SYSTEM ADVANTAGES OF RAMAN AMPLIFIERS

Vittorio Curri

ARTIS Software Corporation
12 S. First Street – Suite 505
San Jose, CA 95113-2403 – USA
E-mail: vcurri@artis-software.com
Tel: +1 408 920 9632
Fax: +1 408 920 9633
and
Dipartimento di Elettronica, Politecnico di Torino
Corso Duca degli Abruzzi 24, 10129, Torino - ITALY
E-mail: curri@polito.it
Tel: +39.011.564 4178
Fax: +39.011.564 4099

Abstract

The theory of Raman amplification is briefly reviewed together with the definition of Noise-Figure for distributed amplification. Erbium-Doped Fiber Amplifiers and Raman Amplifiers are compared on the basis of their non-linear impact. An optimal configuration for Hybrid Raman/Erbium-Doped Fiber Amplifier is derived for the design of multi-span systems. Results obtained through the analytical formalisms are compared with accurate simulation results.

Introduction

Experimental results have demonstrated that Raman Amplifiers (*RA*) with counter propagating pump may be employed as an alternative to the Erbium-Doped Fiber Amplifiers (*EDFA*) in Long-Haul DWDM systems, in order to increase the received Signal-to-Noise Ratio (*SNR*) [1]. *RA'*s can also be used to upgrade already installed systems employing *EDFA*'s, as it has been demonstrated in [2]. Furthermore, recent results [3-5] have shown that Hybrid Raman/Erbium-Doped Fiber Amplifiers (*HFA*) are an enabling and promising technology for DWDM multi-terabit systems. Another application of *HFA*'s is in the design of systems with very large spans between amplifying/pumping stations as required in festoon optical networks [6]. To obtain a flat gain over a ultra-wide (up to 100 nm) bandwidth, a multi-pump configuration can be used as shown in [7].

In this work, the analytical expression for *RA* gain is briefly reviewed for co- and counter-propagating single-pump configuration, together with the expression for the in-line Amplified Spontaneous Emission (*ASE*) noise, including the effect of Rayleigh back-scattering. The rigorous Noise-Figure definition [8] is modified in order to allow a direct comparison between *RA*'s and *EDFA*'s. However, despite using a comparable Noise-Figure definition, a direct comparison between *RA*'s and *EDFA*'s can not be done, because they have different power evolution over the fiber. Therefore, a novel parameter is introduced – the *non-linear weight* - to allow a direct comparison between system configurations with different power distributions.

Using the analytical instruments defined in this work, two different use-cases are studied:

1. *RA*'s and *EDFA*'s are directly compared for the use as preamplifiers in single-span system;
2. *HFA*-based systems are analyzed in order to define an optimal configuration given the overall length of the link and some system constraints, such as the minimum required distance between amplifying stations, low non-linear impact and minimum acceptable Signal-to-Noise Ratio.

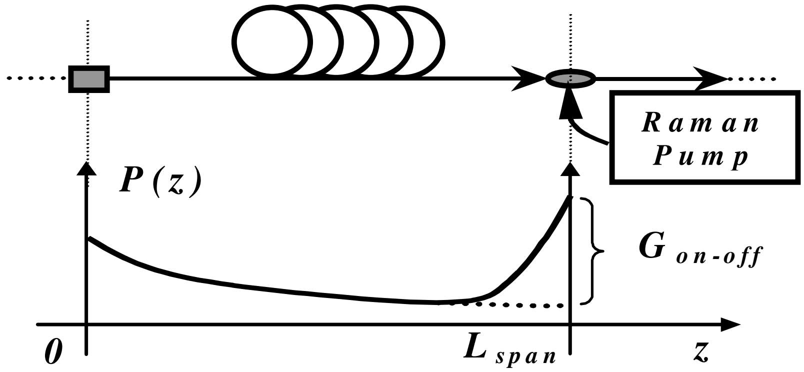

Fig. 1: A qualitative representation of the evolution of the signal power (solid line) in a fiber-span pumped with a counter-propagating single-pump. The un-pumped power profile is also presented (dashed lined) to show the *on-off* gain.

Gain of Raman Amplifiers

Raman amplifiers are composed of a fiber-span with a high-power pump — or a set of pumps —injected in order to excite Stimulated Raman Scattering [9] and to transfer optical power to the spectral region ~100 nm above the pump wavelength (13 THz below the pump frequency). For instance to have a *RA* at 1550 nm a pump at 1450 nm should be used. The pump can co- or counter-propagate with respect to the propagation direction of the signal.

To describe the performance of a *RA,* the *on-off gain* is used [10]. The *on-off gain* is the ratio of the power at the output to the power at the input of the fiber-span divided by the fiber loss. Referring to Fig. 1 the *on-off* gain can be expressed as:

$$G_{on-off} = \frac{P(L_{span})}{P(0)} \frac{1}{\exp\{-\alpha_S L_{span}\}} \qquad (1)$$

where α_S is fiber-loss coefficient and L_{span} is the fiber-span length. In other words, G_{on-off} is the gain measurable at the output of the fiber turning on and off the Raman pump. Fig. 1 depicts *on-off gain* for a counter-propagating, single-pump *RA* system.

For a single-pump configuration, the *on-off gain* has the following expression:

$$G_{on-off}(f) = \exp\left\{ C_R(f) P_{pump} \frac{1-\exp[-\alpha_p L_{span}]}{\alpha_p} \right\} \qquad (2)$$

where P_{pump} is the pump power at the beginning (counter-propagating pump configuration) or at the end (co-propagating pump configuration) of the fiber span, α_p is the fiber-loss coefficient at the pump frequency f_{pump} and

$$C_R(f) = \frac{1}{k_{pol}} \frac{g_R(f_{pump} - f)}{A_{eff}} \cdot \frac{f_{pump}}{f_{ref}} \qquad (3)$$

is the Raman Gain; g_R is the Raman efficiency measured at f_{ref}, A_{eff} is the effective area of the fiber and f is the frequency at which the gain is measured. k_{pol} is a factor that takes into account the polarization of the pump with respect to the signal polarization. If the pump is completely depolarized $k_{pol} = 2$, if the pump and the signal are aligned in terms of polarization $k_{pol} = 1$ [11]. The Raman efficiency curve measured for silica fibers [12] is presented in Fig. 2.

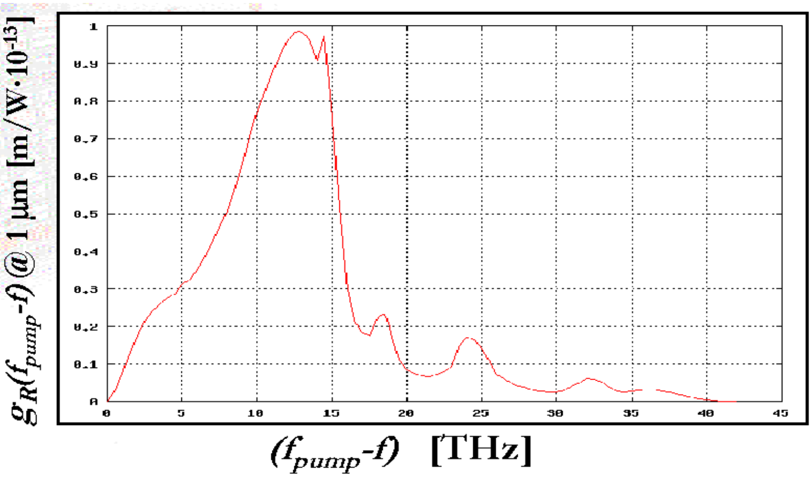

Fig. 2: Raman profile for pure silica fibers. Curve measured at 1 µm and first presented in [12]. The profile is plotted against the difference between the pump and the signal frequency.

As in every amplifying phenomenon, noise generation takes place. In this case, Amplified Stimulated Emission (*ASE*) noise is added to the propagating signal. Since *RA*'s are distributed devices, the *ASE* noise is generated along the complete length of the pumped fiber. At the end of the fiber span, the power spectral density of the noise can be evaluated [10] for the single-pump RA, as follows:

$$S_{ASE}^{RA}(f) = hfC_R(f)G_{on-off}(f)\exp\{-\alpha_S L_{span}\}\int_0^{L_{span}} P_{pump}(z)\exp\left\{-\int_0^z \left[C_R(f)P_{pump}(\xi)-\alpha_S\right]\mathrm{d}\xi\right\}\mathrm{d}z + \sum_{i=1}^{+\infty} r^i S_{ASE}^{(i)}(f) \quad (4)$$

where h is the Planck's constant and $r = R\alpha_S$ takes into account the Rayleigh back-scattering [11]. R is the *Capture Factor* [13] that measures the strength of the Rayleigh back-scattering. The sum of $S_{ASE}^{(i)}(f)$ takes into account of the infinite additive noise components due to the Rayleigh Back-scattering. In [11] it has been shown that in practical situations only the two first scattered components need to be considered to correctly estimate the *RA* performance. These components are called single- and double-scattered ASE noise, respectively. Note that if Rayleigh back-scattering is not considered high-gain *RA*'s can not be correctly designed.

A phenomenon that is not considered in this work is the saturation of *RA*'s due to the pump depletion [14]. This effect begins to be important for high-power signals, therefore all the current analysis is correct for a small-signal regime.

Noise-Figure of Raman Amplifiers

In [8] the Noise-Figure of an optical amplifier is defined by the ratio of the signal-to-noise ratio (*SNR*) at the input to the one at the output of the amplifier:

$$NF(f) = \frac{SNR_{in}}{SNR_{out}} \qquad (5)$$

This definition yields the following well-known formula for the EDFA Noise-Figure:

$$NF_{EDFA}(f) = \frac{1+2n_{sp,EDFA}(f)\left[G_{EDFA}(f)-1\right]}{G_{EDFA}(f)} \approx 2n_{sp,EDFA}, \text{ if } G_{EDFA}(f) >> 1 \qquad (6)$$

where $n_{sp,EDFA}(f)$ is the spontaneous emission factor that governs [8] the spectral density of the noise at the output of the device:

$$S_{ASE}^{EDFA}(f) = hfn_{sp,EDFA}(f)\left[G_{EDFA}(f)-1\right] \qquad (7)$$

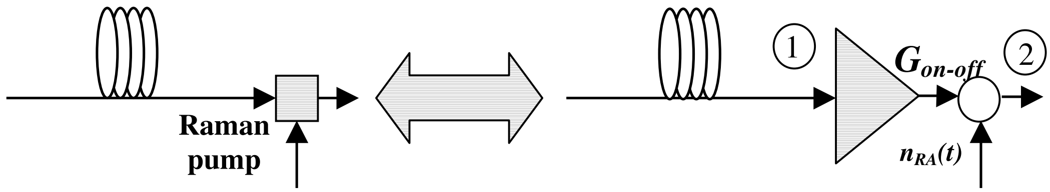

Fig. 3: Equivalent configuration for a Raman pumped fiber-span. The equivalent Noise-Figure definition is based on the ratio between the *SNR*'s in the virtual point 1 and the one in 2.

Applying the same formalism to the *RA*, one obtains the following formula for the Noise-Figure:

$$NF(f) = \frac{1}{\exp\{-\alpha_S L\} G_{on-off}(f)} \left(1 + 2 \frac{S_{ASE}(f)}{hf} \right) \qquad (8)$$

This expression is the ratio of the *SNR* at the input of the pumped fiber-span to the *SNR* at the output [8]. It does not allow a direct comparison, however, with a system based on *EDFA* amplification, because Eq. (8) includes fiber-loss and Eq. (6) doesn't. It is more useful to base the Noise-Figure definition on the *equivalent* configuration of *RA* represented in Fig. 3. A fiber span presenting distributed gain due to Raman pumping may be represented through the fiber-span without distributed amplification followed by a *virtual* amplifier whose gain is the Raman *on-off* gain. The *ASE* noise — the random process $n_{RA}(t)$ whose power spectral density is $S_{ASE}^{RA}(f)$ (see Eq. 4) — is added after the virtual amplifier.

This representation is equivalent to an *EDFA* placed at the end of the fiber span, hence a spontaneous emission factor and Noise-Figure may be defined as they are for *EDFA*'s. This definition allows a direct comparison with an *EDFA* whose gain is G_{on-off}. The equivalent spontaneous emission factor for the *RA* is given by the following expression:

$$n_{sp,RA}(f) = \frac{S_{ASE}^{RA}(f)}{hf\left[G_{on-off}(f) - 1\right]} \qquad (9)$$

where $S_{ASE}^{RA}(f)$ is the power spectral density of the *ASE* noise , h is the Planck's constant, and f is the frequency in question. Therefore, the *RA* Noise-Figure can be expressed as

$$NF_{RA}(f) = \frac{1 + 2n_{sp,RA}(f)\left[G_{on-off}(f) - 1\right]}{G_{on-off}(f)} \approx 2n_{sp,RA}, \text{ if } G(f) >> 1 \qquad (10)$$

Noise-Figure: *RA* vs. *EDFA*

To directly compare performance of an *EDFA* to a *RA*, we considered the simple system scenario represented in Fig. 4. An *EDFA* (Fig. 4a) or a *RA* (Fig. 4b) is employed to completely recover the attenuation of a single-span link whose signal-loss (around 1550 nm) is 0.2 dB/km. To implement a *RA* we assumed to pump the fiber by a counter-propagating high power source at 1450 nm (loss 0.3 dB/km). We swept the fiber-span length L_{span} from 1 to 250 km, considering for each length a pump level P_{pump} ensuring a Raman *on-off gain* G_{on-off} that exactly recovers the fiber-span loss. To evaluate P_{pump} we used Eq. (2). In the *EDFA* configuration, the amplifier gain G_{EDFA} again is considered to completely recover the fiber loss. In both cases it is assumed that the same power-level P_{TX} is used in both configurations. For each span-length, we evaluated NF_{RA} and compared it to the *NF* of an ideal *EDFA* (NF_{EDFA} = 3 dB). The difference between the Noise-Figures corresponds to the difference between the *SNR*'s, that is, $SNR_{RA} - SNR_{EDFA} = NF_{EDFA} - NF_{RA}$. Therefore, by analyzing the Noise-Figure behavior of the *RA* with respect to the *EDFA*, the advantages of *RA* in terms of *SNR* can be evaluated.

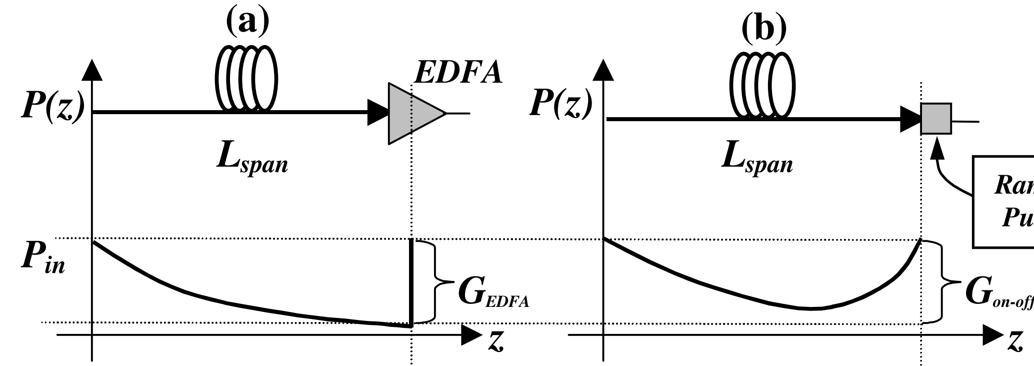

Fig. 4: Schematic of an *EDFA*-based (a) and RA-based (b) single-span link with the same input/output behavior in terms of power levels. The differences in the evolution of the power along *z* can be also observed.

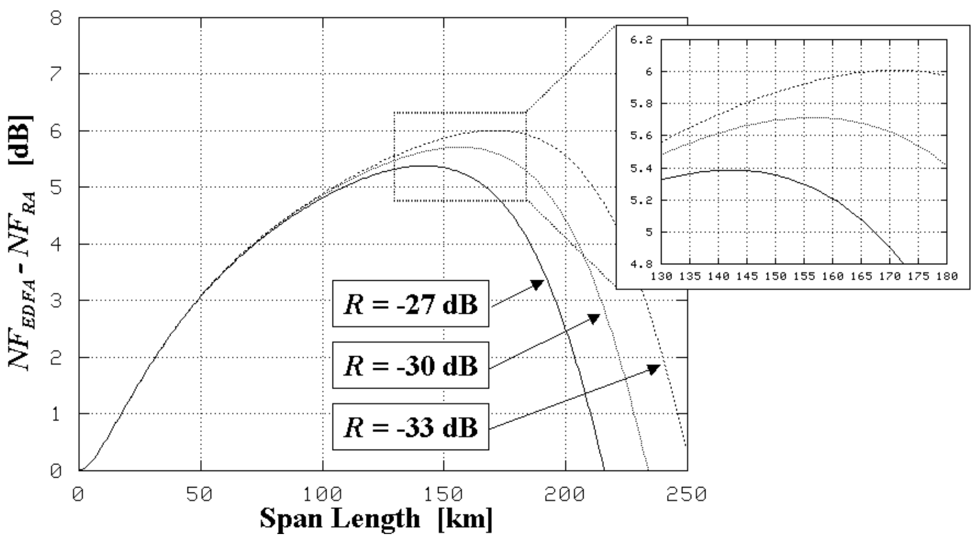

Fig. 5: Difference between the Noise-Figure of the *RA* and an ideal *EDFA*. The difference is plotted as a function of the fiber-span length. Different curves refer to fibers with different Rayleigh back-scattering capture factors.

In Fig. 5 the difference between NF_{EDFA} and NF_{RA} is plotted against the fiber-span length for fibers with different values of Rayleigh back-scattering *Capture Factor R*. For each value of *R,* there exists an optimal fiber-span length. For instance, with R = -30 dB the optimal fiber-span length is around 160 km and results in a Noise-Figure improvement of 5.7 dB (which corresponds to the same improvement in terms of *SNR*). Note that at the typical span length of 50 km, using an *RA* instead of an *EDFA* the system *SNR* can be improved of 3.3 dB, a value that is in good agreement with the experimental results presented in [1]. The pump level required to obtain a given gain depends on the Raman efficiency of the employed fiber, but the optimal length does not change with different Raman efficiencies. The optimal length does vary, however, if the pump and/or signal loss vary. Since the optimal length is a function of Rayleigh back-scattering, this confirms how important it is to consider this phenomenon in the analysis of *RA*'s.
From this initial comparison it can be concluded that *RA*'s always have an advantage, upwards to 5.2 dB in terms of *SNR*, when they are used as preamplifiers in single-span links ranging from 0 to 250 km.

A more realistic comparison of *EDFA's* and *RA's*: the *non-linear weight*

Comparison between *RA*'s and *EDFA*'s based on the Noise-Figure only gives an exact evaluation of the *SNR* behavior over the system in the linear regime, but it does not take into account of the impact of the

non-linearties in *RA*- and *EDFA*-based systems. As it can be observed for the simple single-span *EDFA* example represented in Fig. 4, the power evolution $P(z)$ along the fiber is a monotonically decreasing function of position along the fiber-span, while in the link based on the *RA*, the power decreases in the first part of the fiber-span, then it grows due to the distributed Raman amplification. This fact induces different non-linear impairments even if the launched optical power P_{in} is the same for the two systems.
As a rule of thumb, the impact of fiber non-linearities may be measured using the *overall non-linear phase-shift* that we refer to as the *non-linear weight,* K_{NL}:

$$K_{NL} = \gamma \int_0^{L_{link}} P(z)\mathrm{d}z \quad [\mathrm{rad}] \qquad (11)$$

where γ is the non-linear coefficient.
For single-span links based on *EDFA*'s, K_{NL} for each fiber-span depends on the effective length of the fiber in the following way:

$$K_{NL}^{EDFA} = \gamma\, L_{eff}\, P_{in} = \gamma\, P_{in} \int_0^{L_{span}} \exp\{-\alpha_S z\}\mathrm{d}z \approx \frac{\gamma\, P_{in}}{\alpha_S} \qquad (12)$$

For single-span links based on *RA* the effective length of the fiber grows because of the behavior of the power along the fiber, therefore K_{NL} is:

$$K_{NL}^{RA} = \gamma\, P_{in}\, L_{eff}^{RA} = \gamma\, P_{in} \int_0^{L_{span}} \exp\{-\alpha_S z\} G_{RA}(z)\mathrm{d}z > K_{NL}^{EDFA} \qquad (13)$$

where $G_{RA}(z)$ is the Raman *on-off gain* as a function of z. As a consequence, *EDFA*-based links cannot be directly compared to a *RA*-based ones using the same launched power. The two systems must be compared imposing $K_{NL}^{RA} = K_{NL}^{EDFA} = K_{NL}$, where K_{NL} is the predefined *non-linear weight*. Hence, we get the following relation between the launched powers to ensure the same non-linear impact:

$$\gamma\, P_{in}^{EDFA} L_{eff}^{EDFA} = \gamma\, P_{in}^{RA} L_{eff}^{RA} \quad \Rightarrow \quad P_{in}^{RA} = P_{in}^{EDFA} \frac{L_{eff}^{EDFA}}{L_{eff}^{RA}} \qquad (14)$$

If we consider the system scenario of the previous section composed of a single-span link and receiver preamplifier (*RA* or *EDFA*) that completely recovers the fiber loss ($G_{EDFA} = G_{RA} = G = \exp\{+\alpha_s L_{span}\}$), the *SNR* over the bandwidth B_n after the preamplifier is, as follows:

$$SNR_{EDFA} = \frac{P_{in}^{EDFA}}{n_{sp}^{EDFA}(G-1)hfB_n} \qquad (15)$$

$$SNR_{RA} = \frac{P_{in}^{RA}}{n_{sp}^{RA}(G-1)hfB_n} = \frac{P_{in}^{EDFA}}{n_{sp}^{RA}(G-1)hfB_n}\frac{L_{eff}^{EDFA}}{L_{eff}^{RA}} = SNR_{EDFA}\frac{n_{sp}^{EDFA}}{n_{sp}^{RA}}\frac{L_{eff}^{EDFA}}{L_{eff}^{RA}} \qquad (16)$$

From Eqs (15) and (16) the equivalent spontaneous emission factor can be derived for the *RA* substituting the *effective* equivalent spontaneous emission $n_{sp,eff}^{RA}$ that needs to be employed in a direct comparison with the *EDFA*. Its expression is:

$$n_{sp,eff}^{RA} = n_{sp}^{RA}\frac{L_{eff}^{RA}}{L_{eff}^{EDFA}} > n_{sp}^{RA} \qquad (17)$$

Also the Noise-Figure for a *RA* (large gain approximation) must be corrected by the ratio of the effective lengths:

$$NF_{RA,eff}(f) \approx 2\frac{L_{eff}^{RA}}{L_{eff}^{EDFA}}\frac{S_{ASE}(f)}{hf\left[G_{on-off}(f)-1\right]} \qquad (18)$$

Therefore, curves in Fig. 5 are re-plotted considering the difference between NF_{EDFA} and $NF_{RA,eff}$ in Fig. 6. The results shown in Fig. 6 confirm the benefit of employing *RA's* even though the power is reduced of the factor L_{eff}/L_{ef}^{RA} to keep the non-linear impact on the same level for both cases. The optimal span length is still the same and the *SNR* improvement is still estimated to be greater than 4.7 dB for the optimal span length. In Fig. 7 the *SNR* improvement evaluated with the same transmitted power is compared with the *effective* one for *R* = -30 dB. It can be observed that the optimal span-length shifts 5 km and the optimal *SNR* improvement decreases by 0.5 dB.

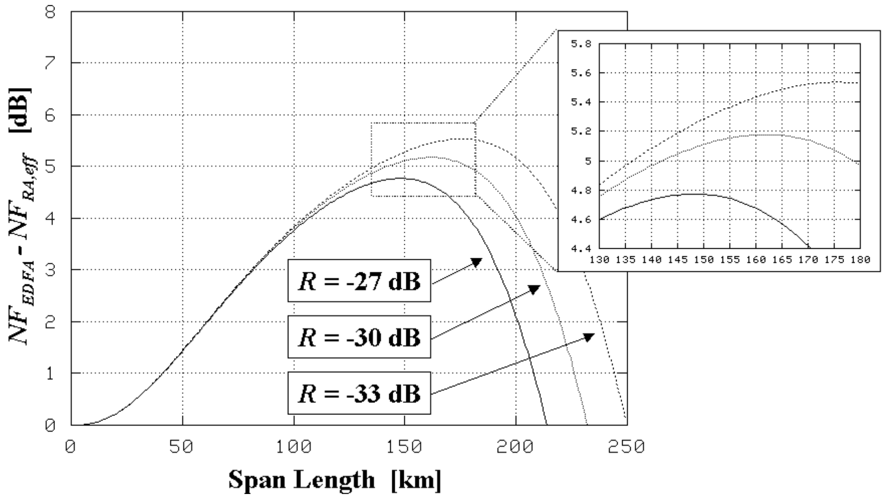

Fig. 6: Difference between the Noise-Figure of the *EDFA* and the *effective* one for the *RA*. The plot is a function of the fiber-span length. Different curves refer to fibers with different Rayleigh back-scattering capture factors.

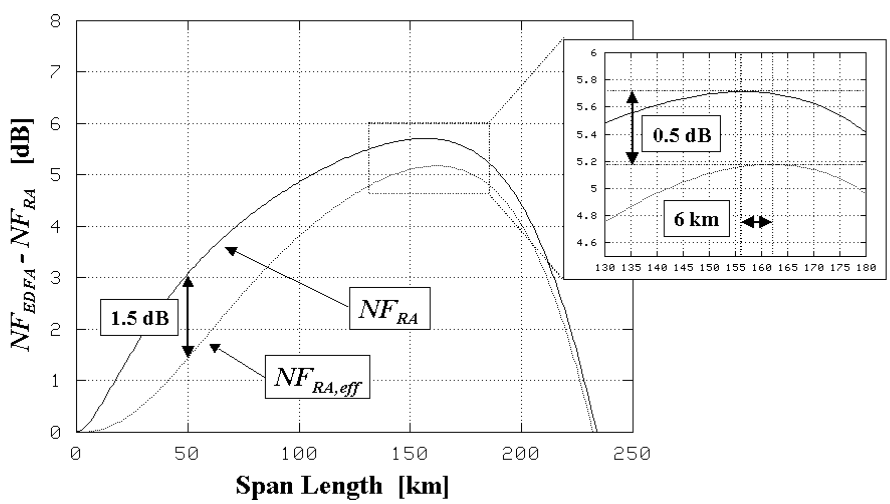

Fig. 7: Comparison between the *SNR* improvement evaluated with the same transmitted powers and the improvement calculated on the basis of the same non-linear impact (*R* = -30 dB). At the optimal span-length, the difference is only 0.5 dB while at L_{span} = 50 km the difference is about 1.5 dB.

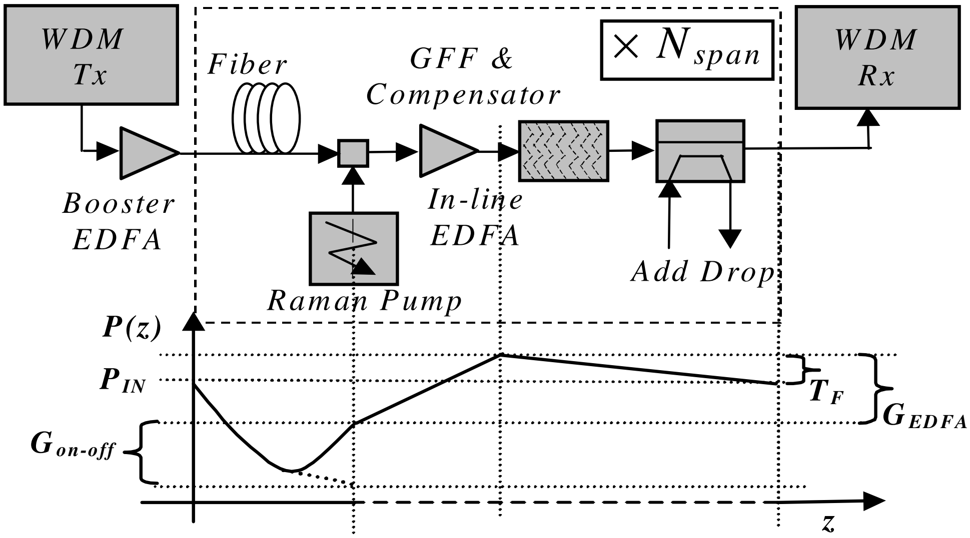

Fig. 8: The system scenario analyzed in order to determine the optimal *HFA* configuration. The lower part of the figure shows the power-profile along each of the periods.

Hybrid Raman/Erbium-Doped Fiber Amplifiers (HFA)

After the analysis of *RA* vs. *EDFA* on single-span links, we focus our attention on the multi-span link and analyze the use of *HFA*'s in order to investigate if there exist an optimal configuration with respect to the *SNR*, the impact of the non-linearities or the distance between the amplifying/pumping stations.

Since each configuration of *HFA* implies a different power-profile along the link, the criterion based on the *non-linear weight* has been used. We considered the scenario represented by the periodic link shown in Fig. 8. It is composed of N_{span} fiber spans, each L_{span} long and is backward pumped to obtain a Raman *on-off gain* $G_{on\text{-}off}$. The total link length is $L_{TOT} = N_{span} \cdot L_{span}$. Each fiber is followed by an *EDFA* with gain G_{EDFA}, a Gain Flattening Filter (*GFF*), a Dispersion Compensator (*DC*) and an Add/Drop Multiplexer (*ADM*EQ). We assume that the amplifier gains are set so as to perfectly compensate for the loss of the passive components and of the fiber in each span, yielding:

$$\exp\left\{-\alpha_S L_{span}\right\} G_{on-off} T_F G_{EDFA} = 1 \qquad (19)$$

where α_S is the fiber loss coefficient and T_F is the loss introduced by all passive components (*GFF*, *DC* and *ADM*). The power-profile along each period of the link is shown in Fig. 8. A Raman pump with the proper power level is injected to get the required gain $G_{on\text{-}off}$. Under these assumptions, we found that the *SNR* at the output of the system has the following expression:

$$SNR = \frac{P_{IN}}{hfB_n} \cdot \frac{\exp\left\{-\alpha_S \dfrac{L_{TOT}}{N_{span}}\right\}}{N_{span}\left(n_{eq}^{RA} + \dfrac{n_{eq}^{EDFA}}{G_{on-off}}\right)} \qquad (20)$$

where P_{IN} is the average power-per-channel at the input of each fiber span, γ is the non-linear coefficient of the fiber, h is Planck's constant, f is the optical carrier frequency, B_n is the bandwidth over which noise is integrated and n_{eq}^{RA} and n_{eq}^{EDFA} are the *equivalent input noise factors* for the in-line *RA*'s and *EDFA*'s, respectively. They are related to the corresponding *spontaneous emission factors* in the following way [8]:

$$n_{eq} = n_{sp}\,\frac{G}{G-1} \qquad (21)$$

The factor n_{eq}^{RA} depends on the pump power, over the fiber-span length, on the Raman efficiency and on the Rayleigh back-scattering [11], [13]. n_{eq}^{EDFA} depends on the EDFA Noise-Figure and gain of the amplifier [8]. To compare different system configurations we used the *non-linear weight* K_{NL}, which for a multi-span link is defined as:

$$K_{NL} = \gamma P_{IN} L_{eff}^{RA} N_{span} \ \ [rad] \qquad (22)$$

where the effective length L_{eff}^{RA} takes into account the fiber loss and the distributed Raman amplification. K_{NL} typically assumes values between 0.1 and 1 radians. Expressing the *SNR* as a function of K_{NL}, we obtain:

$$SNR = \frac{K_{NL}}{\gamma h f B_n} \cdot \frac{\exp\left\{-\alpha_S \frac{L_{TOT}}{N_{span}}\right\}}{N_{span}^2 L_{eff}\left(n_{eq}^{RA} + \frac{n_{eq}^{EDFA}}{G_{on-off}}\right)} \qquad (23)$$

Eq. (23) is one of the main results of this work. Assuming that the total length of the link, the fiber characteristics, and the concentrated loss T_F are given, Eq. (23) has four degrees of freedom: *SNR*, K_{NL}, N_{span} and the percentage of loss (in dB) recovered by the *RA* or by the *EDFA*. In order to determine the configuration that optimizes the system performance, one of the first three degrees of freedom must be fixed as the percentage of gain is swept from 0 to 100%. Three different optimization may be carried out:

1. *SNR* fixed: given a required *SNR* value, the system is optimized in order to minimized the *non-linear weight* K_{NL} versus the number of spans N_{span}.
2. K_{NL} fixed: given a non-linear weight K_{NL}, the *SNR* is maximized versus the number of spans N_{span}.
3. N_{span} fixed: given the distance between the stations ($L_{span} = L_{TOT}/N_{span}$), the system is optimized to maximize the *SNR* for each K_{NL}.

As an example, we present an optimization of type 2. We studied the percentage of *RA* and *EDFA* amplification needed to obtain the minimum number of spans N_{span} for a given required *SNR* at the receiver. As a typical scenario, we considered a 32-channel, 10 Gbit/s, 50 GHz spaced, medium-haul (L_{TOT} = 1500 km) WDM system. Spans are made up of NZ-DSF fiber with loss = 0.2 dB/km at 1550 nm and 0.3 dB/km at 1450 nm, D = 5.7 ps/nm/km and D' = 0.037 ps/nm^2/km at 1550 nm, A_{eff} = 55 µm^2 and Rayleigh back-scattering [13] *capture factor* R = -30 dB. Dispersion, dispersion slope and variations of the gain spectral-shape are assumed to be completely compensated at each span. We also considered a concentrated loss T_F = 10 dB to take into account the attenuation introduced by the *GFF*, the *DC* and the *ADM*. The Noise-Figure of the *EDFA*'s has been set at 4.77 dB ($n_{sp}^{EDFA} = 1.5$). In order to achieve to achieve a Q = 16 dB (*BER* = 10^{-9}) for a 10 Gbit/s system, a *SNR* equal to 19 dB (over a bandwidth B_n = 0.1 nm) is required, so long as no other system impairments influence the performance. We take a 3 dB margin over this value, so our target *SNR* is 22 dB.

Fig. 9 shows the optical *SNR* versus N_{span} for three different amplification schemes: *EDFA* only, *RA* only, and the best combination of *EDFA* and *RA* resulting from Eq. (23), which was found to be 30% *EDFA* and 70% *RA* (percentages refer to gain in dB). The *SNR* scale on the left and right of Fig. 9 are for K_{NL} = 0.2 and 1, respectively. Horizontal lines mark the *SNR* = 22 dB target for both cases.

For each curve, the crossing of the 22 dB line yields the minimum number of spans needed to guarantee the required performance. For K_{NL} = 0.2 the optimal *HFA* configuration requires 11 spans (L_{span} = 136.4 km), which yields a significant advantage over the *RA* only solution (13 spans, L_{span} = 115.4 km) and over the *EDFA* only solution (19 spans, L_{span} = 78.9 km). For K_{NL} = 1 the span numbers are 8, 10 and 11, respectively.

In terms of average launched power, for K_{NL} = 0.2 the system requires -3.60 dBm/ch (optimal *HFA* with +28.30 dBm Raman pump), –7.30 dBm/ch (*RA* only with +29.30 dBm Raman pump) and -5.30 dBm/ch (*EDFA* only). For K_{NL} = 1 the results are +5.10 dBm/ch (optimal *HFA* with +29.30 dBm Raman pump), +1.50 dBm/ch (*RA* only with +30.10 dBm Raman pump) and +3.90 dBm/ch (*EDFA* only).

Further inspection of Fig. 9 reveals some other interesting facts. The optimization of the amplification percentage of *EDFA* and *RA* results in a very substantial *increase* of the span length and a consequent *decrease* of the number of spans. In addition, this beneficial effect is most evident for systems operating at low signal levels, i.e., for small *non-linear weights* K_{NL}. This suggests that the use of an optimized *HFA* could be key to obtaining longer span lengths while keeping the impairment of non-linearities at a minimum.

The presented use-case is only an example of optimization based on the presented analysis that can be adapted to several system configurations.

Validation of Analytical Results with the Optical System Simulator OptSim®

In order to validate our analysis and demonstrate that the *non-linear weight* is a good parameter with which to compare different systems, we numerically simulated the described system in two different configurations: *HFA*'s (optimal) or *EDFA*'s only, with K_{NL} = 0.2. We used the optical system simulator *OptSim®* that includes all relevant linear and non-linear propagation effects. Fig. 10 shows that the resulting *SNR*'s for all channels are between 21 and 22 dB, close to the value of 22 dB predicted by Eq. (23). This small penalty is due to low-level non-linearities consistent with the low value K_{NL} = 0.2. Eye-diagrams for channel 16 confirm the pseudo-linear propagation behavior of both systems and the *Q* values were found to be greater than 17 dB for all channels. The fact that both cases presents comparable performance confirms that the *non-linear weight* is a good parameter for the estimation of the impact of non-linearities.

Conclusions

Raman amplification has been briefly reviewed concluding with an analytical expression for the *on-off gain* and for the power spectral-density of the *ASE* noise. *RA* and *EDFA* are compared in terms of the resulting *SNR* and it has been shown that *RA*'s always yield advantages for span-lengths ranging from 1 to 250 km. The presence of Rayleigh back-scattering induces an optimal span length for *RA*'s around 150 km.

Since power distribution in *RA*- and *EDFA*-based systems is not the same, the concept of *non-linear weight* has been introduced to allow a more realistic comparison. Even with the resulting correction, RA's result in advantages of up to 5 dB at the optimal fiber-span length.

The concept of *non-linear wei*ght has also been applied to multi-span systems in order to optimize the *HFA* configuration. This analysis concludes that Hybrid amplifiers can substantially improve system performance, particularly in the case of pseudo-linear systems with large distance between amplifying/pumping stations.

Acknowledgements

The author would like to thank Andrea Carena, Roberto Gaudino and Peter Parrish for their fruitful suggestions.

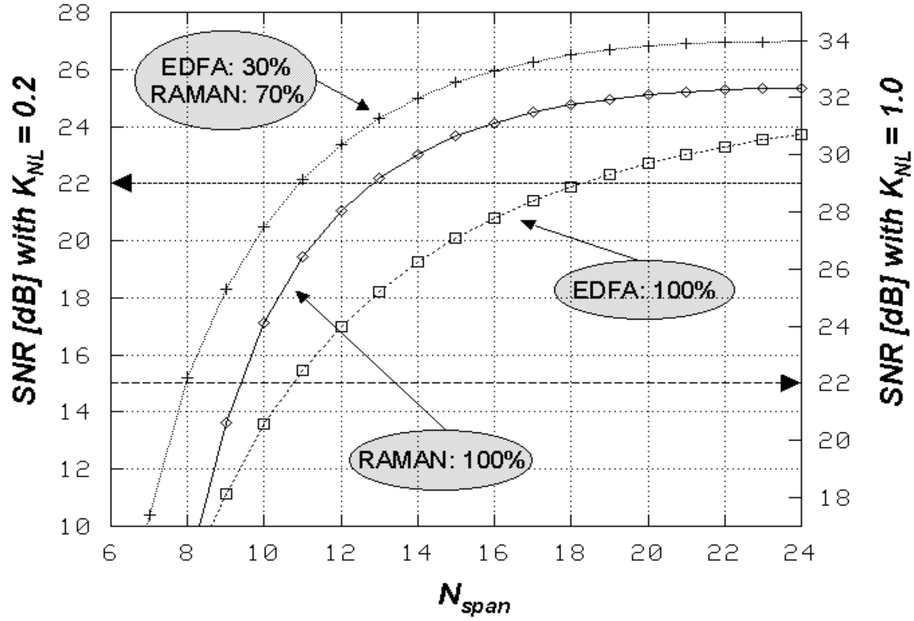

Fig. 9: ***SNR*** **vs. number of spans for different percentages of loss recovered by the** ***RA*** **and by the** ***EDFA*****. Left and right scales refer to** K_{NL} **= 0.2 and 1, respectively. Assuming a fixed number of periods** N_{span}**, an optimum configuration is one that yields a maximum** ***SNR*****. In this case the optimum occurs with 70% of loss recovery (in dB) for the** ***RA*** **and 30% for the** ***EDFA*****.**

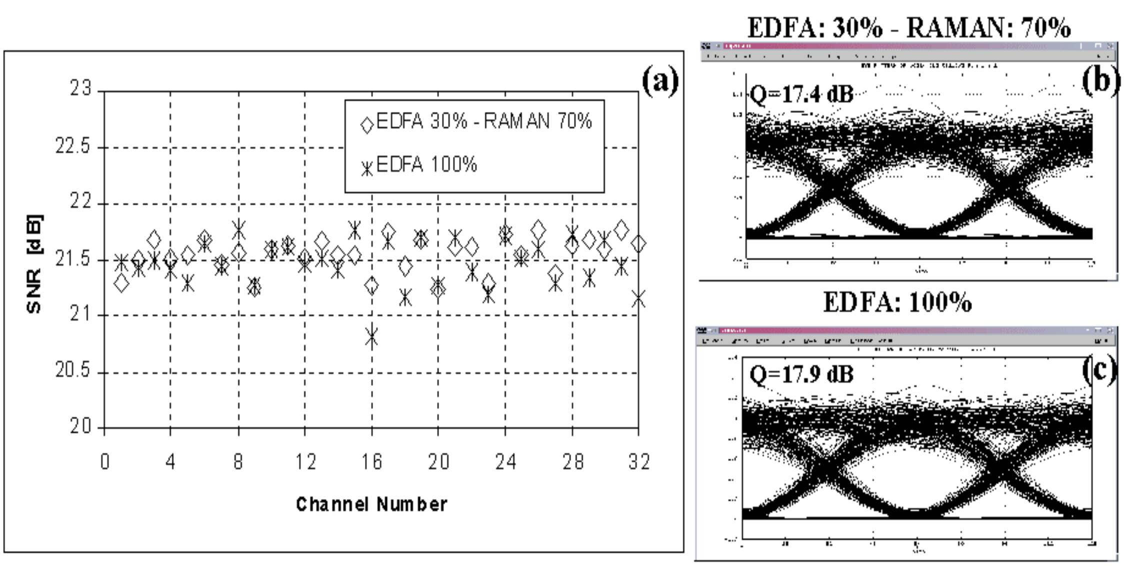

Fig. 10: Simulation results at 1500 km for both configurations studied. (a) ***SNR*** **for each channel. All values are in the neighbourhood of 21.5 dB as predicted from the theory. Eye-diagrams for central channel #16 for the optimal HFA configuration (b) and for the one based on EDFA amplification only (c).** ***Q*****'s greater than 17 dB confirm that the 3 dB margin was wide enough to** ***absorb*** **the non-linear effect. Very similar** ***Q*** **values confirm that the** ***non-linear weigh*****t is a good parameter for the comparison of system with different power distribution.**

References:

[1] M. Nissov *et al.*, "100 Gb/ (10x10 Gb/s) WDM transmission over 7200 using distributed Raman amplification," ECOC 97, Edimburgh, UK, Sep. 1997.

[2] P. B. Hansen *et al.*, "Capacity upgrades of transmission systems by Raman amplification," IEEE Photonics Technology Letters., Vol. 9, No. 2, Feb. 1997.

[3] T. N. Nielsen *et al.*, "1.6 Tb/s (40x40 Gb/s) transmission over 4x100 km nonzero-dispersion fiber using hybrid Raman/Erbium doped inline amplifiers," ECOC 99, Nice, France, Sep. 1999.

[4] T. Ito *et al.*, "3.2 Tb/s – 1,500 km WDM transmission experiment using 64 nm hybrid repeater amplifiers," OFC 2000, Paper PD24, Baltimore, MA, USA, Mar. 2000.

[5] T. N. Nielsen *et al.*, "3.28-Tb/s (82x40 Gb/s) transmission over 3x100 km nonzero-dispersion fiber using dual C- and L-band hybrid Raman/Erbium-doped inline amplifiers," OFC 2000, Paper PD23, Baltimore, MA, USA, Mar. 2000.

[6] J. P. Blondel *et al.*, "Network application and system demonstration of WDM systems with very large spans (error-free 32×10 Gbit/s 750 km transmission over 3 amplified spans of 250 km ," OFC 2000, Paper PD31, Baltimore, MA, USA, Mar. 2000.

[7] Y. Emory *et al.*, "100 nm flat gain Raman amplifiers pumped and gain equalized by 12-wavelength channel WDM high power laser diode," OFC 99, Paper PD19, San Diego, CA, USA, Feb. 1999.

[8] E. Desurvire, Erbium-Doped Fiber Amplifiers, principles and application, Wiley-Interscience, New York, 1994.

[9] R. G. Smith, "Optical power handling capacity of low loss optical fibers as determined by Stimulated Raman Scattering and Brillouin Scattering," Applied Optics, Vol. 11, No. 11, Nov. 1972.

[10] E. Desurvire *et al.*, "Theory and implementation of a Raman active fiber delay line," IEEE/OSA Journal of Lightwave Technology, Vol. 4, No. 4, Apr. 1986.

[11] P. B. Hansen *et al.*, "Rayleigh scattering limitations in distributed Raman pre-amplifiers," IEEE Photonics Technology Letters., Vol. 10, No. 1, Jan. 1998.

[12] R. H. Stolen *et al.*, "Raman response function of silica-core fibers," Journal of Optical Society of America B, Vol. 6, No. 6, Jun. 1989.

[13] P. Wan *et al.*, "Impact of double Rayleigh Backscatter noise in digital and analog fiber systems, ," IEEE/OSA Journal of Lightwave Technology, Vol. 14, No. 3, Mar. 1996.

[14] S. A. E. Lewis *et al.*, "Gain saturation in silica-fibre Raman Amplifier," IEE Electronic Letters, Vol. 35, No. 11, 27th May 1999.