Signal Gain and Degradation in Fiber Raman Amplifiers

Shirley P. Neves, Marcio Freitas, Luiz C. Calmon
Telecommunications Laboratory, Federal University of Espírito Santo, Vitória ES, Brazil

Abstract – **Raman Fiber Amplifiers will be important for the next generation high speed dense WDM optical communications systems due to its inherent broadband characteristics, fast response, moderate gain, and low noise figure. Signal gain characteristics of Raman amplifiers have been investigated recently, but very little has been said about signal degradation caused by dispersion and nonlinear effects in Raman amplifiers. This paper analyses different types of fibers as candidates for Fiber Raman Amplifiers considering signal gain issues, but also takes into account dynamic aspects related to signal degradation caused by group velocity dispersion and diverse nonlinear effects such as self-phase and cross-phase modulations.**

I. INTRODUCTION

RAMAN amplifiers are recently receiving much attention because of advances in high-power laser diodes, and the ability to extend the wavelength range of optical gain beyond that of erbium-doped fiber amplifiers, while providing the following beneficial characteristics: flexibility in the location and width of the amplification window, possibility of flat gain operation with simple adjustment of multiple pumps, low noise figure, and moderate gain. Fiber Raman Amplifiers (FRAs) can be used in two basic configurations: co-pumped FRAs, where signal and pump travel in the same direction along the fiber; and counter-pumped FRAs where signal and pump travel in opposite directions along the fiber. In co-pumped FRAs, fluctuations in the pump power can be coupled into the signal power as noise, and therefore is not the preferred choice between designers, and generally the signal is at its strongest at the beginning of the fiber link, barely necessitating strong amplification at this point, while in the counter-pumped FRAs the signal is amplified most strongly at its weakest points.

There are currently a variety of approaches to the implementation of Fiber Raman Amplifiers and there is no consensus on what gain fiber and length, pump source or amplifier configuration to use. In fact these factors are interrelated, but with appropriate simulations we can determine general guidelines for the design of Raman amplifiers. This is the purpose of this paper, where we will determine the optimal gain of Raman amplifiers for different fiber types, fiber lengths and pump powers, and an account will be also given for the signal degradation through these amplifiers.

II. MODELING GAIN IN FIBER RAMAN AMPLIFIERS

Raman Amplifier Configuration with Co-Propagating and Counter-Propagating Pumping and Signal schemes is shown in Fig.1. Values for pump and signal wavelengths and powers were taken from [1]:

Pump Wavelength = 1480 (nm)
Signal Wavelength = 1586 (nm)
Pump Power = 0.3 (W);
Signal Power = -20 (dBm)

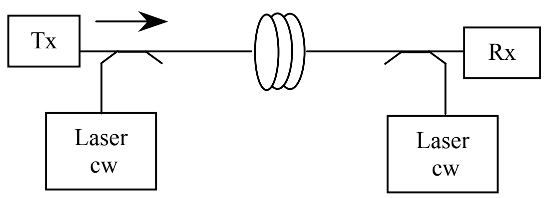


Fig 1: General Configuration of Raman Amplifiers in co-pumping and counter-pumping schemes

The equations which govern power evolution and exchanges between pump and signal , disregarding noise temperature dependence, are [2], [4]:

$$\frac{dP_P}{dz} = -\alpha_P P_P - g_P\left(P_S^+ + P_S^- + 4N_E\right)P_P \quad \text{(forward pumping)}$$

$$\frac{dP_P}{dz} = \alpha_P P_P + g_P\left(P_S^+ + P_S^- + 4N_E\right)P_P \quad \text{(backward pumping)}$$

$$\frac{dP_S^+}{dz} = -\alpha_S P_S^+ + g_S P_P (P_S^+ + 2N_E) + \gamma_R P_S^- \quad \text{(Sinal forward)}$$

$$\frac{dP_S^-}{dz} = \alpha_S P_S^- - g_S P_P (P_S^- + 2N_E) - \gamma_R P_S^+ \quad \text{(Scattered Signal)}$$

(1)

Where $g_R = \frac{(f_P - f_S)}{1.5\times 10^{13}} G_R$ is the Raman Gain coeficiente between pump and signal [3]

$g_S = \frac{g_R}{A_{eff}}$, and $g_P = \frac{\omega_P}{\omega_S} g_S$.

$N_E = h\, f_S\, \Delta\nu$ is the Raman spontaneous emission noise power, with bandwidth $\Delta\nu$ around frequency f_S. ($\Delta\nu = 0.5nm$ [1])

γ_R is the Rayleigh scattering coefficient

$\alpha_{P,S}$ is the attenuation coefficient for pump and signal

Fiber types and parameters were taken from [1], [4], [5]and [6], and are shown on Table 1

TABLE 1

FIBER TYPES ANALYSED

Fiber Parameters	Single Mode **SMF**	Dispersion Shifted **DSF**	Dispersion Compensat **DCF**	Dispersion Flattened **DFF**
$\alpha_{p,s}$ (dB/km)	0.19	0.3	0.412	0.215
A_{eff} $(\mu m)^2$	80	50	15.3	28
$G_R \times 10^{-14}$ (m/W)	1.52	2.08	3.93	2.81
γ_R (dB/km)	-38	-38	-38	-38
D_{1480} ps/(km-nm)	13.08	-5.25	-0.84	-
D_{1586} ps/(km-nm)	19.016	2.7	-1.052	-

For Raman gain analysis the following curves were obtained: Net Gain (NG) and Signal Gain (GP).

$$NG = 10\log_{10}\left(\frac{P_S}{P_{Sa}}\right) \qquad (2)$$

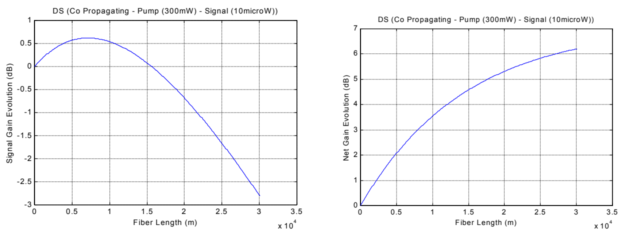
P_{Sa} = signal power, only attenuated along the fiber

$$GP = 10\log_{10}\left(\frac{P_{S(in)}}{P_{S(out)}}\right) \qquad (3)$$

$P_{S(in)}$ = input signal power into the fiber

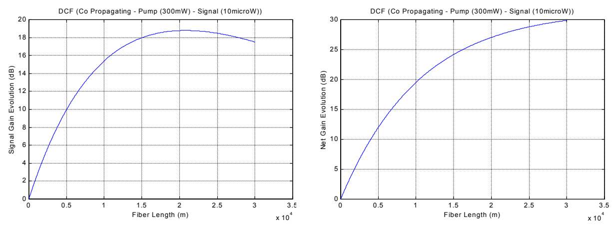
$P_{S(out)}$ = output signal power from the fiber

Net Gain (NG) shows the signal power evolution related to the fiber loss, and the Signal Gain (GP) shows signal power evolution related to the input signal into the fiber.



(a) (b)

Fig 2: Co-Pumping (a) Signal Gain (b) Net Gain evolution along a 30 Km DSF, for pump power of 0.3 Watts



(a) (b)

Fig 3: Co-Pumping (a) Signal Gain (b) Net Gain evolution along a 30 Km DCF, for pump power of 0.3 Watts

These figures (2) and (3) show that in the co-propagating pump scheme the Signal Gain (GP) reaches a maximum at a particular fiber length, and the Net Gain reaches a saturation value at a particular fiber length, which is not a very desirable feature. The Raman gain in a DCF fiber is much higher than in a DSF (approximately 20 dB higher), and this is due to its smaller effective area.

The following figures show the NG and the GP evolution in a counter-pumping scheme along the same fibers and lengths as above (30 Km of DSF and DCF), for different pump powers (0.3, 0.5, 0.7, 1 Watt)

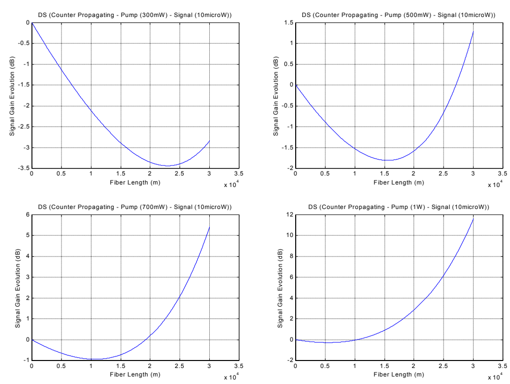


Fig 4: Counter-Pumping Signal Gain evolution along a 30 Km DSF, for pump powers of 0.3, 0.5, 0.7 and 1 Watt

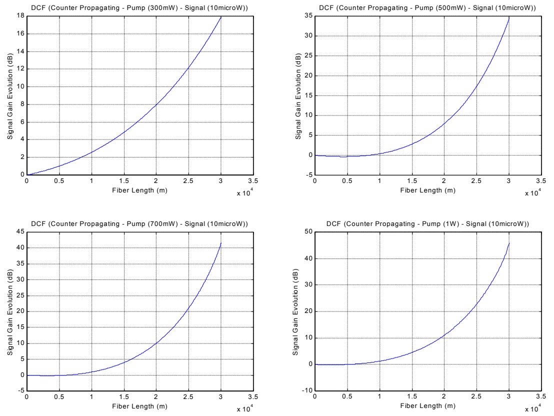


Fig 5: Counter-Pumping Signal Gain evolution along a 30 Km DCF, for pump powers of 0.3, 0.5, 0.7 and 1 Watt

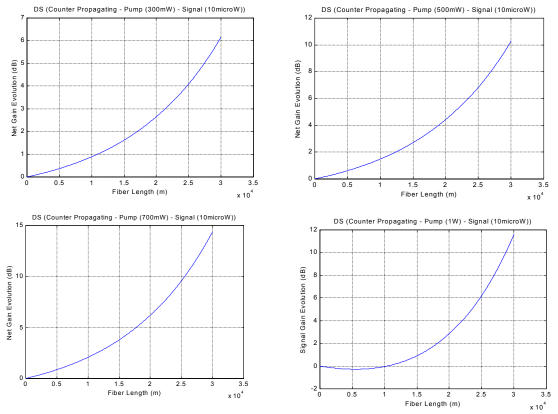


Fig 6: Counter-Pumping Net Gain evolution along a 30 Km DSF, for pump powers of 0.3, 0.5, 0.7 and 1 Watt

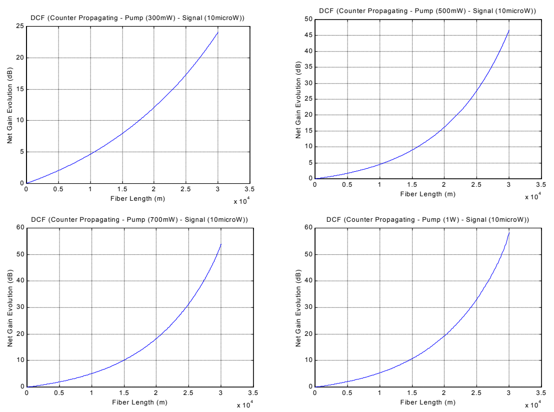


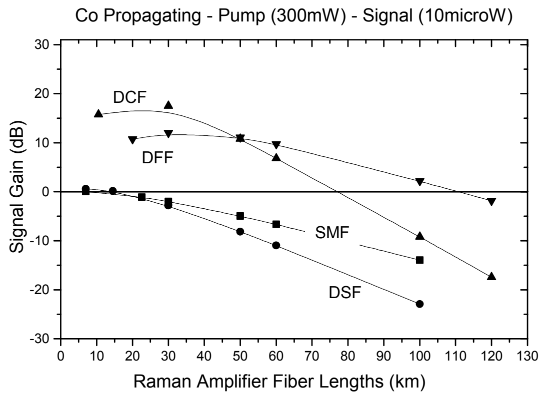
Fig 7: Counter-Pumping Net Gain evolution along a 30 Km DCF, for pump powers of 0.3, 0.5, 0.7 and 1 Watt

Figs (4), (5), (6) and (7) show that in the counter-pumping scheme neither the Signal Gain nor the Net Gain reach saturation values along the fiber, and that both gains increase with the pump power.

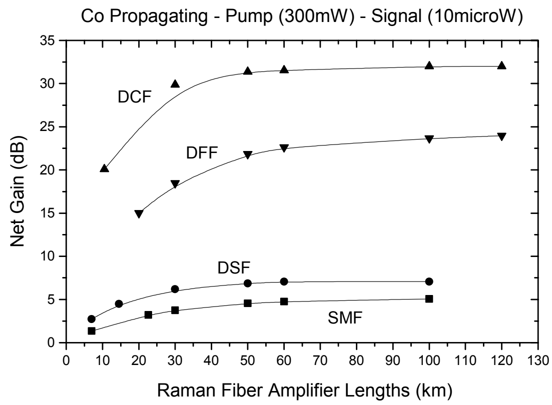
III. Optimizing Gain and Fiber Lengths in Raman Amplifiers

Doing various simulations for different fibers, with different amplifier fiber lengths and pump powers in co-propagating and counter-propagating schemes, we obtained the following results for the Signal Gains and the Net Gains.

Co-Propagating Scheme:



(a)



(b)

Fig 8: (a) Signal Gain and (b) Net Gain obtained for Co-Pumping Fiber Raman Amplifiers of various lengths for pump power of 0.3 Watt in DCF, DFF, DSF and SMF fibers.

In figs 8 (a) and (b) it can be seen that co-pumping fiber Raman amplifiers of lengths between 30 and 50 Km give the best results for gain in this case. Longer fiber lengths do not improve the Net Gain, and deteriorates the Signal Gain. Similar conclusions apply for the counter-pumping scheme, as shown on the following Figs 9 and 10. In this case the optimal fiber lengths for higher Signal Gains are between 30 and 50 Km for 0.3 Watt pump power, and slightly increases as the power increases. Net Gain saturation also occurs at longer lengths with higher pumps.

Counter-Propagating Scheme

Net Gain

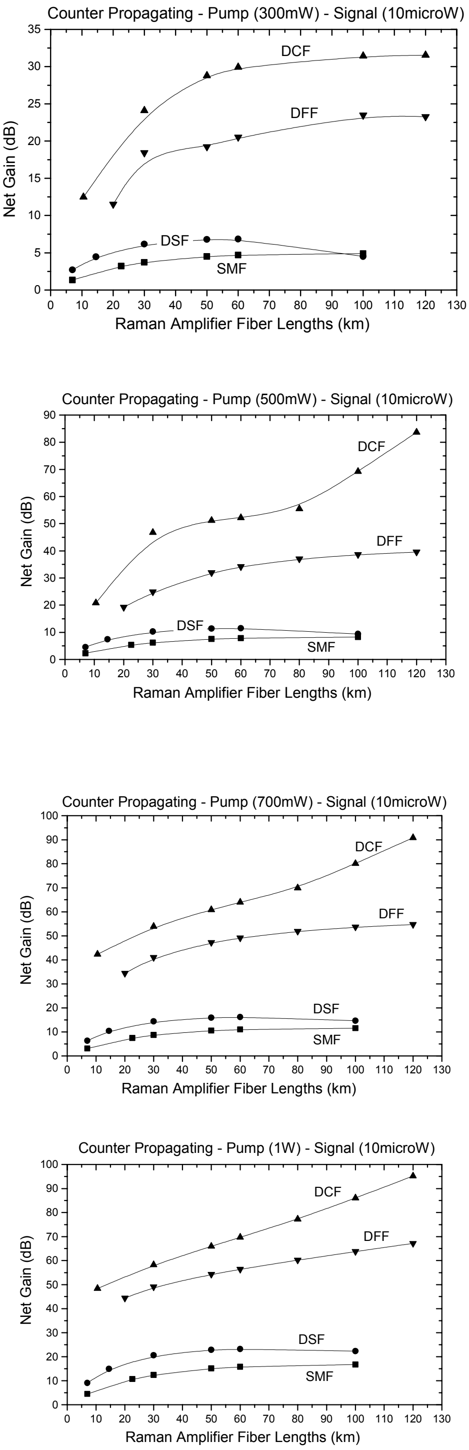


Fig 9: Net Gain in Counter-Pumped Raman Amplifiers against amplifier length for different fibers and pump powers

Signal Gain

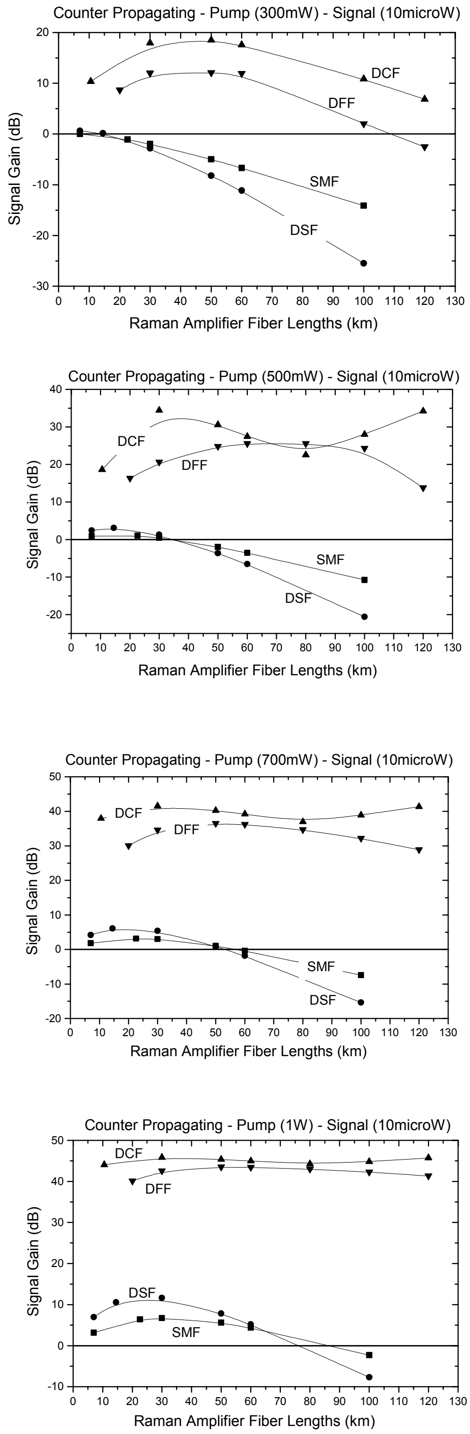


Fig 10: Signal Gain in Counter-Pumped Raman Amplifiers against amplifier length for different fibers and pump powers

IV. SIGNAL DEGRADATION IN RAMAN AMPLIFIERS

A NRZ signal format with super gaussian pulses of degree n=2 is used, forming a pseudo random sequence of 64 bits in a counter-pumping scheme with 0.3 Watts pump power. Raman amplifier fiber length is 30 km.

The following coupled differential equations for amplitudes A (pump and signal) apply in this case:

(counter-pumping) (4)

$$\frac{\partial A_P}{\partial z}+\frac{j}{2}\beta_{2_P}\frac{\partial^2 A_P}{\partial T^2}-\frac{j}{6}\beta_{3_P}\frac{\partial^3 A_P}{\partial T^3}-\frac{\alpha_P}{2}A_P=$$
$$j\gamma_P\left(|A_P|^2+2|A_S|^2\right)A_P+\frac{g_P}{2}\left(|A_S|^2\right)A_P$$

(signal forward) (5)

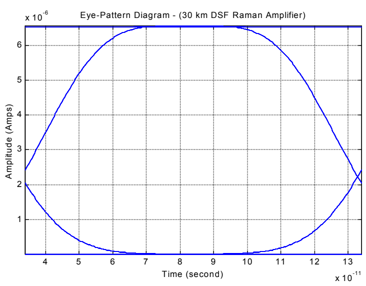
$$\frac{\partial A_S}{\partial z}+\frac{j}{2}\beta_{2_S}\frac{\partial^2 A_S}{\partial T^2}-\frac{j}{6}\beta_{3_S}\frac{\partial^3 A_S}{\partial T^3}+\frac{\alpha_S}{2}A_S=$$
$$j\gamma_S\left(|A_S|^2+2|A_P|^2\right)A_S+\frac{g_S}{2}\left(|A_P|^2\right)A_S$$

First and second order GVDs are $\beta_{2_{P,S}}$ and $\beta_{3_{P,S}}$.

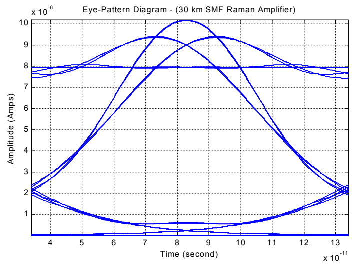
$\gamma_{P,S}=\dfrac{2\pi N_2}{\lambda_{P,S}\,A_{eff}}$ is the nonlinear parameter.

g_P and g_S are the same as defined before.

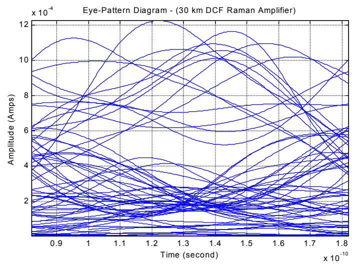
Signal bit sequence of –20 dBm peak power is injected at one end of the fiber (z=0), and Equations (4) and (5) were solved using the split-step Fourier method in conjunction with a interactive scheme to achieve the correct pump power of 0.3 Watts injected at the opposite end of the fiber (z=30 Km). Eye penalty diagrams were obtained for SMF, DSF and DCF.



(a) DSF



(b) SMF



(c) DCF

Fig 11: Eye Penalty degradation for different types of Raman Amplifiers made with 30 Km of (a) DSF, (b) SMF and (c) DCF fibers. Pump power is 0.3 mWatt.

V. CONCLUSION

According with the present analysis an optimal fiber choice for a Raman amplifier would be a fiber with a smallest effective area (high gain) and lowest group velocity dispersion (low eye penalty). An optimal gain design can be obtained through simulations for a given fiber type, choosing the correct fiber length and pump power for a particular application. Using a DCF fiber in a Raman amplifier, it is mandatory to design a proper dispersion compensation scheme to avoid bit degradation. Presently work is been done in characterizing noise figure of Raman amplifiers.

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[6] ITU Recommendation G.652, Geneve, Oct. 2000.