Distributed and Lumped Raman Amplifiers in Optical Communication Systems

Shirley P. Neves Cani and Luiz C. Calmon

Abstract—**This work analyzes distributed and lumped Raman amplifiers in SMF_DCF systems. Analytical formulations to estimate gain in such amplifiers is presented for the first time and are in good agreement with numerical results. Gain and noise performance of these amplifiers are obtained analyzing numerically 8 WDM signals in a counter-pumped configuration.**

***Index Terms*— Optical amplifier, optical communication, optical fiber amplifiers, optical pumping, Raman scattering.**

I. INTRODUCTION

Raman amplifiers are being deployed in almost every new long-haul transmission system, making them one of the first widely commercialized nonlinear optical devices in telecommunications industry. The flexible use of signal wavelengths and the technological advances in the field of high-power laser diodes are the main attractive in implementing Raman amplifiers. The use of a fiber with high gain in line with a standard transmission fiber also serves as a dispersion compensating element.

When pumping is only confined into the dispersion compensating fiber (DCF), it is called lumped Raman amplifier (LRA) and when it extends over the entire link length, is called distributed Raman amplifier (DRA).

In [1] a DRA is compared to an EDFA lumped amplifier. In [2] are shown some characteristics of a DRA in composition with EDFAs. The present work compares DRAs and LRAs in optical links without recourse to EDFAs, as illustrated in Figure 1. In section II system modeling is presented. In III analytical expressions for gain in co and counter-pumped DRAs and LRAs are for the first time presented. In IV a rigorous numerical analysis is employed to obtain the noise performance of these amplifiers studying 8 WDM signals in a counter-pumped configuration.

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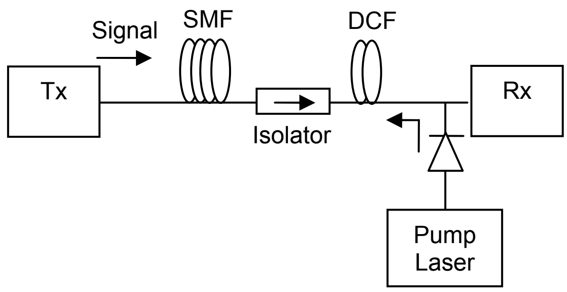
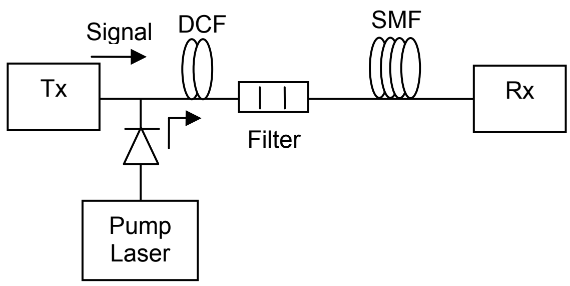
II. SYSTEM MODELING

Figure 1 (a) and (b) show lumped Raman amplifiers in counter and co-pumped configurations respectively. For distributed amplifiers the isolator in 1 (a) and the filter in 1 (b) would be absent.



(a)



(b)

Fig. 1. Raman amplifier configurations: (a) Lumped counter-pumped, (b) Lumped co-pumped.

The analysis was made varying the total link length from 5km to 117.35km. The respective lengths of standard SMF and DCF were obtained to achieve total dispersion compensation and are shown in Table 1.

TABLE 1
TOTAL LINK LENGTH

Link length (km)	SMF (km)	DCF (km)
5	4.3	0.7
10	8.5	1.5
15	12.8	2.2
25	21.3	3.7
50	42.6	7.4
75	63.9	11.1
100	85.2	14.8
117.35	100	17.35

The evolution of the power of signals and pumps are expressed by equation (1). In (1) are included pump-pump, pump-signal, signal-signal interactions, double Rayleigh scattering (DRS), amplified spontaneous emission (ASE) and its temperature dependence. The equation (2) governs the power evolution of ASE at the signal wavelengths [1], [3].

$$\begin{aligned}\frac{dP_\nu^\pm}{dz} &= \mp\alpha_\nu P_\nu^\pm \pm \varepsilon_\nu P_\nu^\mp \\ &\pm P_\nu^\pm \sum_{\mu>\nu}\frac{C_{R_{\mu\nu}}}{\Gamma}\left(P_\mu^+ + P_\mu^-\right) \\ &\mp P_\nu^\pm \sum_{\mu<\nu}\frac{\omega_\nu}{\omega_\mu}\frac{C_{R_{\mu\nu}}}{\Gamma}\left(P_\mu^+ + P_\mu^-\right) \\ &\mp P_\nu^\pm \sum_{\mu<\nu}\frac{\omega_\nu}{\omega_\mu}\frac{C_{R_{\nu\mu}}}{\Gamma}4N_{E_\mu}\left[1+\frac{1}{\exp\left[\frac{h(\nu-\mu)}{kT}\right]-1}\right]\end{aligned} \tag{1}$$

$$\begin{aligned}\frac{dP_{ASE,\nu}^\pm}{dz} &= \mp\alpha_\nu P_{ASE,\nu}^\pm \pm \varepsilon_\nu P_{ASE,\nu}^\mp \\ &\pm P_{ASE,\nu}^\pm \sum_{\mu>\nu}\frac{C_{R_{\mu\nu}}}{\Gamma}\left(P_\mu^+ + P_\mu^-\right) \\ &\pm 2N_{E_\nu}\sum_{\mu>\nu}\frac{C_{R_{\mu\nu}}}{\Gamma}\left(P_\mu^+ + P_\mu^-\right)\left[1+\frac{1}{\exp\left[\frac{h(\mu-\nu)}{kT}\right]-1}\right]\end{aligned} \tag{2}$$

In (1) and (2) subscripts ν and μ denote optical frequencies, superscripts + and – denote forward and backward-propagating waves, respectively, P_ν is the optical power, $P_{ASE,\nu}$ is the ASE optical power, α_ν is the attenuation coefficient, ε_ν is the Rayleigh backscattering coefficient, $C_{R\mu\nu} = g_{\mu\nu} / Aeff_\mu$ is the Raman gain efficiency between frequencies μ and ν, $g_{\mu\nu}$ is the Raman gain at frequency ν due to pump at frequency μ, $Aeff_\mu$ is the effective area of optical fiber at frequency μ, $N_{E\nu} = h\nu\Delta\nu$ is the noise power of spontaneous emission in a bandwidth Δν around frequency ν, h is the Planck's constant, k is the Boltzmann constant, T is temperature and Γ is the polarization factor which is assumed equal to 2 (depolarized light) [4].

Table 2 shows standard SMF and DCF parameters at 8 WDM signal wavelengths from λs = 1547.71nm to λs = 1558.98nm, with 200GHz channel spacing [5], [6].

TABLE 2
FIBER PARAMETERS

	SMF	DCF
λ_s (nm)	1547.71 - 1558.98	
C_R ($W^{-1}km^{-1}$)	0.4	3
α (dB/km)	0.1892 - 0.1896	0.5
Aeff (μm)^2	76.16 - 76.99	21.77 - 23.23
ε (dB/km)	-35.91 - -36.02	-32.51 - -32.71

III. ANALYTICAL ANALYSIS

Analytical net gain for co and counter-pumped DRAs and LRAs composed by two different fibers is obtained solving equation (1) neglecting pump depletion by signals, ASE noise and DRS.

Equation (3) is for DRAs with the pump near the highest gain fiber (DCF), identified by the notation *DCF_SMF*. In (4) the analytical net gain is for DRAs with the pump near the lowest gain fiber (SMF), identified by the notation *SMF_DCF*. Both equations apply for co and counter-pumped configurations indistinctly.

$$\begin{aligned}NG_{anal,DCF\_SMF}^{DRA} &= \exp\left[-\alpha_{\nu,1}d_1 - \alpha_{\nu,2}d_2\right] \\ &\exp\left[\frac{C_{R\mu\nu,1}\,P_\mu\,L_{eff\,\mu,1}}{\Gamma}\exp\left(-\alpha_{\mu,2}d_2\right)\right] \\ &\exp\left[\frac{C_{R\mu\nu,2}\,P_\mu\,L_{eff\,\mu,2}}{\Gamma}\right]\end{aligned} \tag{3}$$

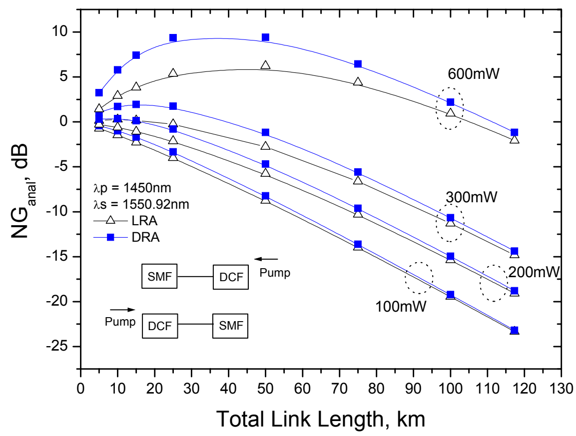
$$\begin{aligned}NG_{anal,SMF\_DCF}^{DRA} &= \exp\left[-\alpha_{\nu,1}d_1 - \alpha_{\nu,2}d_2\right] \\ &\exp\left[\frac{C_{R\mu\nu,1}\,P_\mu\,L_{eff\,\mu,1}}{\Gamma}\right] \\ &\exp\left[\frac{C_{R\mu\nu,2}\,P_\mu\,L_{eff\,\mu,2}}{\Gamma}\exp\left(-\alpha_{\mu,1}d_1\right)\right]\end{aligned} \tag{4}$$

For co and counter-pumped LRAs the analytical net gain does not depend on the relative position of the fibers and is given by:

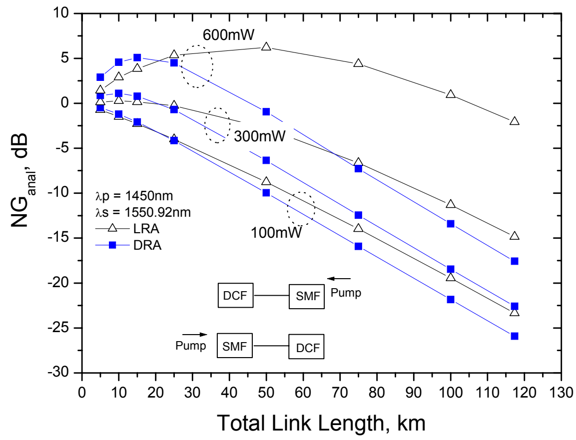
$$NG_{anal}^{LRA} = \exp\left[-\alpha_{\nu,2} d_2 - \alpha_{\nu,1} d_1\right] \exp\left[\frac{C_{R\mu\nu,2}\, P_\mu\, L_{eff\,\mu,2}}{\Gamma}\right] \quad (5)$$

where subscripts 1 and 2 refer to the lowest and the highest Raman gain fiber respectively (in our case it refers to standard SMF and DCF). Subscripts ν and μ accounts for signals and pumps respectively, *d* is the length of each fiber, P_μ is the full pump power launched into the fiber and $Leff = (1/\alpha_\mu)\,(1\text{-}\exp\,(\alpha_\mu d))$, is the fiber effective length.

Figure 2 shows the analytical net gain for different link lengths and pump powers for DRAs and LRAs utilizing (3), (4) and (5).



(a)



(b)

Fig. 2. Analytical net gain for co and counter-pumped DRAs and LRAs against total link length. (a) Curves obtained by equations (3) and (5). (b) Curves obtained by equations (4) and (5). Signal and pump wavelength, pump powers and the schematic of DRAs are given in the inset.

In Figure 2 (a) and (b) it can be seen that the position of the maximum net gain of DRAs and LRAs depends on the pump power. Increasing the pump power, fiber link losses will only catch up Raman gains at increasingly longer distances.

The nonlinear effect of stimulated Raman scattering (SRS) is set by the fibers effective lengths. For longer links the effective length become independent of fiber length. In Figure 2 (a) net gains for DRAs became similar to LRAs in longer links since the pump power in SMF is previously attenuated in the DCF and the interaction between pump and signal occurs during a small length into the standard SMF, as can be observed comparing equations (3) and (5).

For the DRAs illustrated in Figure 2 (b), the pump power is previously attenuated in standard SMF before arriving at DCF. Increasing the link length, weaker the pump will arrive at the DCF and consequently net gain for DRAs will be smaller than in LRA.

For amplifier configurations analyzed in Figure 2 (a) the difference between DRAs and LRAs only become significant for higher pumps and shorter link lengths. For configurations analyzed in Figure 2 (b) the difference between DRAs and LRAs becomes more significant for higher pumps and longer link lengths.

IV. NUMERICAL ANALYSIS

Counter-pumped Raman amplifiers present less signal penalties due to nonlinearities, given a smaller signal power where the pump is strong. DRAs with the pump power near the highest gain fiber (DCF), presents better gain when compared to the DRA with the pump near the lowest gain fiber (SMF), as shown in Figures 2 (a) and (b). Due to these advantages, only will be analyzed LRAs illustrated in Figure 1 (a) and DRAs with the pump near the higher gain fiber (obtained suppressing the isolator in Figure 1 (a)).

Analytical analysis do not provide noise estimates therefore, numerical analysis will be applied to obtain systems parameters such as optical signal to noise ratio (OSNR), noise figure (NF), ASE noise power, as well as net gain (NG).

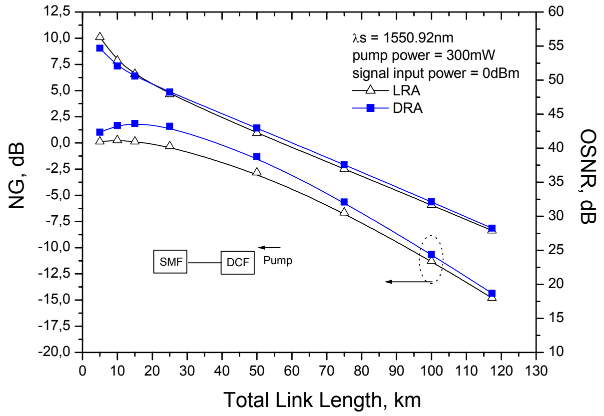
Numerical results were obtained solving (1) and (2) to a set of 8 WDM signals, whose fiber related parameters are shown in Table 2, with one pump at λp = 1450nm. Bandwidth of Δν = 0.2nm is assumed. NG, NF and OSNR are given by [7]:

$$NG_{dB} = 10\log_{10}\left(P_\nu(L)/P_\nu(0)\right) \quad (6)$$

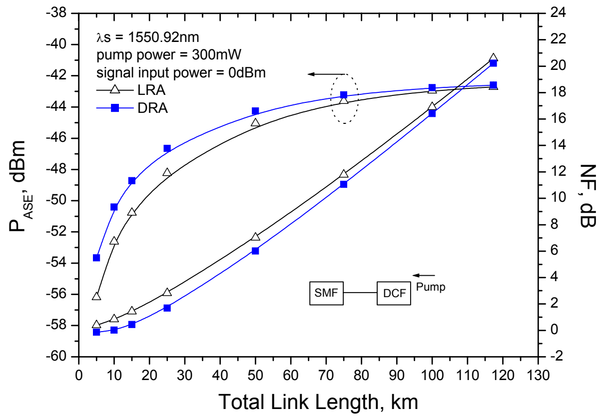
$$NF_{dB} = 10\log_{10}\left(\left(1/NG\right) + \left(P_{ASE,\nu}/N_E NG\right)\right) \quad (7)$$

$$OSNR_{dB} = 10\log_{10}\left(P_\nu(L)/P_{ASE,\nu}(L)\right) \quad (8)$$

Figure 3 (a) and (b) show NG, OSNR, NF and P_{ASE} against total link length for the signal allocated in 1550.92nm with 0dBm signal input power and 300mW pump power. Similar results were obtained for the other wavelengths.



(a)



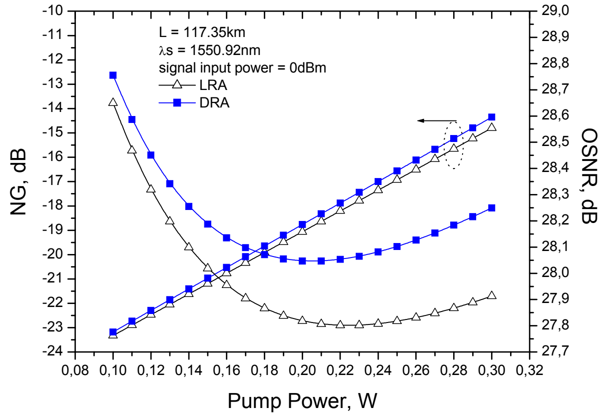
(b)

Fig. 3. Calculated parameters for counter-pumped DRA and LRA versus total link length. (a) NG and OSNR and (b) P_{ASE} and NF. Signal wavelength, pump and signal input power, and the schematic of DRA are given in the inset.

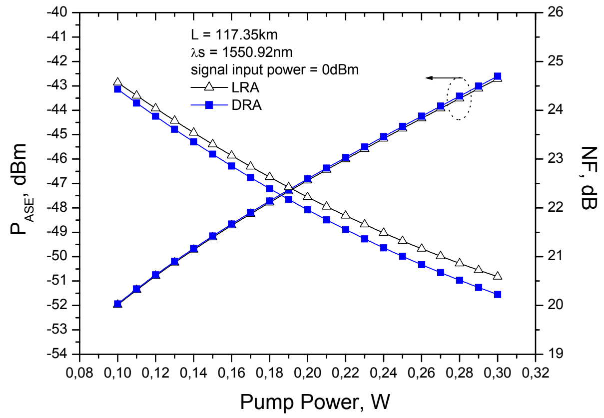
It can be seen in Figure 3 (a) that the net gain obtained by (6) is approximately the same as those obtained by analytical means shown in Figure 2 (a).

For shorter links in Figure 3 (b) P_{ASE} is amplified due to strong pump power. For longer links in a counter-pumped configuration P_{ASE} is mostly amplified near the injected pump, and becomes independent of link length for longer links. Despite of the saturation of P_{ASE} in longer links, OSNR and NF degrades with increasing distances due to the decreasing NG. In Figure 3 (a) and (b) it can also be seen that OSNR and NF for DRAs are closer to LRAs because of the low amplification of noise in the standard SMF.

Figure 4 (a) and (b) show NG, OSNR, P_{ASE} and NF against pump power for a 117.35km link length. This length was chosen because it represents a standard long distance SMF optical link as recommended by G 692 ITU [8]. In Figure 4 (a) the OSNR first drops because of the P_{ASE} behavior, until the increase in P_{ASE} falls below the increase in signal gain. Using a DRA, slightly reduces the overall excursion that the signal level experiences when propagating in the standard SMF fiber, consequently the OSNR is somewhat higher in the DRA. In the receiver, due to its better OSNR, DRA presents lower noise figure than LRA, as shown in Figure 4 (b).



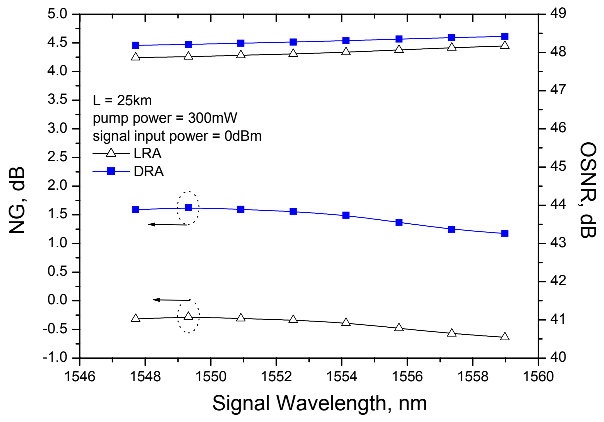
(a)



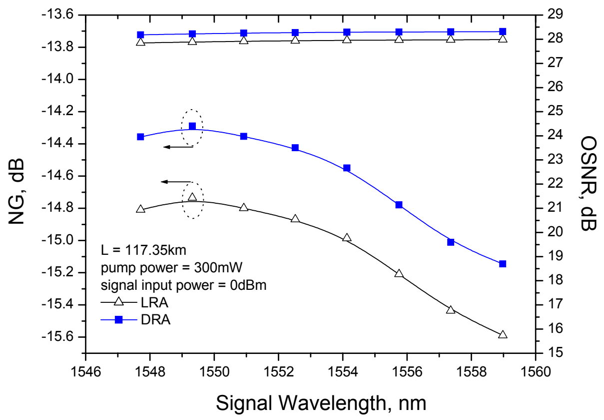
(b)

Fig. 4. Calculated parameters for DRA and LRA versus pump power. (a) NG and OSNR (b) P_{ase} and NF. Total link length, signal wavelength and signal input power are given in the inset.

Figure 5 (a) and (b) show NG and OSNR for 25km and 117.35km DRAs and LRAs for the different signal wavelengths. The link length of 25km was chosen because it presents the greatest difference in the net gain between the configurations proposed. It can be observed that improvements of 2dB (for 25km link length) and 0.4dB (for 117.35km link length) in the NG are obtained using a DRA. The improvement obtained in OSNR when using a DRA does not depend on the distance and is approximately 0.3 dB for 300mW pump power.



(a)



(b)

Fig. 5. Calculated parameters for DRA and LRA versus signal wavelength. (a) NG e OSNR for 25km, (b) NG e OSNR for 117.35km. Total link length, pump power and signal input power are given in the inset.

There are some challenges in using DRAs, for example, for longer links and pump wavelengths around 1450nm, the effective length in standard SMF is around 20km, this means that the interaction between pump and signals occurs only during 20km into the standard SMF. The second challenge is the high pump power propagating in the transmission fiber (SMF). High powers can damage more rapidly the fiber and connectors. Another important point to be observed using a DRA is the penalty caused by the amplification of spurious reflections from double Rayleigh scattering (DRS) in the standard SMF.

Using a LRA the penalty from DRS is minimized and those challenges pointed out in a DRA are avoided, but on the other hand, it is mandatory the use of an optical isolator or a filter between the standard SMF and DCF to isolate the pump power.

V. Conclusions

This work compares distributed and lumped counter-pumped Raman amplifier implemented in optical *SMF_DCF* systems without recourse to EDFAs. Analytical formulations for co and counter-pumped DRAs and LRAs are presented for the first time and are shown to be reliable approximations to estimate gain in Raman amplifiers, when pump depletion by signals can be neglected.

Numerical results for 8 WDM signals with 0dBm each and a pump with 300mW in a counter-propagating configuration show that improvements of 2dB in gain can be obtained when using a DRA instead of a LRA with 25km link length, but this improvement drops to negligible levels for longer links. The system impairments caused by noise amplification is approximately the same for DRAs and LRAs, and is independent of the link length.

This work also points out some challenges about implementing such amplifiers. In a DRA the presence of a strong pump power into the standard SMF can damage more rapidly the fiber and connectors. Implementing a LRA the impairments in the standard SMF caused by a strong power pump are avoided, but on the other hand it is mandatory the use of an isolator or a filter between SMF and DCF.

References

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