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Raman Amplifiers for Use in WDM Systems

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Resumo **- Neste artigo abordam-se os Amplificadores de Raman (RAs) em sistemas de fibra óptica com Multiplexagem no Comprimento de Onda (WDM). Inicia-se explicando os princípios físicos da amplificação, e enumerando as principais características e vantagens do uso destes amplificadores.**

A técnica de múltipla bombagem (MP) para obtenção de amplificadores de grande largura de banda e ganho equalizado é estudada, e são apresentados alguns dos resultados obtidos por simulação (80nm com 1.3dB de variação de ganho).

Uma configuração simples de amplificação distribuída num sistema WDM de longo curso é desenvolvida, com o objectivo de aumento da taxa de transmissão para 40Gb/s, sem alterar o dimensionamento do sistema ou diminuir a Relação Sinal Ruído (SNR).

Abstract **- In this paper Raman Amplifiers (RAs) for Wavelength Division Multiplexed (WDM) fiber optic systems are analysed. We start by explaining the physical principles of this kind of amplification are explained, and the principal characteristics and advantages of using these amplifiers are enumerated.**

The technique of multiple pumping (MP) is studied aiming to obtain broadband amplifiers with equalized gain, and some results are obtained by simulation (80nm with 1.3dB in gain variation).

It is performed a simple configuration of distributed amplification for a long haul WDM system, where a bit rate increase to 40Gb/s can be done, without changing the system configuration or decrease Signal Noise Ratio (SNR).

I. INTRODUCTION

The dramatic growth of the Internet has invited unprecedented rapid deployment of WDM transmission systems based on Erbium-Doped Fiber Amplifiers (EDFAs), which are a cutting-edge technology yet [1]. Because the typical gain bandwidth of EDFAs is on C-band or L-band for a specific design [2], which is much narrower than the low loss window of standard optical communication fibers, there is interest in wideband flat-gain optical fiber amplifiers to exploit more of the available fiber bandwidth and increase the capacity of WDM systems.

Fiber RAs are recently attracting much attention in WDM systems due to their distinctive flexibility in bandwidth designs and growing maturity on high power pump module technologies [3]. For this type of optical fiber amplifiers in a distributed configuration using MP, the gain profile can be adjusted by appropriately choosing the relative wavelengths and powers of the pump waves, which allow the design of amplifiers with approximately required gain spectra. Distributed Raman Amplifiers (DRAs) with single pump and MP issues and applications in WDM systems are treated here.

In section II we start analysing the RAs physical principles. The main characteristics of RAs are presented in section III, where some simulations are presented to enhance the amplifier characterization. In section IV the MP technique is discussed and designs with three and eight pumps are presented. The upgrade of a submarine link from 10Gb/s to 40Gb/s by RA is studied in section V, and the paper ends with some conclusions, section VI.

II. RAMAN AMPLIFICATION IN OPTICAL FIBERS

When a monochromatic light beam passes through a transparent substance, the beam is scattered, i.e., the line spectrum of the scattered light will have one prominent line corresponding to the original wavelength of the incident radiation, plus additional lines to each side of it corresponding to the shorter or longer wavelengths of the altered portion of the light. This is called the 'Raman Effect' and was discovered by C. V. Raman in 1928.

In Spontaneous Raman Scattering only a small fraction ($\sim 10^{-6}$) of the incident power from an optical beam is converted to another optical beam, which is downshifted in frequency (Stokes frequency) by an amount determined by the vibrational modes of the medium.

In the early 1970s, Stolen and Ippen demonstrated that for an incident intense beam (pump), where the response of any dielectric to light becomes nonlinear [4], the

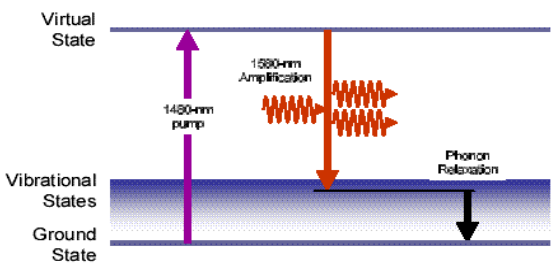

Fig. 1 - Energy Diagram representing the Raman gain process.

phenomenon of Stimulated Raman Scattering (SRS) can occur, making possible amplification in optical fibers. In terms of quantum-mechanical, a photon of the incident field is annihilated to create a photon at the downshifted Stokes frequency and a phonon with the right energy and momentum to conserve the energy and the momentum, see Fig. 1.

Raman amplification in optical fibers makes use of this last phenomenon, SRS, a non-linear process, to make broadband amplifiers, as we will see.

III. Properties of Raman Amplifiers

In this section we'll analyse some of the main characteristics of a RA, specifically for a DRA. Some parameters, like gain and Noise Figure (NF), are discussed theoretically and by means of simulation.

A. Distributed vs. Discrete Raman Amplifiers

Discrete or lumped amplifier refers to a lumped element that is inserted into the transmission fiber to provide gain, where all the pump power is confined to the lumped element. Contrarily, in a distributed amplifier the pump power extends into the transmission line fiber, using it as the gain medium. The RA could be either used in Distributed (DRA) or Lumped (LRA) configuration [5].
In Fig. 2 we show the most common configurations used in the design of DRAs and LRAs.

Distributed amplification, retain the optical signal level over a long distance along the transmission line, reducing the overall excursion. A DRA does not require a high signal level, which reduces nonlinear effects. Also the signal does not dip down to much, which maintains the SNR, see Fig. 3. The use of this type of configuration increases the transmission distance along any type of fiber, and can be conjugated with the use of WDM [6].

Lumped amplification is less attractive than distributed amplification, in terms of performance, however LRA is actually employed in the exploitation of new transmission windows, like S-band [7].

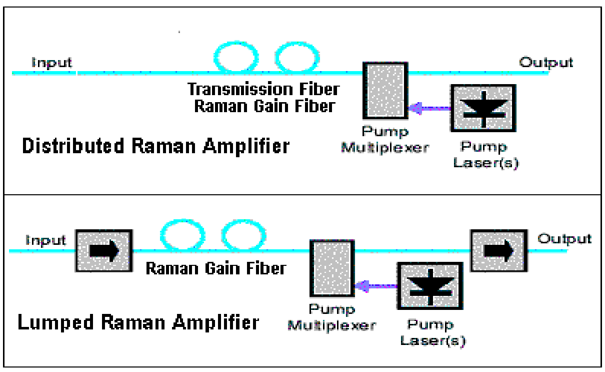

Fig. 2 - DRA vs. LRA configuration. In order to avoid noise effects, signal and pump are counter-propagating. Some DRAs are deployed with in-line discrete amplifiers, such as EDFAs.

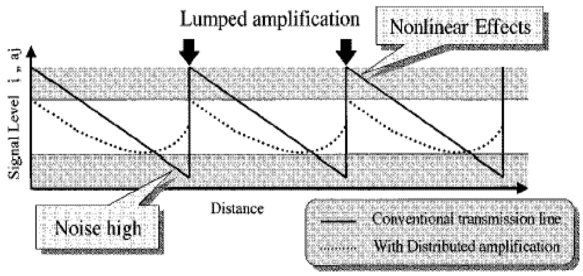

Fig. 3 - Schematic diagram that compares the dynamic range of a DRA and a LRA. In a DRA the power budget is improved and could be used to enhance capacity of in WDM systems. Source: [6].

B. Gain Properties of RA

The gain bandwidth in RA is over 40THz wide, with the dominant peak downshifted 13.2THz, relatively to the pump frequency. Fig. 4 shows the Raman-gain coefficient, g_R, for fused silica as a function of the frequency shift at a pump wavelength $\lambda_p = 1.5\mu m$.

The parameter g_R, is related to the cross section of spontaneous Raman scattering, an experimentally measurable quantity, and, in general, depends on the composition of the fiber and is also extremely dependent with the state of the polarization state between the pump and signal beams ($g_R \approx 0$ if orthogonal polarization).

For a fiber, with some dozens of meters, the propagation of the signal and pump trough it, will make that both of the states of polarization rotate between them, decreasing gR. There are some methods to minimize the problem of polarization dependence, as for example pumping with polarization diversity [4].

In a simple approach, valid under cw or quasi-cw conditions, the initial growth of the Stokes wave can be described by (1), where I_S is the Stokes intensity, I_P is the pump intensity, and z is the axis associated to the length of the fiber.

$$\frac{dIs}{dz} = g_R IpIs \tag{1}$$

The propagation equations are obtained directly from (1), and are described by (2) and (3), for the signal and pump respectively. In (2), (3), A_{eff} represents the effective core area, P_S and P_P are the power of signal and pump respectively, with frequencies w_S and w_P, and attenuations in fiber α_S e α_P respectively.

$$\frac{dPs}{dz} = -\alpha_s Ps + (g_R / Aeff)PpPs \tag{2}$$

$$\frac{dPp}{dz} = -\alpha_P Pp - (wp/ws)(g_R / Aeff)PsPp \tag{3}$$

The second term in the right side of (3) is responsible for pump depletion, if we neglect it and solve the equation and substitute in (2) we obtain (4), where P_{PO} is the pump power at z=0.

$$\frac{dPs}{dz} = -\alpha_s Ps + (g_R / Aeff)(P_{PO}\exp(-\alpha_P z)Ps \tag{4}$$

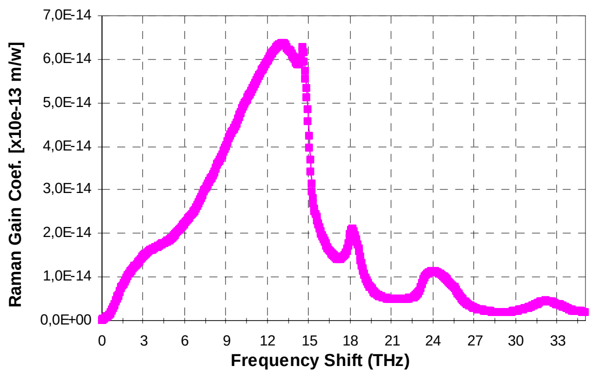

Fig. 4 - Raman-gain coefficient (g_R) in standard SMF for copolarized pump and signal beams, the pump wavelength was 1450nm. Source: [10].

Similarly, the resolution of (4) for $z=L$ results in (5), where P_{SO} is the signal power at z=0, and L_{eff} is given by (6) and represents the effective length of interaction, which is usually approximated to $1/\alpha_P$ for sufficiently long fibers such that $\alpha_P L$>>1.

$$P_S(L) = P_{SO}\exp\left(\frac{g_R P_{PO} L_{eff}}{A_{eff}} - \alpha_s L\right) \quad (5)$$

$$L_{eff} = \left[1-\exp(-\alpha_P L)\right]/\alpha_P \quad (6)$$

Gain in RA is defined as the ratio between the output signal power with the pump on over the output signal power with pump off, then from (5) and (2) considering P_P=0, the non-saturated gain is given by (7). In this expression *Pol* expresses the dependence of gain with polarization states between pump and signal beams, *Pol* = 1 for copolarized states, *Pol*=2 for unpolarized states, and *Pol*=∝ for orthogonal states.

$$G(ws) = \exp\left(\frac{gR*(wp-ws)P_P*Leff}{Aeff*Pol}\right) \quad (7)$$

From (7) we can see that to increase *G* we could increase L_{eff} that implies a decrease of attenuation, increase the pump power, or use a fiber with smaller core area.

C. Raman Threshold

The Raman threshold (P_{th}) is defined, as the input pump power at which the Stokes power becomes equal to the pump power at the fiber output, which means that half of the input power, is lost in SRS.

An expression for P_{th} is obtained in [4], using the last equations deduced for the gain. In (8), P_{th} is presented for forward SRS, and for backward SRS the expression is (9), we note here that P_{th} is reached first at a given pump power for forward SRS.

$$g_R P_{th} L_{eff}/A_{eff} \approx 16 \quad (8)$$

$$g_R P_{th} L_{eff}/A_{eff} \approx 20 \quad (9)$$

For a long Single Mode Fiber (SMF) where the loss is typically 0.2dB/Km at λ_P= 1.5µm, L_{eff}≈20Km, A_{eff} = 50µm^2, g_R = 1e-13m/W, then P_{th} = 400mW by (8), and P_{th} = 500mW by (9). We confirm here that high values of P_{th} are needed to achieve SRS, making that the principal limitation for the use of RAs.

D. Noise in RA

The RA has essentially four sources of noise that contribute to degrade the NF, they are:

- Double Rayleigh Scattering (DRS)
- Short Upper-state Lifetime (SUL)
- Amplified Spontaneous Emission (ASE)
- Temperature Phonon Stimulation (TPS)

Rayleigh scattering is due to the microscopic glass composition non-uniformity, which imposes several limitations in systems with optical amplifiers [8]. DRS corresponds to two scattering events, one backward and the other forward. ASE traveling in the backward direction will be reflected in the forward direction by DRS and experience gain due to SRS, in addition, the multiple reflections of ASE will also lower the SNR degrade NF [9]. Furthermore the ASE contribution, multipath interference of the signal from DRS induces limitations in the performance of the systems as for example crosstalk. DRS is proportional to the length of the fiber and the gain in the fiber, so it is particularly important in DRA.

SUL arises from the short upper-state lifetime of Raman amplification, as short as 3fs to 6fs. This virtually instantaneous gain can lead to a coupling of pump fluctuations to the signal. Usually is used backward pumping, which as the effect of introducing an effective upper-state life equal to the transit time through the fiber. For this reason in this paper we only consider backward pumping.

ASE is the typical noise to any optical amplifier, and is derived from the spontaneous emission of photons. At receiver, where the dominant noise component is signal-ASE, the *NF* can be written as (10), where *G* is the optical gain, *h* is the Planck's constant, *w* is frequency, *Bo* is the bandwidth of the optical filter, and P_{ASE} is the power of ASE and is given by (11). Note that, in (11) n_{SP} represents the inversion of population given by (12), and *Bm* is the bandwidth used for noise measurement, *K* is the Boltzman's constant, and *T* is temperature in Kelvin.

$$NF = \frac{P_{ASE}}{G*h*w*B_o} + \frac{1}{G} \quad (10)$$

$$P_{ASE} = 2*n_{SP}*(G-1)*h*\nu*Bm \quad (11)$$

$$n_{SP} \equiv \frac{N_2}{N_2-N_1} = \frac{1}{1-e^{((\nu s-\nu p)*\frac{h}{K*T})}} \quad (12)$$

TPS appears at room or elevated temperatures where exists a population of thermally induced phonons in the glass that can spontaneously experience gain from the pumps, thereby creating additional noise to for signals close to the pump wavelengths.

E. Characterization of RA using Simulation

For the simulations we used the VPIcomponentMaker™ Optical Amplifiers from Virtual Photonics Incorporated, which provides the module 'Fiber NLS Bidirectional' to model Raman amplification. This module is a wideband non-linear transmission medium for optical fibers, and accounts bi-directional transmission, DRS, Spontaneous Raman Scattering, SRS, dispersive effects, and Kerr non-linearities [10]. The physical parameters were adjusted to the typical values for a SMF, with 0.2dB/Km of attenuation, 16e-6 s/m^2 of dispersion, 80e-12 m^2 of core area, and for g_R we consider the spectra presented in Fig. 4.

In Fig. 5 is shown the setup used for in the implementation of the DRA. We considered a span length of 100Km, a pump with wavelength 1450nm and 300mW of pump power, alignment in polarization of pump and signal throughout the fiber. The gain and NF are plotted in Fig. 6. As we can see, the NF appears negative, and the gain is high at the output of the transmission fiber. A negative NF may appear unbelievable at first, even for a system with little overall gain. The reason for this performance is that the Raman amplification extends along the fiber towards the transmitter thus it is equivalent to placing a string of line amplifiers in the transmission

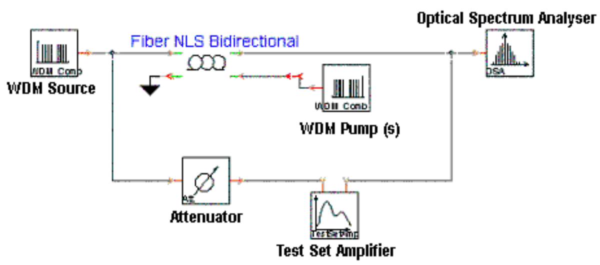

Fig. 5 - A DRA implementation in the VPIcomponentMaker™ using the module 'Fiber NLS Bidirectional' illustrating the method of obtaining Gain and NF accordingly to the definition.

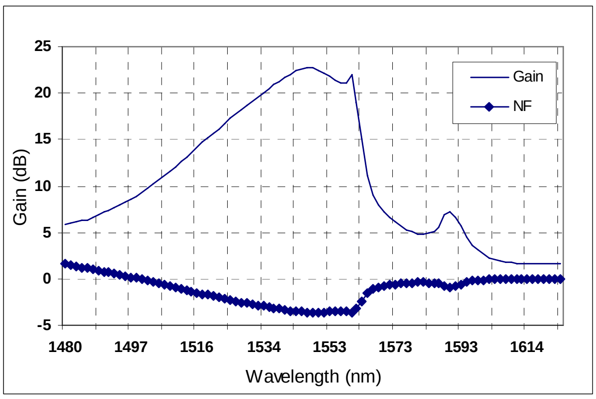

Fig. 6 - Gain and NF obtained after simulation of the above with SMF = 100Km, Pump=1450nm/300mW, g_R-parallel. Note that NF is negative and gain is high after 100Km of signal propagation.

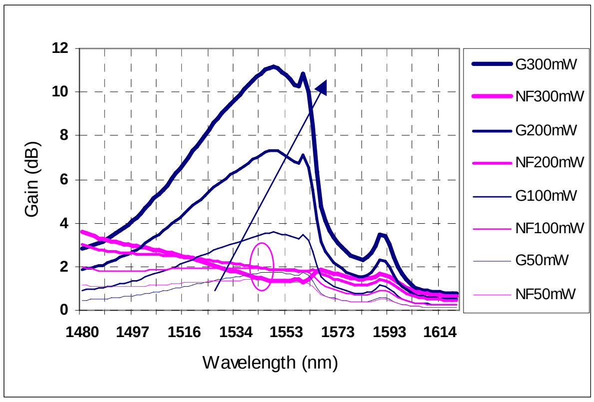

Fig. 7 - Gain and NF obtained after simulation, with SMF of 100Km, Pump@1450nm and variable power, g_R-unpolarized. Note that NF maintains approximately constant with the pump power decrease.

fiber, and so the signal level is always better than the one at the end of an umpumped transmission fiber.

In a fiber long as a few tens of meters, the polarization states between the pump and signal varies along the fiber, and so g_R will be halved for the signal, but not for the spontaneous noise. In Fig. 7 we verify that in the same conditions of pump power as in Fig. 6, the gain is halved and NF remains constant. It's interesting to verify that, decreasing the pump power does not affect the greatly NF.

IV. Multiwavelength Pumped Fiber Raman Amplifier

The use of MP or multi-wavelength pump in RAs allows considerable widen of the overall gain-bandwidth while simultaneously reducing its spectral non-uniformity, therefore making them ideal for use in WDM systems. In this type of amplifier we used several pumps, which increases the complexity, principally because of the interaction between pumps, in order to control the gain spectrum.

To date, there have been numerous calculations of spontaneous Raman Scattering, Raman pump interactions, and simplified propagation equations, but there has been little work to develop an optimisation technique for MP design. Perlin and Winful present recently a method of calculating the pumps distribution (frequencies and powers), for a given WDM-signal input spectrum and power level, as a function of the output spectrum flatness [11].

Here, we begin by presenting the equation that describes the propagation for MP used by the simulator, and then by iteration we design the amplifier. We design two broad bands amplifiers, one having only three pumps and the other using eight pumps.

One model that includes the most significant physical effects that affects Raman gain, was developed by Kirdof et al. [12], where he contempt the effects of spontaneous Raman emission and temperature dependence, Rayleigh Scattering including multipath reflections, SRS and amplification, arbitrary interactions between an unlimited number of pumps and signals from either direction: pump-pump, pump-signal, and signal-signal interactions, and high-order Stokes generation. In (13) we present the global propagation equation, where subscripts μ and ν denote optical frequencies, super-scripts + and – denote forward- and backward-propagating waves, respectively, P_ν is optical power within infinitesimal bandwidth around ν, α_ν is attenuation coefficient, ε_ν is Rayleigh-backscattering coefficient, A_ν is the effective area of optical fiber at frequency ν, $g_{\mu\nu}$ is Raman gain coefficient at frequency ν due to pump frequency μ, h is Planck's constant, k is Boltzmann's constant, and T is temperature.

$$
\begin{aligned}
\frac{dP_\nu^\pm}{dz} &= -\alpha_\nu * P_\nu^\pm + \varepsilon_\nu P_\nu^\mp \\
&+ P_\nu^\pm * \sum_{\mu>\nu} \frac{g_{\mu\nu}}{A_\mu} * (P_\mu^+ + P_\mu^-) \\
&+ 2*h*\nu*\sum_{\mu>\nu} \frac{g_{\mu\nu}}{A_\mu} * (P_\mu^+ + P_\mu^-) \\
&* \left[1 + \frac{1}{\exp\left[\frac{h(\mu-\nu)}{kT}\right] - 1} \right] \\
&- P_\nu^\pm * \sum_{\mu<\nu} \frac{\nu}{\mu} \frac{g_{\nu\mu}}{A_\nu} * (P_\mu^+ + P_\mu^-) \\
&- 4*h*\nu*P_\nu^\pm * \sum_{\mu<\nu} \frac{g_{\nu\mu}}{A_\nu} \left[1 + \frac{1}{\exp\left[\frac{h(\nu-\mu)}{kT}\right] - 1} \right]
\end{aligned}
\tag{13}
$$

In Fig. 8 we present the result of a first design using three pumps, in a configuration similar to Fig. 5. If we require a broadband amplifier is logical to use a pump for each band, however this results in a non-equalized gain, Fig. 8. Considering that high frequency pumps are more depleted, we perform a new simple design by diminishing the power of the C- and L- pumps, and as we can see the improvement is quite significant. We have shown that it is possible to obtain gain in all the bands just using three pumps, and with a more careful adjusting is possible to improve the performances [13] reducing the ripple from 20dB to approximately 5dB.

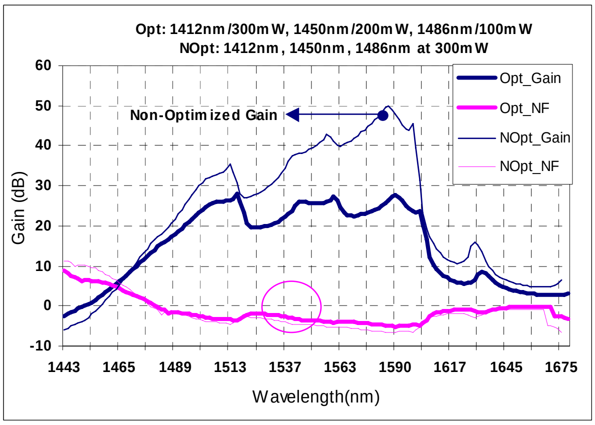

Fig. 8 - Raman gain and NF for three pumps and 100Km of SMF. The pumps are used for gain in S, C, and L bands.

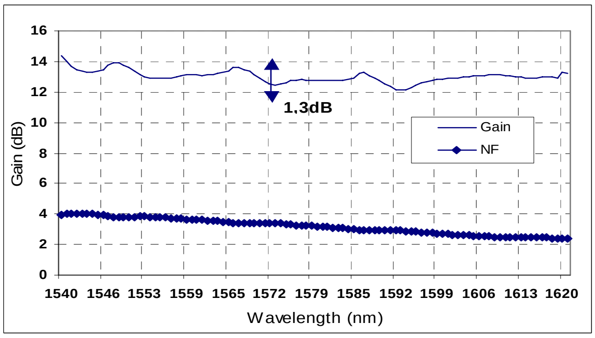

Fig. 9 - Raman gain and NF for eight pumps and 45Km of SMF.

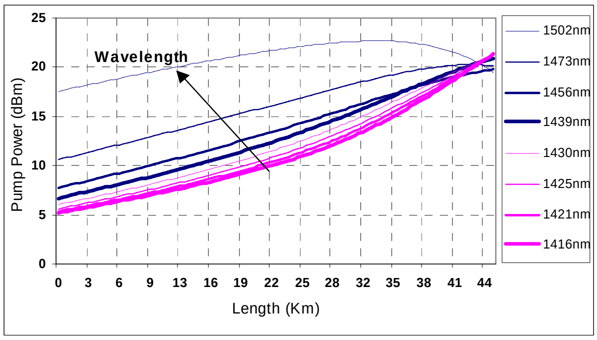

Fig. 10 - Pump power evolution along the length of the fiber

The use of only three pumps is an economical solution, however to obtain good performances it's necessary to use more number of pumps [14]. In Fig. 9 we show the results when are used eight pumps. It's achieved good gain flatness (1.3dB) in a large bandwidth (81nm) without using any filter or auxiliary device to perform equalization. In Fig. 10 we illustrate the pump power evolution along the length of the fiber, where it can be seen that higher frequency pumps become more depleted early, which is accordingly with (13).

V. Capacity Upgrades Using Raman Amplification

As was discussed with respect to Fig. 3, a distributed amplifier improves the power budget margin in system design. This extra budget could be used in WDM systems to enhance spectral efficiency and increase the bit rate, and also extend the fiber span distance between amplifiers. Hansen et al. showed experimentally that a DRA using a single diode pump source can facilitate the upgrade of a transmission system without changes to the fiber span, achieving a single channel upgrade from 2.5 Gb/s to 10Gb/s and a 4× 10Gb/s to a 4× 40Gb/s WDM system[15].

Here, we perform an experience that shows an upgrade in an unrepeatered link, using a booster EDFA and a pre-amp EDFA, for a WDM system. Fig. 11 depicts the system, where we consider a link of 175Km of SMF, pumped by a 500mw laser diode. The transmitter consists of 40 channels spaced 100GHz, each one with 0.125mW of power, and at the bit rates previously mentioned.

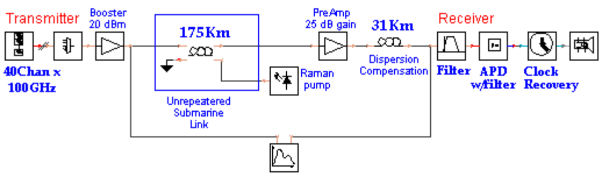

Fig. 11 - Schematic showing a DRA applied to a 175Km unrepeatered link, with a booster EDFA at the transmitter and pre-amp EDFA at the receiver.

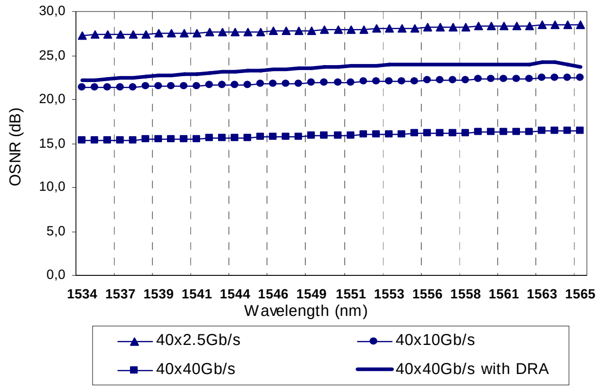

Fig.12 - OSNR at the receiver for different bit rates. A degradation of 6 dB in OSNR occurs due to the 6 dB increase in receiver bandwidth, which can be recovered if a DRA is used.

The measurement of OSNR shows that 6dB of degradation occurs when increase in 6dB the receiver bandwidth, however for 40Gb/s this situation can be recovered, by the use of a DRA where the performance is maintained from the 10Gbit/s setup to the 40Gbit/s, Fig. 12.

VI. CONCLUSIONS

The principles of Raman amplification were analysed and for performing RAs for use in communications systems.

The DRA present good SNR and useful optical gain can be obtained for all low loss attenuation spectrum of optical fibers.

By using MP in a RA it is possible to compose the gain, allowing designs of broadband with equalized gain amplifiers. A simple design with three pumps reveals an economical solution, however a design with eight pumps is preferable for WDM systems since the gain is flatter and broad.

A capacity upgrade to installed systems is demonstrated, without changes on the fiber span. Specifically, we have seen that an upgrade from 10Gb/s to 40Gb/s can be done without degradation of the OSNR just by adding a DRA with a single pump.

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