This case is called bidirectional pumping. When \( S = 1 \) (forward pumping), \( P_{\text{pf}} \) equals 100% and \( P_{\text{pb}} \) 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 \( S = 0.9 \).

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, has 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 W\(^{-1}\)/km and bandwidth of optical filter is 2.4 MHz.
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 OSNR 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. 9 displays the OSNR for forward pumping at different values of $S$, where OSNR decreases exponentially with the input signal power.

When $S=0.30$, $P_{pf}$ equals 30% and $P_{pb}$ equals 70% which gives a higher OSNR that equals 15 dB. When $S=0.20$, $P_{pf}$ equals 20% and $P_{pb}$ equals 80% which gives a moderate value of OSNR; 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 OSNR, 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 OSNR 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.

Although, we study the OSNR versus input pump power which varies from 100 to 1000 mW for different pumping configurations. We observe that OSNR 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.

References