# Improvement of the Optical Channel Noise Characteristics Using Distributed Raman Amplifiers

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*Abstract* – **In this paper a theoretical basis for simulation of amplifier noise parameters is provided. On the base of propagation equations the evolution of the net system gain and the added noises due to the spontaneous Raman scattering and the double Rayleigh backscattering of the signal is simulated. A mathematical model for the carrier-to-noise ratio (*CNR*) of the distributed Raman amplifier due to the noise components is obtained. The influence of the pump power, the net gain and the length of the transmission span on the noise parameters is researched and the working regime of the amplifier is optimized so that maximum of the *CNR* and improvement of the amplifier performance are attained.**

*Keywords* – **Distributed Raman Amplifier, Amplified Spontaneous Emission, Amplifier Noise.**

## I. INTRODUCTION

One of the most usable in the contemporary submarine and long-haul terrestrial networks are the distributed Raman amplifiers (DRA), which is due to many advantages: stimulated Raman amplification can occur in any fiber at any signal wavelength by proper choice of the pump wavelength; the Raman gain process is very fast and the effective noise figure (*NF*) of the DRA is smaller than the *NF* of erbium-doped fiber amplifier (EDFA) and the semiconductor optical amplifier (SOA) [1].

In contrast with the EDFA which is a discrete device with an input and an output, DRA can be described as a system which consists of two pumping sources placed at the beginning and at the end of the transmission span which length is more than 100 kilometers. The optical fiber is used as an active medium. The projecting of a DRA is related with the choice of a pump power value in accordance with the transmission span length; the needed net gain coefficient and the magnitude of the added noises.

The high level of the pump power and the long actual transmission span of the distributed Raman amplifier are the reason for adding the noises due to spontaneous emission and double Rayleigh backscattering of the signal.

Finally the authors' goal is to use the presented mathematical model and the research results for designing an optical line that uses DRA at minimum level of the added noises.

## II. MATHEMATICAL MODEL OF A DISTRIBUTED RAMAN AMPLIFIER

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

In this research it is assumed that the power of the pump source PS1 is $SP_p$ and the power of PS2 is $(1-S)P_p$ respectively, where $P_p$ is the pump power and $S$ is a coefficient showing the power that is being pumped in the signal direction.

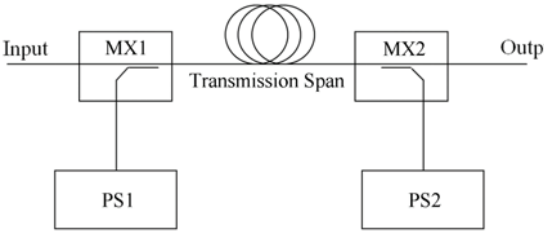

Fig. 1. Distributed Raman Amplifier.

The evolution of the signal ($P_s$) and the power of the pump source propagating along the optical fiber can be quantitatively described by differential equations called propagation equations. The signal and the pump power can be expressed as [1], [2]:

$$\pm\frac{dP_p}{dz}=-\frac{\upsilon_p}{\upsilon_s}g_R P_p P_s-\alpha_p P_p \tag{1}$$

$$\frac{dP_s}{dz}=g_R P_p P_s-\alpha_s P_s \tag{2}$$

where $g_R$ [$W^{-1}m^{-1}$] is Raman gain coefficient of the fiber, $\alpha_s$ and $\alpha_p$ are the attenuation of the signal and the pump power in silica fiber, $v_s$ and $v_p$ – signal and pump frequencies. The signs of „+" or „–" correspond to forward and backward pumping.

Since $P_p >> P_s$, the first term in equation (1) is negligibly low compared with the second and its influence can be neglected. Therefore expression (1) can be solved when both sides of the equation are integrated. When using forward pumping ($S=1$), the pump power can be expressed as the following:

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

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In the backward pumping case ($S=0$) the pump power is respectively:

$$P_p(z) = P_p(0)\exp\left[-\alpha_p(L-z)\right] \tag{4}$$

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

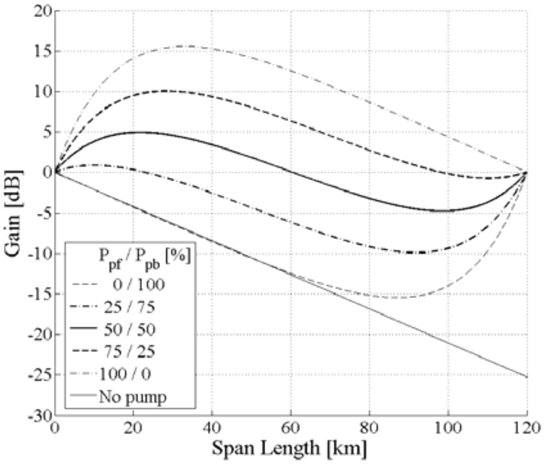

Fig. 2. Net gain vs span length in several pumping regimes.

In the general case when a bidirectional pumping [3] is used ($S=0\div1$) the laser sources work at the same wavelength and at different pump power. Therefore to calculate the pump power at point $z$ it can be used the equation:

$$\begin{aligned} P_p(z) &= S\,P_p(0)\exp\left(-\alpha_p L\right) + \\ &+ (1-S)P_p(0)\exp\left[-\alpha_p(L-z)\right]. \end{aligned} \tag{5}$$

If the values of $P_p$ are substituted in differential equation (2) and it is integrated from zero to $L$ for the signal power in the forward and the backward pumping can be written:

$$\begin{aligned} P_s(L) &= P_s(0)\exp\left\{g_R S P_0 \frac{1-\exp\left(-\alpha_p z\right)}{\alpha_p} - \alpha_s z\right\} = \\ &= G_f P_s(0) \end{aligned} \tag{6}$$

$$\begin{aligned} P_s(L) &= P_s(0)\exp\{g_R(1-S)P_0 \times \\ &\times \frac{\exp\left(-\alpha_p L\right)\left[\exp\left(\alpha_p z\right)-1\right]}{\alpha_p} - \alpha_s z\Bigg\} = G_b P_s(0) \end{aligned} \tag{7}$$

where $G_f$ and $G_b$ are the net gain in the forward and the backward pumping.

The net gain [4] is one of the most significant parameters of the DRA. It describes the signal power increase in 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 the expression:

$$G_{NET}(L) = P_s(L)/P_s(0) \tag{8}$$

Using equation (8) it is calculated a group of characteristics shown on fig. 2. They describe the evolution of the net gain along the optical fiber in several pumping regimes. The results of fig. 2 can be used for describing the signal evolution and for analysis of the noise components which are amplified along the silica fiber.

When using forward pumping, the signal in position $z$ is higher than the input signal power and the added noise from spontaneous emission is not as significant as the backward case. Conversely, when the signal power is very high the noise from the double Rayleigh backscattering and the nonlinear distortion from self-phase modulation increase.

## III. DISTRIBUTION OF THE ASE AND THE DRB NOISE POWER ALONG THE TRANSMISSION SPAN

In this section it is presented the evolution of the noise power of an amplified spontaneous emission (ASE) and a double Rayleigh backscattering (DRB) of the signal in the transmission span.

### *A. Amplified Spontaneous Emission*

The molecular unstimulated transition from virtual excited state to vibration state is the reason for spontaneous photon emission. Since the generated photons are uncorrelated with the signal power they are emitted in all directions and only small fraction of them propagate in the optical fiber medium.

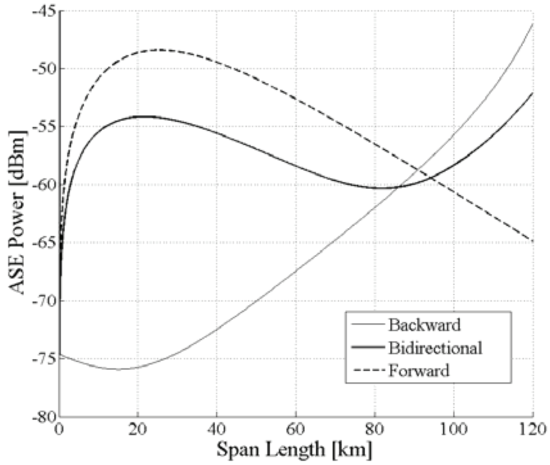

Fig. 3. ASE Power as a function of the span length in several pumping regimes.

Differently from $P_p$ and $P_s$, the noise power due to the spontaneous emission is equal to zero at the system input and it is totally created in the excited medium of the transmission span. The process of creating, amplifying and attenuating of the ASE noise is modeled by differential equation (9) and corresponds to its first, second and third terms [5].

$$\pm\frac{dP_{ASE}}{dz} = n_{sp} g_R P_p h\upsilon_{ASE}\Delta\upsilon + \frac{g_R}{2}P_p P_{ASE} - \alpha_s P_{ASE} \tag{9}$$

where $g_R$ is Raman gain coefficient, the plus and minus signs correspond to the forward and backward ASE noise power components and parameter $n_{sp}$ is is defined by the expression:

$$n_{sp} = \left\{1-\exp\left[-h\left(\upsilon_p-\upsilon_{ASE}\right)/kT\right]\right\}^{-1}. \tag{10}$$

Figure 3 shows the evolution of the ASE noise power in a 120 km distributed Raman amplifier that uses a Sumitomo large effective area fiber ($A_{eff} = 72$ µm and $g_R = 0.45$). In the discussed amplifier, pump power $P_p = 810$ mW and input signal power $P_s = 1$ mW are applied so that the signal has the same value at the input and the output of the transmission span, i.e. $G_{NET} = 0$ dB.

To simulate the signal and the noise power evolution, all differential equations are transformed in a discrete form of type: $P(i+1) = P(i) + g(i)\,P_p(i)\,P(i)\,\Delta z + \ldots$[6], where $P(i+1)$ is the predicted value of the studied power at the point $(i+1)\Delta z$, $P(i)$ is the calculated value of previous step of calculation at point $i\Delta z$, $\Delta z$ is a discretization step and $g(i)$ is gain coefficient.

The simulations are accomplished with the main pumping schemes – forward, backward and bidirectional. It is easy to view that at the end of the amplifying section the noise power is highest for the backward pump; therefore it is the most unfavorable scheme in respect of the ASE.

If the explanation relates to the fig. 2 it can be noticed that this is due to the high gain at the end of transmission span which is applied upon the spontaneously emitted photons accumulated along the whole fiber length. On the contrary, at forward pumping high amplification is applied only upon the photons emitted around the optical channel input.

### *B. Double Rayleigh Backscattering*

When the signal is transmitted along the fiber small fraction scatters in all directions. The phenomenon is known as Rayleigh scattering and due to small inhomogeneities or microscopic variation of the refractive index. Small fraction of the scattered light couples back into the fiber medium and propagates in the opposite direction. The backscattered light amplifies along the fiber and creates new backscattered light which direction is the same as the signal. It is added to the signal as a noise power and the phenomenon is known as double Rayleigh backscattering of the signals [7].

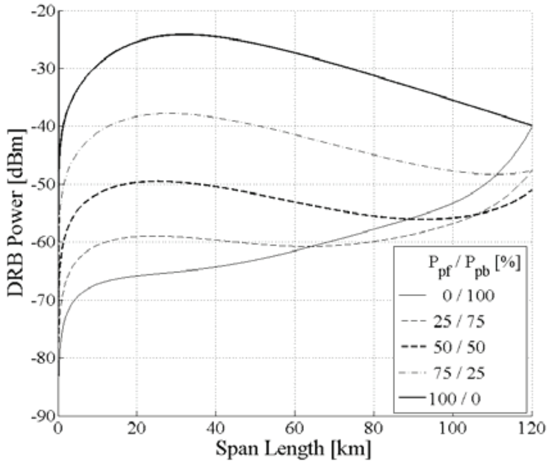

Fig. 4. DRB Power as a function of the span length in several pumping regimes.

Differently from the ASE, the DRB noise depends on the pump and the signal power and it is strongly correlated with the signal. The spectral terms of the DRB noise power are distributed in a narrow waveband around the carrier and they overlap with the signal.

The phenomenon can be modeled by using the propagation equations where (11) represents the Rayleigh backscattering and (12) – the DRB [1].

$$-\frac{dP_{BS}}{dz} = \frac{\omega_p}{\omega_s} P_p P_{BS} - \alpha_s P_{BS} + \alpha_R s \left( P_s - P_{DRB} \right) \qquad (11)$$

$$\frac{dP_{DRB}}{dz} = \frac{\omega_p}{\omega_s} P_p P_{DRB} - \alpha_s P_{DRB} + \alpha_R s P_{BS} \qquad (12)$$

The amplifier parameters which are used to simulate the curves on the fig. 3 are also used to compute the noise power of double Rayleigh backscattering and the results are presented on fig. 4. The most appropriate in this case is the bidirectional pumping (50/50 %), which ensures at about ten times less generation of noise power compared with the forward and the backward pumping.

Intriguingly, when the full power is pumped at one of the ends of the transmission span, unfavorable results are attained. This can be explained with the high pick of the gain coefficient. Therefore good noise performance can be achieved when the net gain coefficient is equally distributed though the optical fiber length.

## IV. RESEARCH RESULTS OF THE INFLUENCE OF DIFFERENT FACTORS ON *CNR*

The quality of the received signal can be evaluated by the parameter carrier-to-noise ratio (*CNR*) which is determined by the standard. On analogy with [8], the following equations for $CNR_{ASE}$ and $CNR_{DRB}$ are obtained:

$$CNR_{ASE} = \frac{m^2 P_s \Delta\upsilon}{2 P_{ASE} B} \qquad CNR_{DRB} = \frac{m^2 P_s \Delta\upsilon}{2 P_{DRB} B}, \qquad (13)$$

where $m$ is optical modulation depth, $B$ and $\Delta v$ are electrical and optical waveband.

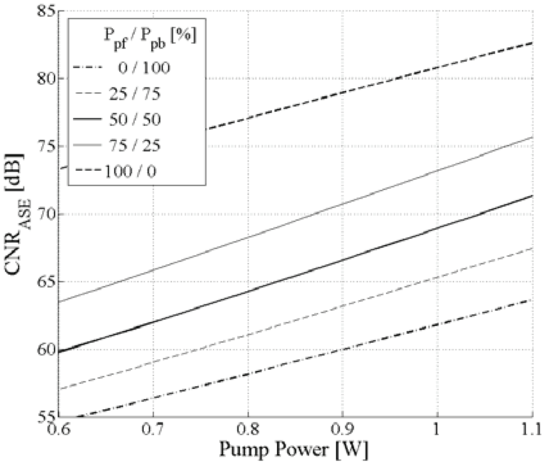

Fig. 5. $CNR_{ASE}$ as a function of the pump power in several pumping regimes.

If we assume that $m = 0.035$, $\Delta v = 13.2$ GHz, $B = 4.75$ MHz, then equations (13) can be presented in the following convenient for engineer calculations way:

$$CNR_{ASE}\left[\text{dB}\right]=P_s\left[\text{dB}\right]-P_{ASE}\left[\text{dB}\right]+12.3 \tag{14}$$
$$CNR_{DRB}\left[\text{dB}\right]=P_s\left[\text{dB}\right]-P_{DRB}\left[\text{dB}\right]+12.3$$

and the total *CNR* can be calculated by:

$$CNR\left[\text{dB}\right]=-10\log\left(10^{-CNR_{ASE}[\text{dB}]/10}+10^{-CNR_{DRB}[\text{dB}]/10}\right). \tag{15}$$

On fig. 5 and fig. 6 are shown the *CNR* values of the reviewed noise components as a function of the pump power. It can be seen that the increase of the pump power improves the $CNR_{ASE}$ but at the same time deteriorates the $CNR_{DRB}$ .

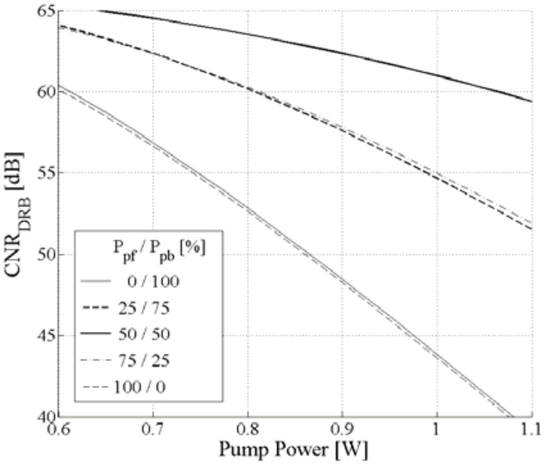

Fig. 6. $CNR_{DRB}$ as a function of pump power in several pumping regimes.

In the first case the increase of the signal and the noise by ASE depend on their current values and the value of the pump power. Therefore the higher signal amplifies more times than the noise power.

In the second case, however, the DRB noise power depends not only on the pump power but also on the value of the signal. By equations (11) and (12) it can be seen that the noise power is proportional to the product of $P_p$ and $P_s$ so that the DRB noise power increase faster than $P_s$.

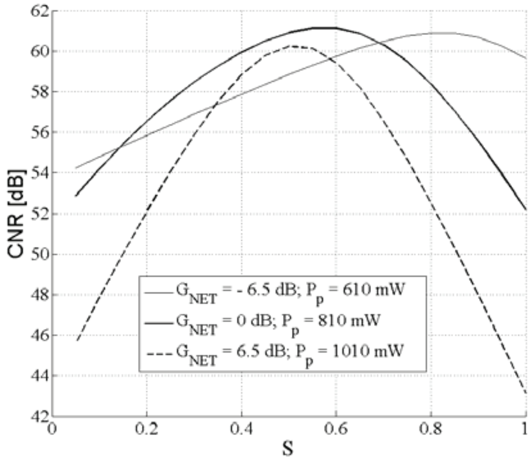

Fig. 7. *CNR* as a function of the splitting coefficient *S* in several values of $G_{NET}$.

In order to find the optimum pumping regime, it is shown a group of curves on fig. 7. The total *CNR* is expressed as a function of the parameter *S*. The curves present the three main working regimes at less, equal or higher than zero net gain coefficient. In this case we have net gain - 6.5 dB, 0 dB and 6.5 dB respectively.

The results show that maximum ratio *CNR* can be achieved when the net gain coefficient is higher than 5 dB and the value of the parameter *S* is at about 0.5. When the DRA just compensate the optical fiber attenuation the optimum value of *S* is 0.6. When the net gain is less than zero, the *CNR* is maximal at *S* equal to 0.8.

The optimized distributed Raman amplifiers guarantee that the *CNR* is higher than 60 dB. This allows cascading many amplifiers in one optical channel and the total *CNR* remains more than 52 dB which is required for CATV applications.

## V. CONCLUSION

On the base of the presented mathematical models the evolution of the two most essential noise components for the distributed Raman amplifier due to the spontaneous emission and double Rayleigh backscattering of the signal is researched.

The analysis of the results show that forward pumping provides lowest levels of noise power by ASE whilst minimum of DRB noise power is achieved when bidirectional pumping is used.

In order to find out the optimum working regime of the distributed Raman amplifier, three cases are reviewed: I. $G_{NET}=-6.5$ dB, II. $G_{NET}=0$ dB и III. $G_{NET}=6.5$ dB. It appears that when the net gain is more than 5 dB, maximum *CNR* is achieved when the parameter $S=0.5$. When $G_{NET}=0$ dB, the optimum value of *S* is 0.6 and when the net gain coefficient is less than zero, *CNR* is maximum at $S=0.8$.

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