Raman Amplifier Numerical Model

Meire C. Fugihara[1,2], Micaela Bernardo[1,2], Armando Nolasco Pinto[1,2], Sergio Stevan Jr[1,2], Hypolito J. Kalinowski[3]

[1]Institute of Telecommunications, 3810-193 Aveiro, Portugal
[2]Department of Electronic, Telecommunications, and Informatics, University of Aveiro, 3810-193 Aveiro, Portugal
[3]Federal University of Technology – Paraná, 80230-901 Curitiba – PR, Brazil
Phone: +351 234 377900, Fax: +351 234 377901, e-mail: meire@av.it.pt

***Abstract* — We validate a Raman amplifier model with experimental data. We show comparisons between numerical and experimental results for an amplified system in a forward configuration, using three different wavelength pumps, and for a backward configuration, with one single pump. The predictions obtained with the numerical model agree well with the measurements for both cases, presenting a maximum deviation of 0.32 dB in terms of Raman gain.**

I. INTRODUCTION

Raman amplifiers can provide gain over a large bandwidth. This is a considerable advantage over standard Erbium doped fiber amplifiers. Erbium doped fiber amplifiers provide gain over a spectral window of 40 nm centered around the 1.55 µm wavelength. This restriction is quite limitative for several transmission systems. In particular this restriction precludes the use of Erbium doped fiber amplifiers in CWDM (*Coarse Wavelength Division Multiplexing*) [1] systems.

CWDM is attractive for links where the required capacity is small; in the order of few tens of Gigabits per second or less. In this situation by using several wavelengths quite far apart is possible to design a system with low cost components. The reason why the components for CWDM are less expensive than the same components for DWDM (*Dense Wavelength Division Multiplexing*) is because as the wavelengths are much far apart, 20 nm versus 0.8 nm, the tolerance in the components is much larger, for instance, the central wavelength of the laser can fluctuate substantially because the cross talk between channels are virtually negligible due to their large separation.

However, as the channels are far apart the spectrum used tends to be of the order of hundreds of nanometers. This excludes the use of Erbium doped fiber amplifiers. Therefore some other form of optical amplification must be used in order to increase the reach of the systems. In this work we present a model for a Raman amplifier that can suits CWDM systems.

This work was partially supported by the Portuguese Scientific Foundation, FCT, through the Ph.D. fellowship SFRH/BD/16734/2004, and the "PMD - Polarization Mode Dispersion in High-Speed Optical Communication Systems" project (POSI/CPS/47389/2002), and by the PT Innovation through the IT project P289, "Raman Amplification for CWDM systems".

In the next section we present the Raman amplification model. In section III, we validate the model with experimental data obtained in our laboratory, and we conclude the paper with a brief discussion about the obtained results.

II. THEORETICAL MODEL

The mathematical model used in this work is based on the following set of coupled equations for optical signals propagating along an optical fiber [3]

$$\begin{aligned}\frac{dP^{+}_{\nu_k}(z)}{dz} &= -\alpha_{\nu_k} P^{+}_{\nu_k}(z) + \sum_{j\neq k}\left\{ g_{jk}\left[P^{+}_{\nu_j}(z)+P^{-}_{\nu_j}(z)\right]P^{+}_{\nu_k}(z)\right\} \\ \frac{dP^{-}_{\nu_k}(z)}{dz} &= \alpha_{\nu_k} P^{-}_{\nu_k}(z) - \sum_{j\neq k}\left\{ g_{jk}\left[P^{-}_{\nu_j}(z)+P^{+}_{\nu_j}(z)\right]P^{-}_{\nu_k}(z)\right\}\end{aligned} \quad \textbf{(1)}$$

where $P^{+}_{\nu}(z)$ and $P^{-}_{\nu}(z)$ are the optical powers of the forward and backward propagating signals given in W, respectively, α is the attenuation coefficient given in W/m, g_{jk} is the Raman gain coefficient at frequency ν_k due to frequency ν_j given in $(W.m)^{-1}$. The value of g_{jk} depends on the separation between frequencies as can be seen in the following expression [3]

$$g_{jk} = \begin{cases} \dfrac{g_R(\nu_j-\nu_k)}{K_{eff}A_{eff}} & \nu_j \geq \nu_k \\ -\dfrac{\nu_k}{\nu_j}\cdot\dfrac{g_R(\nu_j-\nu_k)}{K_{eff}A_{eff}} & \nu_j < \nu_k \end{cases} \quad \textbf{(2)}$$

where K_{eff} accounts for the mismatch in polarization between the signals, A_{eff} is the effective mode area of the fiber in m^2, and $g_R(\nu_n - \nu_m)$ is the Raman gain coefficient given in m/W. The values used for the Raman gain coefficient, $g_R(\nu_n - \nu_m)$, were obtained by us experimentally. To obtain the function $g_R(\nu_n - \nu_m)$, a set of Gaussian functions was used to fit the data [4].

Since we use multiple functions for the fitting, a general expression for g_R can be written as a sum of Gaussian functions,

$$g_R(\nu_j - \nu_k) = \sum_{q=1}^{n} A(q) \cdot e^{-\frac{((\nu_j - \nu_k) - x_c(q))^2}{2\sigma(q)^2}} \quad \textbf{(3)}$$

where $A(q)$ is the amplitude of each Gaussian function, $x_c(q)$ is the peak center, and $\sigma(q)$ is the root mean square, and n is the number of functions.

The fitting uses a set of fourteen Gaussian functions. The results can be seen in the following figure where the points represent the experimental data and the line the fitting.

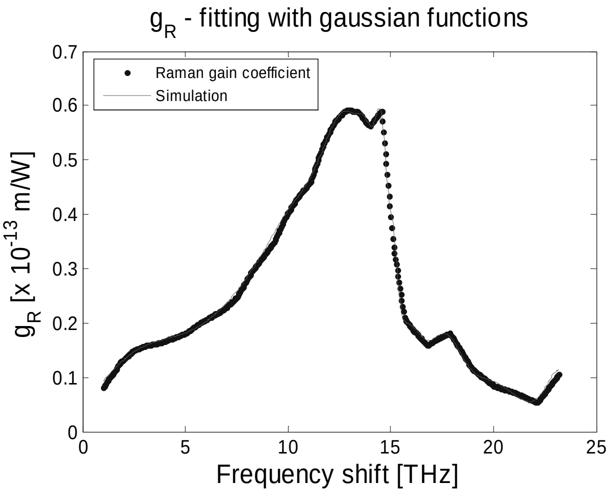

Figure 1. Fitting of the Raman gain coefficient using Gaussian functions. The points represent experimental data and the line the fitting with Gaussian functions.

Generally expression (1) led to a boundary value problem, where the boundary conditions for the different signals are not spatially coincident; this situation is illustrated in Figure 2. The solution of this problem requires a shooting method used iteratively in conjugation with a numerical method to solve coupled differential equations. In this work we used the Runge-Kutta method.

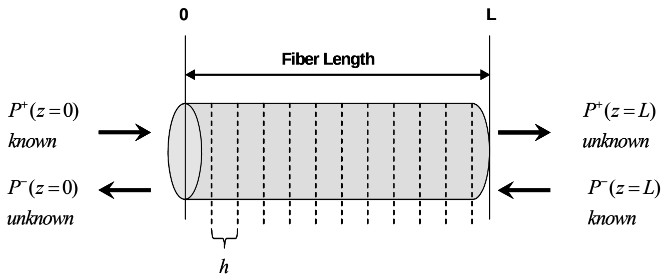

Figure 2. Optical fiber divided in small segments for numerical integration and showing the problem of boundary conditions.

III. VALIDATION WITH EXPERIMENTAL MEASUREMENTS

The purpose of this part of the work is to validate the numerical method with experimental data. To this intent we prepare an experimental setup, see Figure 3. The experimental setup is composed of a CW laser, which generates the probe signal, a set of pumps, which are going to excite the medium, an optical fiber, that serves as a transmission and gain medium, couplers, and an Optical Spectrum Analyzer (OSA) at the receiver side. As the optical fiber is both the transmission and gain medium, this system is usually named distributed Raman fiber amplifier.

Raman amplification can be obtained using three different configurations: (a) co-propagating, when the pumps are sent in the same direction as the signals, (b) counter-propagating, when the pumps and the signals are in opposite directions, and (c) bidirectional, when the pumps propagate in both directions.

In this paper we show results for a system with three forward pumps, and for another system with one backward pump. The reason of using three pumps is to verify the behavior of the Raman amplifier with the insertion of more than one pump and the effects that such multiple pumping can cause in the value and format of the gain spectrum. The second part, with one backward pumping, was used to verify that our model can also be applied in the backward configuration.

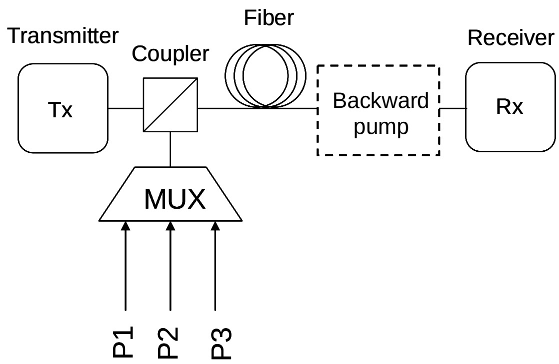

Figure 3. Schematic of the forward three pump Raman amplifier

Figure 3 shows the schematic of the forward three pump configuration. A WDM multiplexer is used to couple the three pump lasers: P1 centered in 1470 nm with 96 mW, P2 centered in 1490 nm with 26.4 mW, and P3 centered in 1508 nm with 37.9 mW, all of the pumps coupled to the signal through an optical coupler. The values of the pump powers, given above, were measured after the coupler. The probe signal has 1 mW, and a tunable wavelength. Measurements and simulations are carried out from 1520 nm to 1660 nm. The fiber is a single mode fiber (SMF), with 40 km of length, with 80 μm^2 of effective area, and attenuation of 0.23 dB/km.

Figures 4, 5, and 6 show the behavior of the gain as function of the wavelength of the probe signal using a single pump. Figure 7 shows the case of multiple pumps.

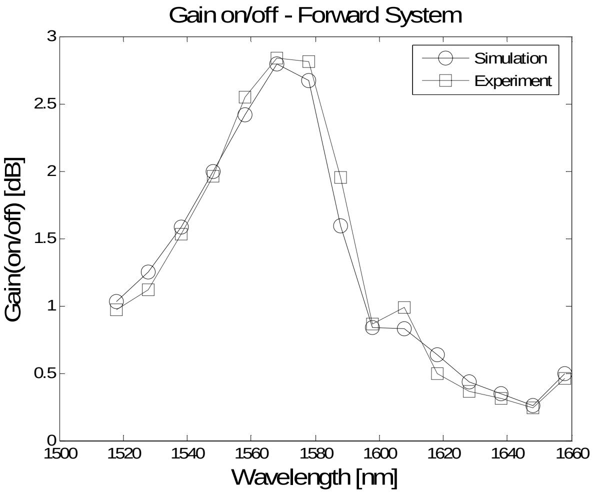

Figure 4. Raman gain due P1 – 1470 nm/96 mW. Simulation results are shown with "○" symbols and experimental results with "□" symbols.

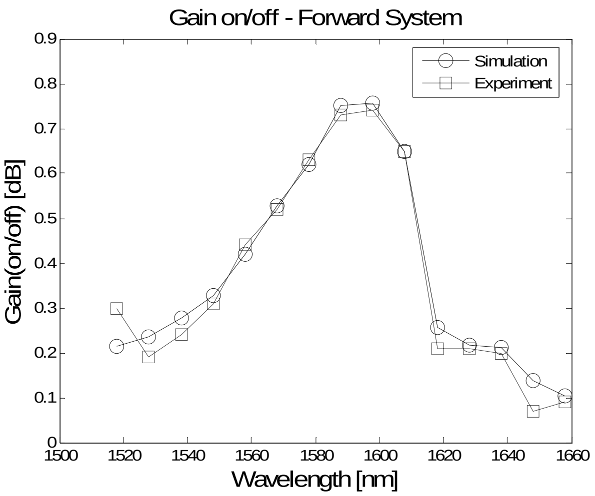

Figure 5. Raman gain due P2 – 1490 nm/26.4 mW. Simulation results are shown with "○" symbols and experimental results with "□" symbols.

Figure 4 shows the on/off gain spectrum due the pump P1, centered in 1470 nm / 96 mW. The on/off gain is the ratio between the output signal power with pump and without pump:

$$G_{on/off} = 10 \cdot \log_{10}\left(\frac{P_s^{with\ pump}(z)}{P_s^{without\ pump}(z)}\right) \quad \textbf{(4)}$$

Values of simulation are in "○" symbols, and experimental values are in "□" symbols. Experimental values of the gain converge to the theoretical values. The maximum difference between them is around 0.15 dB.

Figure 5 shows the results of gain due to pump P2, 1490 nm / 26.4 mW. Comparing the values of gain to simulation and experiment we see that the maximum difference between them is very small, less than 0.09 dB.

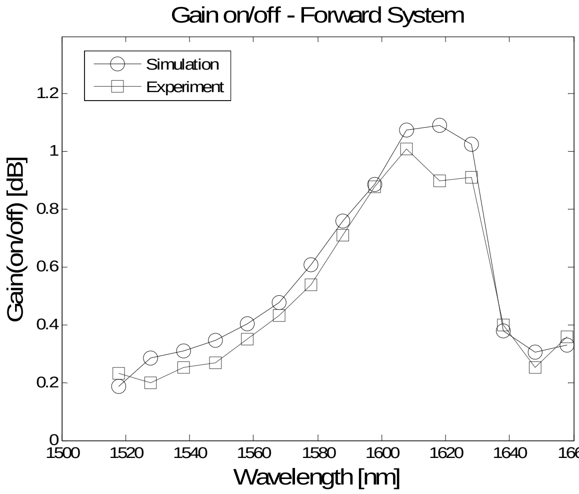

Figure 6. Raman gain due P3 – 1508 nm/37.9 mW. Simulation results are shown with "○" symbols and experimental results with "□" symbols.

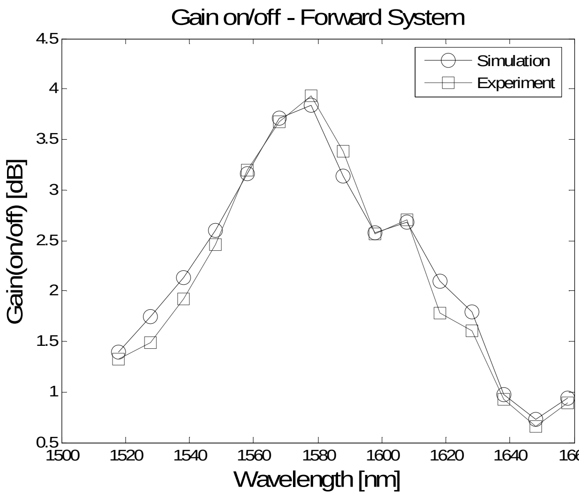

Figure 7. Raman gain due the three pumps. Simulation results are shown with "○" symbols and experimental results with "□" symbols.

Figure 6 shows the gain spectrum due P3, 1508 nm / 37.9 mW. It can be seen in the spectrum of experiment and simulation that the maximum difference between them is equal to 0.19 dB.

Figure 7 shows the gain spectrum with the use of the three pumps. The values of the gain increases and the differences of the values of the gain are around the sum of the values from each pump. We have a maximum difference between the theoretical and experimental gain around 0.32 dB. In figure 7 we can see that the use of multiple pumps can really make difference to improve the gain and the bandwidth of the Raman amplification system. Comparing graphics in figs. 4, 5, and 6 with 7, we can see an improvement of the gain value and bandwidth.

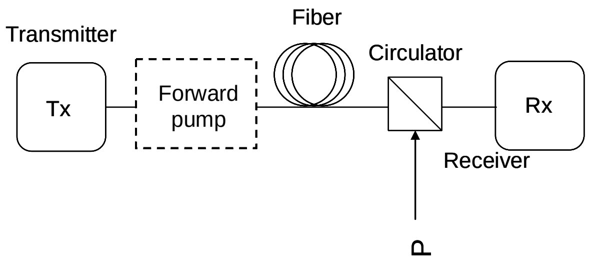

Figure 8. Schematic of the backward Raman system

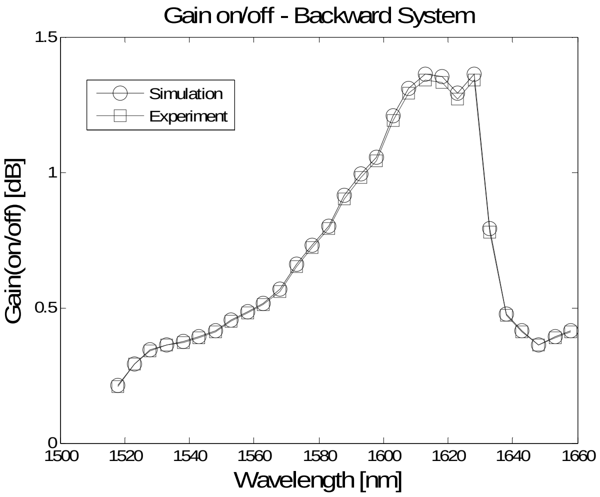

Figure 9. Raman gain to a backward configuration with a pump centered in 1508.8 nm/50 mW. Simulation results are shown with "○" symbols and experimental results with "□" symbols.

Figure 8 shows the schematic used to the backward configuration. The pump has 50 mW and it is centered at 1508.8 nm. In this case the pump was coupled into the fiber using a circulator. It can be seen, in Figure 9, the behavior of the gain spectrum due to the backward pumping. Theoretical and experimental results have a good agreement, with a maximum difference between the values around 0.02 dB.

Table I
Results of the differences between theoretical and experimental results

Pump Characteristics	Maximum Difference (dB)
Forward/1470 nm/96 mW	~0.15
Forward/1490 nm/ 26.4 mW	~0.09
Forward/1508 nm/37.9 mW	~0.19
Forward three pumps	~0.32
Backward/1508.8 nm/50 mW	~0.02

Table 1 shows the differences between the theoretical and the experimental values of the gain. The values are very interesting, showing the good behavior of the theoretical model. It can be seen that backward configuration has a better agreement, 0.02 dB with 50 mW, instead the maximum deviation in forward system with one only pump, 0.09 dB with 26.4 mW. Even considering that the forward power is lower than the backward power, the maximum deviation of the backward setup still lower.

IV. CONCLUSIONS

We validated a theoretical model for Raman amplifiers that compares with experimental data with a good agreement. A maximum difference around 0.32 dB was obtained. The developed model can be used to design, analyze and optimized CWDM optical communication systems.

REFERENCES

[1] ITU -T G.694.2, "Spectral Grids for WDM Applications: CWDM wavelength grid," 2002.

[2] ITU -T G.694.1, "Spectral Grids for WDM Applications: DWDM wavelength grid," 2002.

[3] C. Sheng, M. Xiaoming, L. Jinsong, "Effect of Pumping directions on the Performance of Fiber Raman Amplifiers Bi-directionally Pumped at Multiple Wavelengths," *Journal of Microwaves and Optoelectronics*, vol. 3, pp. 20-26, 2003.

[4] G. E. Walrafen , P. N. Krishnan, "Model analysis of the Raman spectrum from fused silica optical fibers," *Applied Optics*, vol. 21, pp. 359-360, 1982.