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Design methodology for multi-pumped discrete Raman amplifiers: case-study employing photonic crystal fibers

C. E. S. Castellani, S. P. N. Cani, M. E. V. Segatto, M. J. Pontes, and M. A. Romero

1Electrical Engineering Department, Federal University of Espírito Santo, Vitória, ES, Brazil
2Federal Institute of Espírito Santo, IFES, Vitória, ES, Brazil
3Electrical Engineering Department, University of São Paulo, São Carlos, SP, Brazil
*segatto@ele.ufes.br

Abstract: This paper proposes a new design methodology for discrete multi-pumped Raman amplifier. In a multi-objective optimization scenario, in a first step the whole solution-space is inspected by a CW analytical formulation. Then, the most promising solutions are fully investigated by a rigorous numerical treatment and the Raman amplification performance is thus determined by the combination of analytical and numerical approaches. As an application of our methodology we designed an photonic crystal fiber Raman amplifier configuration which provides low ripple, high gain, clear eye opening and a low power penalty. The amplifier configuration also enables to fully compensate the dispersion introduced by a 70-km singlemode fiber in a 10 Gbit/s system. We have successfully obtained a configuration with 8.5 dB average gain over the C-band and 0.71 dB ripple with almost zero eye-penalty using only two pump lasers with relatively low pump power.

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References and links

result is a transparent dispersion compensating module which improves the optical system margin and power budget. One drawback still remaining arises from the fact that conventional Raman fiber amplifiers have attracted attention since the 80’s because a careful combination of pump lasers, regarding both wavelength and optical power, allow wideband and flat spectral response, encompassing optical transmission systems operating all the way from S to L bands [1]. Dispersion compensating fibers (DCFs) are also fundamental components in high-speed optical communication systems. By providing a suitable pump beam it is possible to achieve Raman amplification within these fibers and compensate the DCF loss [2]. The end result is a transparent dispersion compensating module which improves the optical system margin and power budget. One drawback still remaining arises from the fact that conventional Raman amplifiers require relatively high optical power densities and/or long interaction lengths.

In order to solve this problem photonic crystal fibers (PCFs) have been intensively investigated in the past few years. Slope-matched PCFs with very high negative values of the dispersion coefficient D [3] as well as significant on-off gain for Raman amplification in short fiber lengths [4] have already been experimentally demonstrated.

The main obstacle for the practical implementation of PCF Raman amplifiers is the excess background loss [5-6], which is caused by high water (OH) content as well as the scattering losses [7]. OH-contamination will reduce the gain mainly by the introduction of an additional loss factor at the pump wavelength. The scattering loss arising from the inner surface roughness of the PCF air holes can also be very significant, in particular for fibers presenting a small effective area. Nevertheless, recent investigations report the advantageous use of

distributed PCF Raman amplification in a 10 Gbit/s fiber-optic link at 850 nm [8], as well as the demonstration of a 13.3 dB net gain lumped PCF Raman amplifier [9].

However, the design of such Raman amplifiers for wideband operation at determined gain flatness is possible only by a careful association of several pump lasers at specific power levels and emission wavelengths. The Raman amplifiers spectral response is then determined by the mutual interactions between pump and the signal wavelengths, which are described by a set of coupled nonlinear differential equations [1]. Thus, the optimum Raman amplifier design procedure comprises two main steps. First, the Raman amplifier spectral characteristics are obtained by integration of the set of nonlinear coupled differential equations for a given configuration of pump lasers [10]. Next, the actual optimization is often based on the minimization of an error function, which correlates each and every one of the obtained solutions of the previous step to a target value. In this context, the optimization step is usually carried by making use of global search methods, such as neural networks [11], simulated annealing [12] and genetic algorithms (GAs) [13-14].

Unfortunately, these methods can be very time-consuming because the integration of the equations describing the Raman effect is an involved task by itself, task which must be carried out for every investigated pump configuration. As a consequence it is often very difficult to find the global minimum. As an alternative, the methodology presented in this paper makes use of an analytical model as a preliminary step [15]. In this way, the whole solution-space can be inspected at once. Then, the most promising solutions are fully investigated by a rigorous numerical treatment [10] and the Raman amplification performance is thus determined by the combination of analytical and numerical approaches. Therefore, the computation time is significantly reduced.

As a case-study the developed methodology is employed to find a multi-pump Raman amplifier configuration with low-ripple, high gain, low eye-penalty, that also compensates the dispersion imposed by a 70-km singlemode fiber (SMF) in a 10 Gbit/s-20 channel WDM C-band optical link using dispersion-compensating (DC) PCFs. The PCF of interest in this paper is briefly discussed in the Section 2. In Section 3 the analytical and the numerical models utilized in the simulations are presented and the results are provided and discussed in the Section 4.

2. Dispersion compensating PCF geometry

The fiber utilized in our simulations is based on the experimental demonstration of a DCPCF described in detail in [3,16], which presented a very high negative dispersion and a slope-matched dispersion slope designed to compensate the dispersion introduced by commercial SMFs in the C band. In fact, 1 km of the DCPCF allows the total compensation of the dispersion introduced by 70 km of SMF. Other fiber parameters used in our numerical simulations, such as effective area, were supplemented from [17], where they were originally obtained by using a full-vectorial finite element modal solver. This parameter is important, because, since the fiber material is undoped silica, non-linearities, which are fully included in our simulations, are mostly determined by the modal effective area.

It is also worth mention that, although PCF total losses as low as 0.37 dB/km at 1550 nm have already been reported [18] the losses of those PCFs can be extremely high when compared to conventional silica fibers. However, as discussed above, these fabrication related losses are usually caused by undesired roughness on the inner surface of the holes, and the impurity absorption loss, arising mostly from residual OH-contamination. These factors, known as “excess background loss”, are expected to become progressively less important as fabrication technology evolves. Therefore, the results present in the paper assume a baseline loss around 5 dB/km which should be seen as the theoretical limit allowed by the proposed design. This limit should be within reach as the fabrication technology matures to achieve its full potential but may not be within reach by most manufacturers today.
3. Modeling Raman amplifiers

Raman amplifiers modeling, as summarized in the tree diagram shown in Fig. 1, is usually carried out using an extended nonlinear Schrödinger equation (ENLSE) method [10,19,20] or steady-state approximations [20-22]. Numerical methods are then used to analyze the electrical field evolution in the ENLSE modeling. Effects such as pump depletion, dispersion, amplified spontaneous emission (ASE), double Rayleigh backscattering (DRB) and nonlinear effects such as self-phase modulation (SPM) and cross-phase modulation (XPM), are fully computed in the ENLSE method. The optical signal to noise ratio (OSNR) and the eye penalty can also be calculated by this approach.

![Tree diagram showing the relationship among Raman amplifier models.](image)

Regarding the steady-state analysis in the Raman amplifier modeling, both numerical and analytical solutions can be applied. However, the power evolution calculation performed by numerical methods enables the inclusion of effects such as pump depletion, ASE, RBS and the determination of OSNR as well. Those effects are only partially computed or even neglected in the analytical approaches.

In contrast, although some approximations are necessary in analytical approaches, analytical techniques allow accurate evaluation of gain and gain ripple within reduced computing time, a crucial feature to allow the design of Raman amplifiers employing multipump for several distinct signal wavelengths and optical power levels.

3.1 Numerical modeling

As discussed above, there are mainly two types of numerical approaches used to solve signal propagation in optical systems. On one hand, there is the ENLSE method based on the electromagnetic field evolution. This method enables to obtain eye penalties through the propagation of modulated signals. On the other hand there is the steady-state approach based...
on the signals power evolution. For the sake of completeness, both methods are described below.

3.1.1 Extended nonlinear Schrödinger equation

The signal and pump evolution in terms of temporal and spatial analysis can be computed using the Schrödinger nonlinear equations [19], given by Eq. (1), solved by means of the split step Fourier method, as described in detail in [10].

\[
\frac{\partial A^\pm_v}{\partial z} - d_{\text{ref},v} \frac{\partial A^\pm_v}{\partial t} + \frac{\beta_{\nu}^2}{2} \frac{\partial^2 A^\pm_v}{\partial t^2} + \frac{\beta_{\nu}}{6} \frac{\partial^3 A^\pm_v}{\partial t^3} = \pm \frac{\alpha_r}{2} A^\pm_v + j \gamma_r \left[ |A^\pm_v|^2 + \sum_{\mu=1}^\infty 2 |A^\mp_{\mu}|^2 \right] A^\pm_v \nonumber \\
\pm A^\pm_v \sum_{\mu=1}^\infty \frac{C_{\mu\nu}}{2\Gamma} |A^\mp_{\mu}|^2 \\
\mp A^\pm_v \sum_{\mu=1}^\infty \frac{\nu C_{\mu\nu}}{2\Gamma} |A^\pm_{\mu}|^2 \\
\mp A^\pm_v \sum_{\mu=1}^\infty \frac{\nu C_{\mu\nu}}{2\Gamma} \left[ 1 + \frac{1}{\exp \left( \frac{h(\nu-\mu)}{k\Gamma} \right) - 1} \right] |A^\pm_{\mu}|^4 \\
2N_{N_{\nu}}. 
\]

\( A_{\nu} \) is the signals and pumps complex amplitude, where the superscripts + and – denote forward and backward propagating waves respectively, \( t \) is the time, \( z \) is the fiber length, \( \gamma_{\nu} \) is the nonlinear parameter, \( \alpha_r \) is the attenuation coefficient, \( \nu, \mu \) and \( \sigma \) are linear frequencies and \( N_C \) is the total number of complex amplitudes that propagates through the fiber (including pumps and signals). \( C_{\mu\nu} = g_{\mu\nu}/A_{\text{eff},\mu} \) is the Raman gain efficiency between the frequencies \( \mu \) and \( \nu \), and \( g_{\mu\nu} \) is the Raman gain in frequency \( \nu \) due to the pump in the frequency \( \mu \). \( A_{\text{eff},\mu} \) is the effective area of the fiber in the frequency \( \mu \). \( N_{N_{\nu}} = h \nu \Delta \nu \) is the noise power due to the spontaneous emission generated in a band \( \Delta \nu \) around the frequency \( \nu \); \( h \) is the Planck’s constant and \( k \) is the Boltzmann’s constant. \( T \) is the absolute temperature of the fiber and \( \Gamma \) is the polarization factor, which is assumed to be equal to 2 if the lasers are depolarized [23]. The term \( d_{\text{ref},\nu} \) is related to the difference between the group velocity of the reference channel and the other channels (walk-off), and \( \beta_{\nu} \) is related to higher order dispersion. In this paper, in order to solve numerically the Schrödinger nonlinear equations, we have used a technique based on the split-step Fourier method, as reported in [10,19].

3.1.2 Steady-state approach

From the Eq. (1), it is possible to obtain the well known nonlinear coupled equation that governs the power evolution of pumps and signals along \( z \)
\[ \frac{dP_{\nu}}{dz} = \mp \alpha, P_{\nu} \pm \xi, P_{\nu} \pm P_{\mu} \sum_{\mu, \nu} \frac{C_{R, \mu, \nu}}{\Gamma} (P_{\mu}^* + P_{\nu}^*) \]

\[ \pm 2N_{E, \nu} \sum_{\mu, \nu} \frac{C_{R, \mu, \nu}}{\Gamma} (P_{\mu}^* + P_{\nu}^*) \cdot T \mp P_{\mu} \sum_{\nu, \rho} \frac{C_{R, \mu, \nu}}{\Gamma} (P_{\mu}^* + P_{\nu}^*) \]

\[ \mp P_{\nu} \sum_{\mu, \nu} \frac{C_{R, \mu, \nu}}{\Gamma} 4N_{E, \mu} \left[ 1 + \exp \left[ \frac{\hbar (\mu - \nu)}{kT} \right] - 1 \right] \]

Where \( P_{\nu} \) and \( P_{\mu} \) are optical powers at the optical frequencies \( \nu \) and \( \mu \), respectively.

This equation, which provides the foundation for the development of the analytical model used in this work, can be solved numerically as a boundary value problem (BVP).

### 3.2 Analytical approach

Since numerical solutions are often extremely time consuming, we have used a simplified analytical model [15] for an initial prediction of the gain and gain ripple. The analytical approach considers pump-to-pump and signal-to-pump interactions and also takes into account wavelength dependent effects such as effective area variation and individual signal loss coefficients, but neglects the pump depletion by signal and also noise effects. Usually the gain calculation is not significantly influenced by such approximations [10].

The analytical expression that describes the power evolution in a fiber to \( N \) arbitrary number of counter-propagating pumps is obtained from Eq. (2) by an iterative procedure that calculates the iteration between pumps in three different frequencies. More details regarding the deduction of the analytical expressions and also the experimental validation can be found in [15]. This general expression for the pump power evolution as a function of the fiber length is given by

\[ P_{\mu}(z) = P_{\mu}(L) \exp[-\alpha(L - z)] \]

\[ \exp \left[ \sum_{\psi > \mu} A(\rho, \psi) \frac{1 - \exp[\Lambda(z)B(\psi, \phi)]}{B(\psi, \phi)} \right] \]

\[ \exp \left[ \sum_{\psi < \mu} \frac{\rho}{\psi} A(\rho, \psi) \frac{1 - \exp[\Lambda(z)B(\psi, \phi)]}{B(\psi, \phi)} \right] \]

with \( A(\rho, \psi) = C_{R, \rho, \psi} P_{\rho}(L) \), \( B(\psi, \phi) = \sum_{\nu, \rho} C_{R, \rho, \nu} P_{\nu}(L) / \phi - \sum_{\nu, \rho} C_{R, \rho, \nu} \phi(L) \) and

\[ \Lambda(z) = -(1 - \exp(-\alpha(L - z))) / \Gamma \alpha \]

where \( L \) is the total fiber length, \( \rho, \psi, \phi \) are optical pump frequencies, \( P_{\mu} \) is the pump optical powers and \( \alpha \) is the wavelength independent attenuation coefficient. Then, from the pump power evolution equation, it is straightforward to show that, as described in [15], the signal gain can be obtained by

\[ G(\nu, L) = \exp[-\alpha L] \exp \left[ \int_{0}^{L} \sum_{\nu, \rho} C_{R, \rho, \nu} P_{\rho}(z) \, dz \right] \]

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where $\nu$ is the optical signal frequency and $N_p$ is the total number of pumps.

4. Results

In this section, we will examine the performance of discrete multi-pump Raman amplifiers designed using DCPCF to simultaneously compensate dispersion and system losses. Table I presents the proposed methodology. First, it is necessary to define the amplifier configuration, the signal band, the number of channels and the number of pump lasers. In a second step it is necessary to define the range of pump wavelengths and optical power levels of interest as well as the number of configurations to be tested.

Then, the analytical method described in Section 3.2 is used for a preliminary calculation of the gain and ripple of each configuration. The goal is to inspect the complete gain versus ripple solution-space in a very short computation time. After analyzing the solutions it is possible to choose the most promising configurations for a given application. A common choice would be maximum gain within a tolerable gain ripple. Finally, in the fourth step, the ENLSE method is used to rigorously analyze the amplifier performance of the selected configuration(s) in terms of eye penalty and OSNR.

Table I: Schematic algorithm describing the four steps methodology.

<table>
<thead>
<tr>
<th>Step 1:</th>
<th>Define the amplifier configuration, band and number of pumps, $N_p$:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 2:</td>
<td>Define pump wavelengths and optical power levels ranges and the number of configurations to be investigated;</td>
</tr>
<tr>
<td>Step 3:</td>
<td>Run the analytical method described in Section 3.2 and pick the best configuration(s);</td>
</tr>
<tr>
<td>Step 4:</td>
<td>With the chosen configuration(s), run the ENLSE method to compute the amplifier performance in terms of eye penalty and OSNR.</td>
</tr>
</tbody>
</table>

We have used the methodology described in Table I to analyze a two counter-propagating pumps Raman amplifier operating at C band using the DCPCF described in [17] to simultaneously compensate dispersion and system losses. Fig. 2 shows the amplifier setup used in our investigation. The WDM transmitter contains 20 equally spaced C band channels, each carrying a 10 Gbps signal. The SMF was 70 km long and 1 km of DCPCF was used as the lumped gain media. The counter-pumped configuration was used to assure that the signal transmission less affected by the fiber nonlinearities. We have considered depolarized pumps with the polarization factor equal to 2. It is important to mention that gain values substantially higher can be obtained if the polarization state of signal and pump waves are kept constant, meaning polarization factor equal 1. Unfortunately, this is not easy to achieve experimentally. Table II summarizes the parameters used in our analyses.
Fig. 2. The discrete multi-pumped Raman amplifier setup.

Table II. System parameters.

<table>
<thead>
<tr>
<th></th>
<th>SMF</th>
<th>DCPCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{eff}\ (\lambda = 1550\text{nm})$ (µm²)</td>
<td>76.30</td>
<td>1.81 [17]</td>
</tr>
<tr>
<td>$D\ (\lambda = 1550\text{nm})$ (ps/nm/km)</td>
<td>17</td>
<td>-1216 [17]</td>
</tr>
<tr>
<td>Raman peak gain efficiency (W⁻¹km⁻¹)</td>
<td>0.43</td>
<td>21.00</td>
</tr>
<tr>
<td>Noise bandwidth $\Delta_\nu$ (nm)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$L$ (km)</td>
<td>70</td>
<td>1</td>
</tr>
</tbody>
</table>

In the design of this C band amplifier, the analytical model (step 3) has been used to compute a large number of pump configurations with pump wavelengths, $\lambda_{P1}$ and $\lambda_{P2}$, varying randomly from 1410 to 1460 nm and pump power from 100 up to 450 mW. This range of pump powers was chosen because conventional pump lasers with such power levels present relatively lower cost. Fig. 3 shows the average gain versus ripple for 8000 different configurations. We have considered the DCPFC attenuation of 5 dB/km at 1550 nm, as discussed in section II. It took only 29.8 seconds in a 2.64 GHz INTEL processor with 2 GB of RAM to evaluate all points in the solution space depicted in Fig. 3.
As it can be noticed from Fig. 3, it is possible to design a DCPCF Raman amplifier with a large value of gain and of ripple. The gain can vary from -5 to +15 dB and while the ripple ranges from 0.50 to 17 dB, depending on pump configuration. A careful look at this data shows that 0.68% of the configurations present gain between 0 and 9 dB and ripple between 0 and 1 dB. The rate increases to 8.63% if the ripple is allowed to be between 0 and 2 dB.

Among the 8000 possibilities studied we have chosen the configuration which presents maximum gain and an acceptable ripple. The inset in Fig. 3 shows the investigated solution space. The selected pump wavelengths and powers were, respectively, $\lambda_{p1} = 1422.4$ nm, $\lambda_{p2} = 1451.9$ nm and $P_{p1} = 238.9$ mW, $P_{p2} = 435.2$ mW. The achieved average gain was 8.83 dB for a ripple of 0.76 dB. Concerning the optimization variables pump wavelength and optical power, further simulations have shown that, for a given range of interest, increasing the number of points in the solution space beyond 8000 does not improve significantly the gain performance of the amplifier.

Next, we have used the numerical model described in section 3.1.1 in order to more rigorously analyze the performance of this proposed DCPCF Raman amplifier. The analysis was made through the evaluation of the net gain, the optical signal-to-noise ratio (OSNR), and the eye-penalty as a function of the signal wavelength for configurations with different values of signal input power and PCF attenuation. Each of the 20 WDM signals have used Non Return to Zero (NRZ) format and 10 Gbps. Fig. 4(a) shows the influence of the PCF loss and input power on the gain. We have assumed three values for the loss, i.e., $\alpha_{PCF} = 4, 5$ and 6 dB/km, and three values for the optical power of the WDM transmitter, $P_0 = 0, -5$ and -10 dBm. Fig. 4(a) shows that the gain was not significantly influenced by the signal input power in the studied region and, in all cases, we have obtained flat gain with less than 0.83 dB ripple. The average gain and ripple for the signal input power of -10 dBm and 5dB/km fiber
attenuation were respectively, 8.5 dB and 0.71 dB, showing a good agreement with our analytical model results. The same figure shows that fiber attenuation plays an important role in the gain performance but it does not affect the ripple.

Figure 4(b) shows the OSNR for all 20 WDM channels. As it can be seen, improved OSNRs can be achieved for higher signal input powers, and in these cases the fiber attenuation does not significantly influence its value. Nevertheless it is important to notice that all values of OSNR were above 28 dB, which is yet a very satisfactory result. Finally, the eye penalty is presented in Fig. 5. An eye penalty close to zero can be obtained over the entire C-band. Figure 5 suggests that the dispersion introduced by 70 km of SMF can be totally compensated by the DCPCF in all wavelengths, and indicates that systems with 20 WDM channels operating at 10 Gbps in C-band can work without being significantly deteriorated by noise and non-linear effects.

Fig. 4. (a) Gain and (b) OSNR versus the signal wavelength for the discrete counter-propagating multi-pumped DCPCF Raman amplifier. (a) The numbers in the right side represent the input optical power per channel and (b) the PCF attenuation.
5. Conclusion

This paper has discussed the new design methodology for multi-pumped lumped Raman amplifiers employing photonic crystal fibers. Using an analytical model as a preliminary guess has enabled us to inspect the whole solution-space and find a very good combination of pump lasers to result in high gain, low ripple for an almost costless processing time. Then, the performance of the selected amplifier configuration can be rigorously evaluated using a numerical model based on the extended nonlinear Schrödinger equation.

The methodology was applied to photonic crystal fibers that simultaneously amplifies and compensates dispersion. Very low eye penalty was obtained in a high bit-rate transmission system. Our results reinforce the possibility of full dispersion and loss compensation in long distance fiber links using very short lengths of DCPCF.