# Influence of gain distribution on the noise properties in forward and backward Raman amplifiers

V. DALLOT (1), P. GALLION (2)

Communications and Electronics Department, CNRS URA 820 Ecole Nationale Supérieure des Télécommunications 46 rue Barrault, 75634 Paris cedex 13, France (1)Phone:(+33)1 45 81 78 98, fax:(+33)1 45 89 00 20, e-mail address: dallot@com.enst.fr (2)Phone:(+33)1 45 81 77 02, fax:(+33)1 45 89 00 20, e-mail address: gallion@com.enst.fr

Abstract: Signal and noise evolutions in gain-distributed Raman amplifiers are described by using a classical approach taking into account the pump depletion. Characteristics of single and a chain of forward and backward amplifiers are estimated. ©2001 Optical Society of America OCIS codes: (060.2320) Fiber optics amplifiers and oscillators, (250.4480) Optical amplifiers

## 1. Introduction

The development of WDM in long haul optical communications forces the engineer community to consider amplifiers with large amplification bandwidths, high gain coefficients, high saturation powers and long amplification lengths for reasonable pump powers and low loss coefficients. Presently Raman amplifiers seem promising candidates [1]. In parallel, the need of using weaker incident signal to increase the performances implies to consider as non negligible the optical noise effects, in particular zero-point fluctuations, in the signal degradation process. This communication proposes to determine the spatial evolutions of signal and noise powers in Raman amplifiers, and so to evaluate the influence of the amplifier properties on the performances of the latter, in terms of gain and Signal to Noise Ratio (S.N.R.), for different configurations at the signal frequency. In a first part principles of the classical noise formalism are reminded. Then performances of a single, forward and then backward pumped, Raman amplifier followed by those of a chain of cascaded Raman amplifiers are numerically estimated in part three and four respectively. The optimum characteristics and noise factors are also evaluated.

## 2. The classical noise formalism

The classical noise formalism is based on the classical Rice description of fields and noise amplitudes [2,3]. Inquadrature and in-phase amplitude noise, contributing for the phase noise and the intensity noise, are in this way clearly distinguished from each other. This approach also allows to separate contributions linked to zero-point fluctuations ( $hv_0/2$ ) associating with the spontaneous emission from the effects of the intrinsic fluctuations of the incident fields (signal and pump),  $v_0$  being the carrier frequency under consideration. The evolution and the amount of the different noise contributions along the amplification length are then calculated, under the small-signal assumption, by taking into account the effects of the gain and loss coefficients,  $\beta$  and  $\alpha$ , on the incident components and by adding zero-point fluctuations which are known as amplification noise  $\beta hv_0/2$  and partition noise  $\alpha hv_0/2$ . Such a formalism makes, intuitively and rigorously, visible the evolution and the amount of the different noise contributions along the amplification length and allows to identify the incident signal, similarly to the pump, as the sum of a main signal at the carrier frequency under consideration and an added noise contribution.

The Raman amplifiers considered are assumed to have constant and homogeneous gain and loss coefficients all along the effective amplification length. Loss coefficients are frequency dependent and are identified as  $\alpha_S$  and  $\alpha_P$  at signal and pump frequency  $v_S$  and  $v_P$  respectively. The loss contributions  $\alpha_{RS}$ ,  $\alpha_{RP}$  implied by Rayleigh backscattering at signal and pump frequency are taken into account in the process of noise generation and signal degradation [4] as well as the pump depletion resulting from the signal amplification. The fibre is single mode and keeps a constant effective interaction surface A.

# 3. Single Raman amplifiers

This study is interested in the spatial power evolution of signals at frequency  $v_s$  in an optical bandwidth  $B_0$ . The different powers at the output of a Raman amplifier are numerically calculated by firstly divided the effective amplification length in successive slices of equal length dz and then integrated it.

# 3.1. Forward amplifier

In this configuration the pump and signal beam are propagating in parallel and together in a single Raman amplifier. The signal power  $P_S$  and the associated noise power  $P_{NS}$  are given in (1) and (2) for one amplifying slice where  $g_R$  and  $B_0$  are the Raman amplification coefficient and the optical bandwidth.

$$P_S(z+dz) = P_S(z) - (\alpha_{RS} + \alpha_S)P_S(z)dz + g_R P_P(z)P_S(z)dz$$
(1)

$$P_{NS}(z + dz) = P_{NS}(z) + \left[ -\alpha_{RS} - \alpha_{S} + g_{R}P_{P}(z) \right] P_{NS}(z)dz + g_{R}P_{NP}(z)P_{S}(z)dz + \left[ \alpha_{S} + g_{R}P_{P}(z) + g_{R}P_{NP}(z) \right] (hv_{s}/2)B_{0}dz.$$
(2)

Similarly the signal power  $P_P$  and the associated intensity power noise  $P_{NP}$  are written as (3) and (4).

$$P_{P}(z + dz) = P_{P}(z) - (\alpha_{RP} + \alpha_{P})P_{P}(z)dz - (\nu_{P} / \nu_{s})g_{R}P_{S}(z)P_{P}(z)dz$$
(3)  

$$P_{NP}(z + dz) = P_{NP}(z) - \left[\alpha_{RP} + \alpha_{P} + (\nu_{P} / \nu_{S})g_{R}P_{S}(z)\right]P_{NP}(z)dz$$
(4)  

$$-(\nu_{P} / \nu_{S})g_{R}P_{NS}(z)P_{P}(z)dz + \alpha_{P}(h\nu_{P} / 2)B_{0}dz .$$
(4)

The term in square-brackets in (2) and the last one of (4) are introduced as the contribution of zero-point fluctuations. They are commonly included in the A.S.E contribution and are independent of the incident field. Using these equations the output signal power and associated intensity power noise are evaluated as well as the total gain and SNR are. The different noise contributions can be also individually estimated. These equations are numerically integrated with a constant length dz. For a given effective amplification length the evolutions of powers are described along the amplifier length L and for different lengths the total gain, SNR and the noise factor F defined according to the IEEE standard [6] are evaluated (cf. figure 1). F is directly deduced from SNR since the initial incident signal and associated noise are constant at the input. From figure 1, the saturation of the amplifier is clearly shown in the first kilometers of propagation although its SNR is close to this of the backward configuration. It is the consequence of the pump depletion. Indeed due to the latter the absorption losses of the signal cannot be compensated yielding to the complete extinction of the signal and pump for a too long amplifier length. The optimum effective length is estimated as 6500 m for the amplification is maximum and noise amount is minimum.

#### 3.2. Backward amplifier

Presently the pump and signal beam are counterpropagating in a single Raman amplifier. Following the same calculation as previously, the optimum length is evaluated as 19 km (cf. figure 1). The amplifying fibre characteristics are the same as previously. SNR though decreasing with length and gain is better than this of the forward configuration.



**Figure 1**. Performances of forward and backward Raman amplifiers for different fibre lengths in terms of total gain G and SNR(dB) ( $\alpha_p = \alpha_s = 0.2 \text{ dB/km}, \nu_p = 206\text{THz}, \nu_s = 192\text{THz}, g_R = 8.10^{-14} \text{ m/W}, A = 70.10^{-12} \mu\text{m}^2, \alpha_{RP} = \alpha_{RS} = 0.7\text{dB.}\mu\text{m}^4/\text{km}, B_0 = 10\text{MHz}, P_P(0) = 0.6\text{mW}, P_S(0) = 0.06\text{mW})$ . Forward amplifier (dark line)-backward amplifier (red line).

For long length amplification, backward amplifiers are more suitable both in terms of noise and amplification gain while for short amplification length, smaller than 7km, the forward configuration is more advantageous. Using this the parameters of backward Raman amplifiers can also be optimized for a given gain G.

### 4. Chain of cascaded Raman amplifiers

The previous formalism is applied for a chain of isolated Raman amplifiers. In order to simulate the losses resulting from the transmission, each amplifier is followed by a linear attenuating fibre where loss coefficient  $\alpha_f$  is supposed homogeneous along the fibre length  $L_f$ . The signal and the associated intensity power noise propagating in the fibre are attenuated and increased by an additive noise associated to the losses as shown in (5) and (6) using the same formalism as (1)-(4).



$$P_{S}(z + dz) = P_{S}(z) - \alpha_{f} P_{S}(z) dz$$
(5)

$$P_{NS}(z + dz) = P_{NS}(z) - \alpha_f P_{NS}(z) dz + \alpha_f (h\nu_S / 2) B_0 dz$$
(6)

The last term of (6) is the contribution of zero-point fluctuations. The forward and backward output pump components are supposed filtered at both faces of each amplifier, refreshed and identical at the input of each.

#### Forward amplifier and backward amplifier

Assuming that the individual amplification lengths equal the optimum amplification lengths calculated previously, the gain and SNR are evaluated at the output of a chain with different numbers of amplifiers for a given fibre length  $(L_f=100 \text{ km})(cf. \text{ figure } 2)$ .



**Figure 2.** Performances of a chain of cascaded forward and backward Raman amplifiers for a given attenuating fibre length in terms of total gain G and SNR. Forward amplifier (dark line)-backward amplifier (red line);  $L_t=100$ km;  $\alpha_t=0.2$  dB/km).

SNR and the total gain are rapidly decreasing with the number of amplifiers and the total travelled length for any amplifier configuration. However in forward configuration, the relatively high SNR is coupled with a low gain, while in backward configuration, the opposite is observed for a total amplifying length L $\leq$ 50km. Indeed the gain is dramatically increasing for L $\leq$ 50km because of the generation of a high quantity of intensity noise power at the signal frequency which substitutes for the signal and yields to the very low SNR observed.

#### 5. Conclusion

Using a classical formalism, the signal and associated intensity power noise were numerically evaluated taking into account the pump depletion at the output of single and then a chain of forward and backward Raman amplifiers. This has allowed to compare the performances of forward and backward Raman amplifiers, to distinguish the contributions of the intrinsic field noise power from those of the noise generated by the amplifier itself and finally to estimate and compare the optimum characteristics and noise factors of each configuration.

#### 6. References

- [1] E. Dianov, M.V. Grekov and al., "Highly efficient 1.3µm Raman fibre amplifier", Electron. Lett. 34, 669-670 (1998).
- [2] P. Gallion, F. Jérémie, J.L. Vey, "Classical optical corpuscular theory of semiconductor laser intensity squeezed-light generation," Opt. and Qu. Electron. 29, 65-70 (1997).
- [3] P. Gallion, "A classical corpuscular approach to optical noise," Invited paper OSA., Trends in Optics and Photonics (TOPS), Vol. XXX : Optical Amplifier and their Applications, edited by S. Kinoshita, J.J.C. Livas and G. van der Hoven, Optical Society of America, pp. 12-35, Washington DC, 12-35 (1999).
- [4] P. B. Hansen, L. Eskildsen & al., "Rayleigh scattering limitations in distributed Raman preamplifiers", IEEE Photon. Techn. Lett. 10, 1, 159-161 (1998).
- [5] H.A. Haus, "The noise figure of optical amplifier," IEEE Photon. Techn. Lett. 10, 11, 1602-1604 (1998).
- [6] G. P. Agrawal, Nonlinear Fiber Optics (AT&T Academic press Inc, 1989), chap. 8.