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Backward Pumped Distributed Fiber Raman Amplifiers

Nihal M. Anwar (nihal_anwar2005@yahoo.com) and Moustafa H. Aly* (mosaly@aast.edu)

College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport Alexandria, Egypt
* Member of OSA.

Abstract
This paper investigates Raman gain for backward pumping using three different fiber types. The rate and propagation equations characterizing fiber Raman amplifiers (FRAs) are numerically solved. In this way, the gain is simulated for the given FRA parameters or the required fiber parameters and signal/pump power values could be optimized for a desired FRA gain. Gain is obtained as a function of fiber length and pump power. According to the obtained results, gain is strongly dependent on the fiber length and pumping power.

I. Introduction
It is more than 20 years, since fiber-optic communications have been in commercial use and new technological developments are constantly being made. Several years ago dense wavelength-division multiplex (DWDM) transmission using Erbium-doped fiber amplifiers (EDFAs) became the mainstream technology for large-capacity long-haul systems. More recently, to set new records, it has become indispensable to make use of Raman amplifiers (RAs), optimizing the dispersion characteristics of the transmission path. During the 1980s the RA was extensively studied as a promising candidate for use in fiber-optic transmission. When bit-rates were rising from 10 Gbps to 40 Gbps, it was not possible to design systems that used only discrete amplifiers like EDFAs and the advantages of distributed Raman amplification, in which the transmission path as a whole is the amplifying medium, again came to be recognized. Pumps used for RAs may be constructed from semiconductor laser diodes or all fiber lasers [1]. Raman amplifier provides several advantages, such as low noise, simplicity, flexible use of signal wavelengths and broad gain bandwidth compared to EDFA [2]. Raman amplifier uses the stimulated Raman scattering (SRS) phenomenon, where a strong pump laser at shorter wavelength provides gain to signals at longer wavelengths. Raman gain coefficient is strongly dependent on the frequency shift between the pump and signal frequencies.

One of the most usable in the contemporary submarine and long-haul terrestrial networks is the distributed Raman amplifier (DRA), where 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 [2].

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 km. 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 [2].

A FRA is usually designed employing the averaged power analysis considering forward and backward propagation directions for the pump and the signal through the optical fiber. SRS is a nonlinear effect due to interactions between light waves with molecular vibrations in silica fiber as shown in Fig 1.

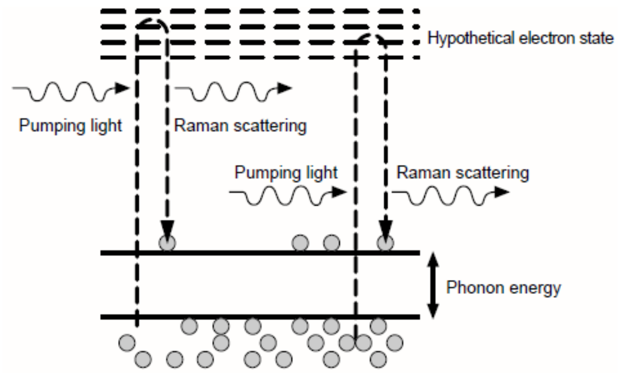

Fig. 1 Stimulated Raman scattering [3].

The paper is organized as follows: Mathematical formulations are presented in Sec. II. Simulation results and discussion are shown in sec. III, followed by the conclusion in Sec. IV.

II. MATHEMATICAL FORMULATIONS

The scheme of a typical DRA which uses two pump sources is shown in Fig. 2. 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 [4]. 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 the present research, it is assumed that the power of the pump source PS1 is S P_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.

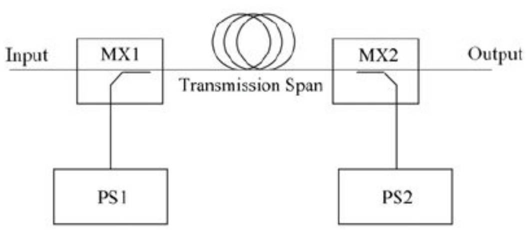

Fig. 2 Distributed Raman amplifier.

The evolution of the signal, P_S, and the power of the pump source, P_p, 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 [5]

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$$\pm\frac{dP_P}{\Box z} = -\frac{\Box_P}{\upsilon_S} g_R P_p P_S - \alpha_P P_P, \quad (1)$$

$$\frac{dP_s}{dz} = g_R P_{\Box} P_S - \alpha_S P_S, \quad (2)$$

where g_R ($W_{-1}.m^{-1}$) is Raman gain coefficient of the fiber α_s and α_p are the attenuation of the signal and the pump power in silica fiber, υ_s and υ_p are signal and pump frequencies. The signs of „+" or „–" correspond to forward and backward pumping. Since $P_p >> P_S$, the first term in Eq. (1) is negligibly low compared with the second and its influence can be neglected. Therefore, Eq. (1) can be solved when both sides are integrated. When using forward pumping (*S*=1), the pump power can be expressed as [6]

$$P_P(z) = P_p(0)e^{-\alpha_P L}. \quad (3)$$

In the backward pumping case (*S* = 0), the pump power is

$$P_P(z) = P_p(0)e^{[-\alpha_P(\Box - z)]}. \quad (4)$$

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

In the general case, when a bidirectional pumping is used (*S* = 0 or 1), 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 [5]

$$P_P(z) = SP_p(0)e^{-\alpha_P L} + (1 - S)P_p(0)\Box^{[-\alpha_P(L-Z)]} \quad (5)$$

If the values of P_p are substituted in differential Eq. (2) and it is integrated from zero to *L,* the signal power in the forward (f) and the backward (b) pumping an be obtained as

$$P_S(L) = P_S(0)\exp\left\{g_R S\Box_o \frac{1 - e^{-\alpha_P z}}{\alpha_P} - \alpha_S z\right\} \quad (6)$$

$$= G_f P_S(0)$$

$$P_S(L) = P_S(0)\exp\left\{g_R(1 - S)P_o \times \frac{\exp(-\alpha_P L)\,[\exp[(\alpha]_P z) - 1]}{\alpha_P} - \alpha_S z\right\}$$

$$= G_b P_S(0) \quad (7)$$

where G_f and G_b are the net gain in the forward and the backward pumping. 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. The the net signal gain, G (L), can be simply described by the expression [5]

$$G_{NET}(L) = {P_S(L)}/{P_S(0)} \qquad (8)$$

Because of pump absorption, the effective amplification length is reduced from L to L_{eff} [6]

$$L_{eff} = \frac{\square - e^{-\alpha_P L}}{\alpha_{\square}}. \qquad (9)$$

For short lengths, the effective length approximates L, and for long length, it reaches $1/\alpha_P$.

If the Raman gain is not sufficient to overcome fiber losses, it is useful to introduce the concept of the on–off Raman gain using the definition [7]

$$G_R(L) = P_S(L)_{\text{with pump on}} / P_S(L)_{\text{with pump off}} = \exp(C_R P_{Po} L_{eff}) \qquad (10)$$

Clearly, $G_R(L)$ represents the total amplifier gain distributed over a length L_{eff}.

III. Simulation results and discussion

Based on the described model, MATLAB ver. 7.5 is used to perform calculations. Table 1 presents the values of the parameters which will be used to numerically solve Raman amplification.

Table 1 Measured fiber parameters

Fiber type	**Freelight**	**SMF**	**Truewave-RS**
α_S(dB/km)	0.2	0.2	0.2
α_P(dB/km)	0.260	0.263	0.256
g_R (1/W.km)	0.54	0.42	0.69

III.1 Raman Gain Characteristics

A. Dependence of Raman Gain on Pump Power (Forward and Backward Pumping)

Figure 3 shows the variation of gain with pump power for different fiber lengths at a constant signal input power. The obtained results showed that forward and backward pumping have the same result. In this simulation, a span of 100 km for three different fiber types is used and the pump power supplied was increased from 0 to 1500 mW. It is clear that, the gain of the FRA linearly increases with pump power As a result; the gain coefficient in dB/W reduces for high pump powers. In addition, a higher gain can be obtained at a longer Raman fiber with sufficient pumping. The Truewave fiber has a higher gain than the two other fiber types [8].

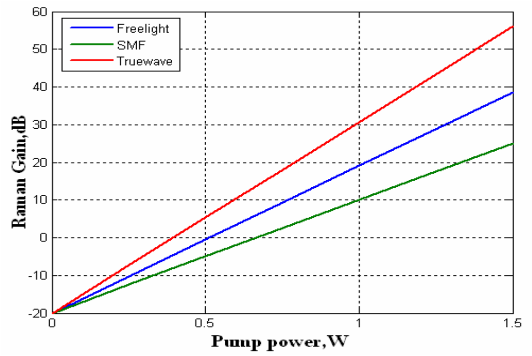

Fig. 3 The Raman gain as a function of pump power for 100 km fiber span of different fiber types [8].

B. Dependence of Raman Gain on Fiber Length (Backward Pumping)

The variation of gain with fiber length is shown in Figs. 4,5 and 6 for different pump powers for the three different fiber types (SMF, Freelight and Truewave) having different Raman gain coefficients and constant signal input power. In these figures, the obtained gain from an amplifier for six different pump power levels are given for a 100 km fiber length. As it is shown, the gain increases with the fiber length until it reaches a certain level between 40-60 km approximately and then decreases until it intersects with axis (reaches zero), keeping in mind that the gain is considered only in the negative region for the backward pumping [8]. It is clear that, in all cases, the gain increases with the pump power.

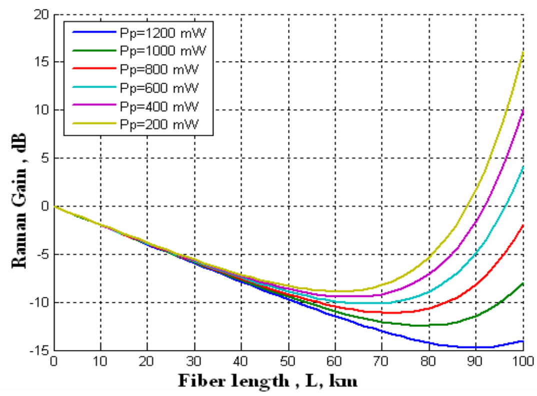

Fig. 4 Raman net gain as a function of fiber length for

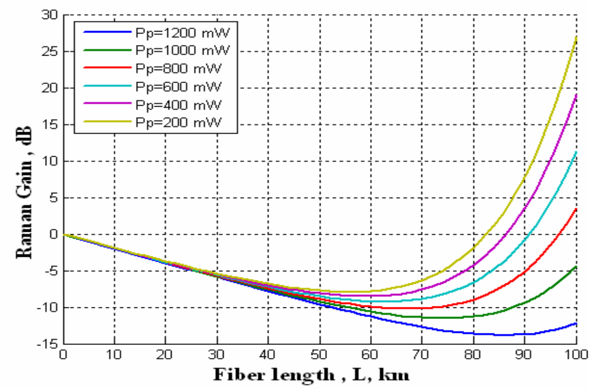

Fig. 5 Raman net gain as a function of fiber length for

SMF at different pump powers. Freelight at different pump powers.

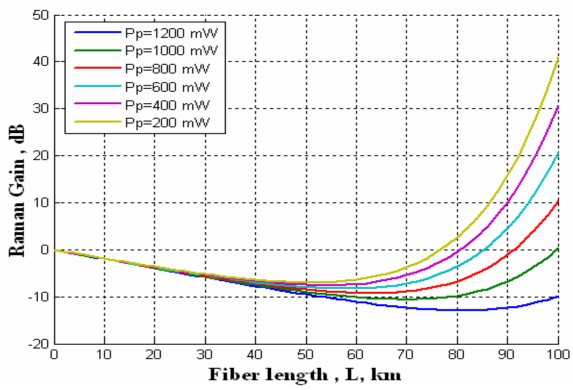

Fig. 6 Raman net gain as a function of fiber length for Truewave fiber at different pump powers.

A comparison between three different fiber types (SMF, Freelight and Truewave) is obtained, as shown in Figs. 7, 8 and 9, at different pump powers for the fiber types having different Raman gain coefficients and constant signal input power.

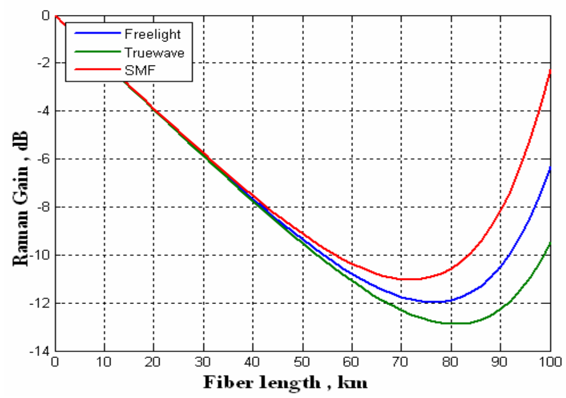

Fig. 7 Raman net gain as a function of fiber length for different fiber types at 350 mW pump power.

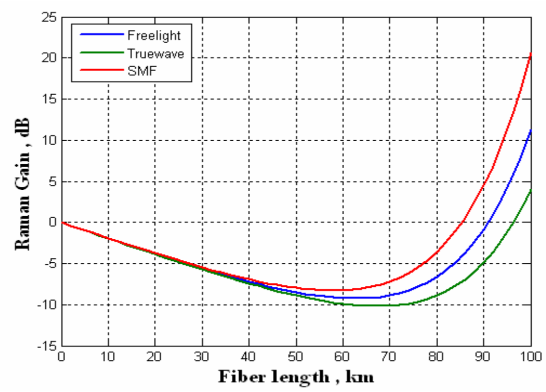

Fig. 8 Raman net gain as a function of fiber length for different fiber types at 800 mW pump power.

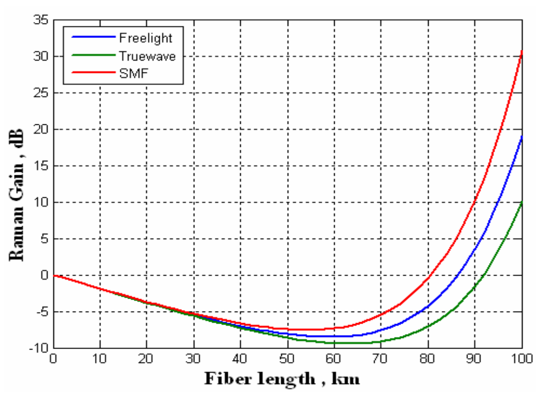

Fig. 9 Raman net gain as a function of fiber length for different fiber types at 1000 mW pump power.

C. Output Signal Power Characteristics (Backward Pumping)

Figures 10, 11 and 12 show how the output signal power varies with the fiber length for different pump powers and fiber span of 100 km at a constant signal power, –5 dBm, applied to the three fiber types.

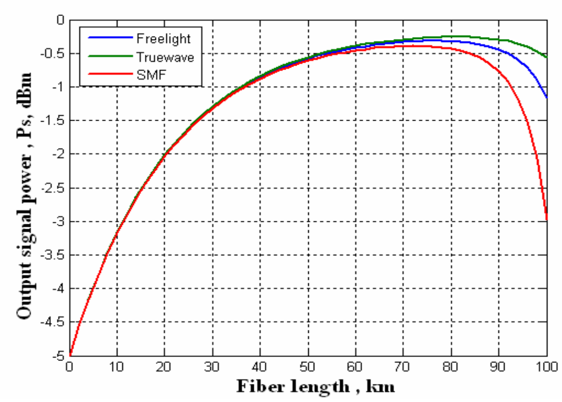

Fig. 10 Output signal power as a function of fiber length for different fiber types at 350 mW pump power and -5dBm input signal power.

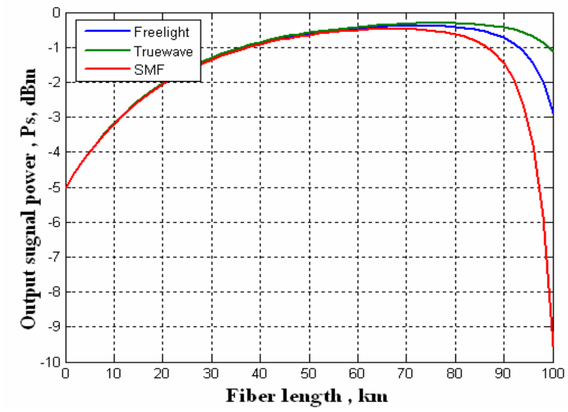

Fig. 11 Output signal power as a function of fiber length for different fiber types at 800 mW pump power and -5dBm input signal power.

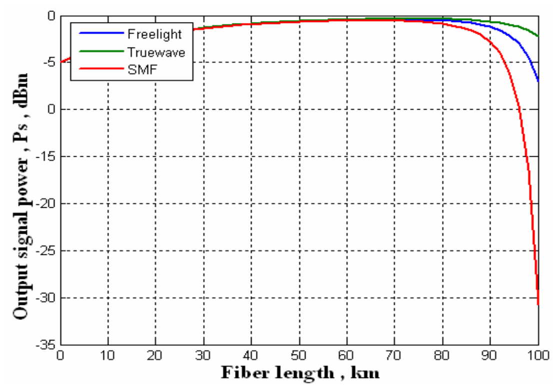

Fig. 12 Output signal power as a function of fiber length for different fiber types at 1W pump power and -5dBm input signal power.

The output signal power increases to reach a saturation level (between 30-80 km) and then decreases after 100 km. This gives a Raman gain around 15 dB at backward pumping. It is also obvious that gain increases with the pump power.

IV. Conclusion

The rate and propagation equations characterizing FRAs are numerically solved. The Raman gain of an optical signal is observed to depend on the selection of pump power. The analysis in this paper is carried out by incorporating backward pumping. The FRA gain is obtained as a function of fiber length and pump power. In this way, the gain is simulated for the given FRA parameters or the required fiber parameters and signal/pump power values could be optimized for a desired FRAs gain. According to the obtained results, gain is strongly dependent on the fiber length and pumping power. The differences between three different fiber types are satisfied. Backward pumping performs better than forward pumping with respect to signal power level and uniformity. At least, 80 km fiber amplifier lengths are obtained for different pumping powers.

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