Study of noise properties in optical distributed Raman amplifiers using a semiclassical model

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ABSTRACT

Using the semiclassical approach the gain and the noise powers, associated to signal and, generated in optical Raman amplifiers, are estimated for forward and backward configurations. Because it combines a corpuscular approach to a phase-amplitude description of the optical field and of the associated noise, this classical formalism allows to identify, to distinguish and to evaluate the respective noise contributions linked, first, to incident fields, such as input zero-point fluctuations, and relative intensity noise associated to the pump, and to the amplifier itself due to the electron momentum fluctuations at the optical frequency. The contribution of Rayleigh backscattering and pump depletion effects are taken into account.
For both configurations, the effects of gain and pump power distribution on noise generation are underlined. The determination of the origin and of the amount of intensity noise at the output constitutes a first step toward the amplification of signal with reduced noise amount in Raman amplifiers.

Keywords : Optical Amplifier, Optical Noise, Spontaneous Emission, Noise Figure, Raman Amplifier, Gain distribution, Non linear Gain.

1. INTRODUCTION

The development of WDM (Wavelength Division Multiplexing) in long haul optical communications forces telecommunication engineers to consider amplifiers with large amplification bandwidths, high gain coefficients, low noise intensity, high saturation powers and long amplification lengths for reasonable pump powers and low loss coefficients. Presently Raman amplifiers are promising candidates [1-3]. The need of using weak incident signal power implies to consider the importance of the optical signal noise effects, in particular input zero-point fluctuations, in the signal degradation process.
In this communication, using a semiclassical formalism [4-6], a theoretical and numerical estimation of the gain and of noise powers associated to signal and, generated in optical Raman amplifiers are proposed in forward and backward configurations.
Because it associates a corpuscular to a wave approach of light, this description allows to distinguish the contributions of the different noise sources which are the fluctuations linked to the incident electromagnetic fields, namely the pump and the signal, and those resulting from amplifier properties themselves. This theoretical model is briefly introduced in section 2, and applied to Raman amplifiers in section 3. The contributions of the different noise sources in the total output noise amount and their effects on noise generation are herein evaluated according to amplifier and input electromagnetic field characteristics. In this calculation, the effects of Rayleigh backscattering [7] as well as those of pump depletion on noise generation are taken into account in both configurations.
Finally in section 4 amplifier performances estimated for both configurations are compared and the roles of gain and pump intensity distribution in noise generation are pointed out.

2. THE SEMICLASSICAL FORMALISM

2.1. Phase - quadrature representation

According to Rice representation, all optical field can be seen as the sum of both independent parts : a deterministic optical field whose complex amplitude is $A\exp j\varphi$, and an additive optical band-limited stationnary Gaussian noise $N(t)$

with a flat spectrum along a pass-band bandwidth equal to B_o. Assuming the same polarization for both fields, a scalar notation is adopted (cf. figure 1).

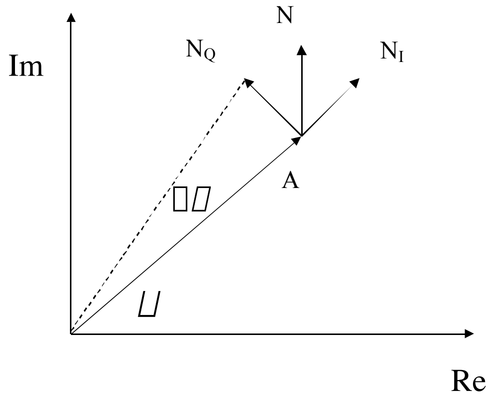


Figure 1: Phasor representation of a small random signal in addition to a deterministic field.

As shown on Figure 1 the amplitude noise N is divided between an in-phase $N_I(t)$ and a quadrature $N_Q(t)$ components [4-6, 8-11]. Assuming an appropriate normalization in which the optical power equals the squared field, the total instantaneous power, under the small noise approximation, is then :

$$P \approx (A + N_I)^2 \approx A^2 + 2.A.N_I \tag{2.1}$$

For coherent light, the principle of equal energy repartition implies an equal sharing of the total noise power P_N between the two noise components. Therefore the optical power fluctuates around its average value A^2 with the mean squared fluctuations induced by the in-phase component $N_I(t)$ given by :

$$\overline{(\Delta P)^2} \approx 4.A^2.\overline{N_I}^2 = 4\overline{P}.\overline{P_I} = 2\overline{P}.\overline{P_N} \tag{2.2}$$

in which $\overline{P} = A^2$, $\overline{P_I} = \overline{P_N}/2$ and $\overline{P_N}$ are the deterministic signal power, the average power of the in-phase noise component and the total noise power, respectively. After a photodetection inside the electrical bandwidth B_e, only the spectral components of the optical noise within the spectral range B_e on each side of the optical carrier frequency produce beating. Moreover the optimum electrical bandwidth being determined as $B_o = 2B_e$, the noise power is then expressed in terms of spectral density as :

$$\overline{P_N} \approx S_N B_0 \approx 2 S_N B_e \tag{2.3}$$

in which S_N is the single-sided optical noise power spectral density.
Similar to the in-phase component $N_I(t)$ inducing amplitude change and so power fluctuations, the quadrature component $N_Q(t)$ induces phase fluctuations whose value is approximated by $\Delta\phi \approx N_Q / A$.
The average squared phase fluctuations is then written as :

$$\overline{(\Delta\phi)^2} \approx \overline{P_Q} / \overline{P} = \overline{P_N} / 2\overline{P} \tag{2.4}$$

in which $\overline{P_Q} = \overline{P_N}/2$ is the average power of the quadrature noise component. The r.m.s. power and phase fluctuation product is independent of the signal power and is :

$$\Delta\phi.\Delta P = \sqrt{\overline{(\Delta\phi)^2}}.\sqrt{\overline{(\Delta P)^2}} = 2\left(\overline{P_I}\,\overline{P_Q}\right)^{1/2} = \overline{P_N} \tag{2.5}$$

2.2. The fundamental noise sources

According to the quantum treatment of noise, the two fundamental noise sources, whose main consequence is the presence of the well-known *Amplified Spontaneous Emission* (A.S.E.), are the input field fluctuations, including zero-point fluctuations, and the electron momentum fluctuations at the optical frequency [12-15]. In this section going from a corpuscular approach of noise, it is shown how the latter is only a simplified and a particular approach of the phase-amplitude description of the optical field and then how both are linked together. Combining these approaches, a new classical formalism is finally derived.

2.2.1. Zero-point fluctuations

In the corpuscular description of light, the optical signal, of frequency ν, incoming on the photodetector device, is pictured as a constant rate flow of photons of individual and unique energy $h\nu$. The absence of correlation between the photons implies that the distribution of the photon number received for an observation time $\tau=1/B_0$ follows the Poisson law and the mean squared fluctuations equals the average photon number value $\bar{n}$:

$$\overline{(\Delta n)^2} = \bar{n} \qquad (2.6)$$

These fluctuations are commonly identified as "shot noise" or "quantum noise" which, on the opposite of its name could let suppose, is not a consequence of using the corpuscular description of light but a counterpart of fundamental optical field fluctuations. Indeed using the proportional relationship between the number of photons and the received optical power $\bar{n} = \bar{P}\tau / h\nu = \bar{P} / (2B_e h\nu)$, the Poisson fluctuations can be directly linked to instantaneous power fluctuations [4-6, 11] :

$$\overline{(\Delta P)^2} = 2h\nu B_e \bar{P} \qquad (2.7)$$

Comparing (2.2) and (2.7), the power fluctuations associated with the shot noise appear to be produced by the in-phase component N_I of an additive noise N whose total power is :

$$\overline{P_N} = h\nu B_e \qquad (2.8)$$

The corresponding single-sided optical power spectral density of noise is then :

$$S_N = h\nu / 2 \qquad (2.9)$$

This optical additive amplitude noise accompanies any optical field and is usually referred in quantum electrodynamics as the *zero-point field fluctuations* or the *vacuum fluctuations*. This noise is only observable through its cross term product with another signal. The addition of the zero-point field fluctuations to a classical deterministic field defines the *coherent state of light* [13-15].

2.2.2. Noise linked to absorption, losses and beam splitting – Partition noise

Similarly the noise linked to localized attenuation, losses or beam splitting is derived in a classical corpuscular approach by using the partition noise [16]. For an elementary slice of width dz in a medium with a lineic absorption coefficient α, the elementary noise contribution to the single sided power spectrum is then :

$$dS_\alpha = \alpha (h\nu / 2) dz \qquad (2.10)$$

2.2.3. Amplification noise

In previous papers it has been proved that amplifiers are noise generators [5-6, 17] in order to verify the minimum value of the Heisenberg uncertainty product. The minimum extra noise power required at the output of the amplifier to avoid the violation of Heisenberg relation was then evaluated as [17] :

$$\bar{P}_A = (G - 1) \frac{h\nu}{2} B_O \qquad (2.11)$$

This result is obtained, namely for a linear and phase insensitive amplifier of gain G and of optical bandwidth B_0, equal to twice the photodetection bandwidth B_e. Since $B_O = 1/\tau$ the product $\overline{P_A}\tau = (G-1)h\nu/2$ can be interpreted as the minimum added noise energy at the output of an amplifier. For large values of G, it corresponds to an additional noise energy of half a photon during each observation time at the input of an equivalent noiseless amplifier. This minimum value is independent of the nature of the optical amplifier.
The corresponding single-sided noise spectral density is :

$$S_A = (G-1)\frac{h\nu}{2} \quad (2.12)$$

From a local point of view, amplification through an elementary slice of width *dz* in a medium of gain per unit of length equal to α, induces the elementary noise contribution to the single sided power spectrum (2.13) which is obtained by substituting *G* to *(1+αdz)* in Equation (2.12) :

$$dS_\nu = \alpha\frac{h\nu}{2}dz \quad (2.13)$$

2.3. Minimum added noise in common amplifiers

2.3.1 Minimum total noise power

The extra noise generated in a lossy amplifier has to be added to the amplification of the unavoidable input zero-point field fluctuations. The minimum overall output optical noise power spectral density is therefore:

$$S_{TOTAL} = \underbrace{(G-1)\,h\nu/2}_{\text{Noise generated in the amplifier}} + \underbrace{G\,h\nu/2}_{\text{Amplification of input zero point fluctuations}} \quad (2.14)$$

For large values of the gain *G* the corresponding and equivalent total input noise at the input of an ideal noiseless amplifier is thus twice the minimum value associated to zero point fluctuations given by Equation (2.9):

$$S_{TOTAL} = h\nu \quad (2.15)$$

This result is currently identified as the minimum attainable *Noise Figure F* of an optical amplifier which is equal to 2 [18-19] and which expresses the noise amount added to the amplified input noise in the amplifier.

2.3.2. Extra noise and noise figure

The present optical amplifiers add a larger amount of noise and operate above the fundamental limit expressed by Equation (2.14). The main reasons are that the net gain *G* is usually the result of the subtraction of the local total gain and loss coefficients while their noise contributions add. This is expressed by multiplying the added noise contribution by a factor *K*, greater than 1, leading to the noise power density :

$$S_{TOTAL} = K(G-1)\frac{h\nu}{2} + G\frac{h\nu}{2} \quad (2.16)$$

An alternative approach is to assume a noise free input signal and to make reference to the unavoidable output shot noise resulting from the output zero point fluctuations. Equation (2.16) is then rewritten :

$$S_{TOTAL} = F(G-1)\frac{h\nu}{2} + \frac{h\nu}{2} \quad \text{with} \quad F = K+1 \quad (2.17)$$

The first term in Equation (2.17) is the total output noise supplementing the minimum output zero point fluctuations and not the noise added to the amplified zero point fluctuations as in (2.16). The latter is partly included in the first term of (2.17). *F* is the optical noise figure of the amplifier. It has to be pointed out that the minimum value of *F* obtained for an ideal amplifier is 2, while the minimum value of *K* is 1. It is a result of not considering the elusive zero-point fluctuations as an input noise producing a part of the output noise but as a property of the amplifier since they are present at the input even when no signal is detectable. This limiting factor 2 is not directly related to polarization, bandwidth or double cross-term considerations, as sometimes believed, but results from Heisenberg conjugation between the two noise quadratures.

2.3.3. Comparison with Amplified Spontaneous Emission formulation

The output optical noise of laser amplifier is usually described in terms of *Amplified Spontaneous Emission* (ASE). The average amplified spontaneous emission power for a single polarization in a single sided optical bandwidth B_o is [20-23]:

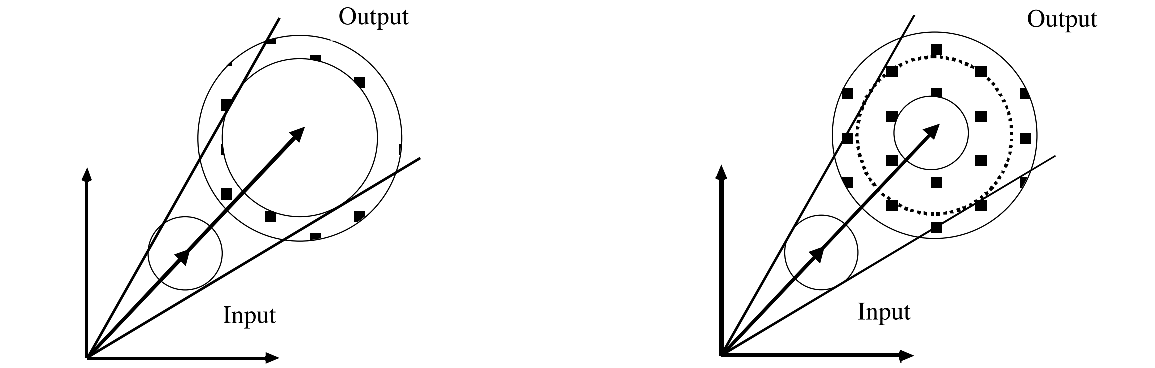
$$\overline{P}_{ASE} = n_{SP}(G-1)h\nu B_o \tag{2.18}$$

in which n_{SP} is the population inversion factor. This mean power value is not the noise itself, as it has been sometimes considered to be the case, but the root mean square of the power fluctuations of a Gaussian process with the single sided optical spectral density :

$$S_{ASE} = 2n_{SP}(G-1)\frac{h\nu}{2} \tag{2.19}$$

The noise figure is in this case $F = 2n_{SP}$ with a lower limit of 2 for the fully inverted situation. In this case, the 2 factor is explained by considering the input zero-point fluctuations as one of the sources of the spontaneous emission in the amplifier, while the other is produced by momentum fluctuations of the electrons at optical frequencies associated to the gain process itself.

Since a part of it is produced by input noise amplification, the amplified spontaneous emission is not the noise added to the amplified input fluctuations but the noise added to the zero-point output fluctuations. A 2 factor must eventually multiply this value to take into account the two orthogonal polarization states. This additive optical signal on the receiver generates its own shot noise contribution, a noise beating with the useful signal and also a noise resulting from its own power fluctuations, interpreted as noise against noise beating. The Figure 2 shows the comparison of the classical additive noise and ASE noise descriptions.



$$S_{NNout} = \underbrace{(2n_{SP}-1)(G-1)\,h\nu/2}_{\text{Noise generated in the amplifier}} + \underbrace{G\,h\nu/2}_{\text{Amplification of input zero point fluctuations}}$$

Classical additive noise description

$$S_{NNout} = \underbrace{2\,n_{SP}(G-1)h\nu/2}_{\text{Noise excess as compared to minimun uncertainty}} + \underbrace{h\nu/2}_{\text{unavoidable zero point fluctuations at the output}}$$

ASE noise description

Figure 2 : Phasor comparison of the classical additive noise and ASE noise descriptions.
The doted areas correspond to the noise added by the amplifier

3. EVALUATION OF NOISE PROPERTIES IN RAMAN AMPLIFIERS : THEORETICAL MODEL

Noise evolution in Raman amplifiers is now described by using the classical formalism previously introduced [4-6]. Due to the configuration of Raman amplifiers and because of pump depletion, the output signal power at frequency ν_S and accompanying noise powers depend on power properties of pump at frequency ν_P and on its associated noise component [24]. In order to consider the effects of these interactions between the pump and the signal on noise generation, additive crossed noise terms have to be introduced in the propagation noise equations.

Signal and associated noise powers at the output of a Raman amplifier are numerically calculated in an optical bandwidth B_0. The considered Raman amplifiers are assumed to have homogeneous gain and loss coefficients all along the effective amplification length. Loss coefficients are frequency dependent and are identified as α_S and α_P at signal and pump frequency. The loss contributions induced by Rayleigh backscattering, with loss coefficient α_{RS}, α_{RP} at signal and pump frequency respectively, are taken into account in the process of noise generation and signal propagation [7]. The incident signal and the input pump are assumed to be shot noise limited, meaning zero-point fluctuation input condition, to remain coherent through propagation and without any correlation between the in-phase and quadrature components. The fiber is assumed single mode with a constant effective interaction area.

The introduced formalism is in the first order approximation and crossed signal and pump noise contribution terms in noise generation are not considered here. Furthermore any effects of transmission fiber temperature on noise generation are neglected [25].

Adding the different noise contributions, introduced previously and in [5, 6], the differential equations for an amplifying slice of Raman amplification coefficient, g_R, are for the signal power P_S and for the associated noise power N_S:

$$P_S(z+dz) = P_S(z) - \left[\alpha_{RS} + \alpha_S\right] P_S(z) dz + g_R P_P(z) P_S(z) dz \tag{3.1}$$

$$N_S(z+dz) = N_S(z) + \underbrace{\left[-\alpha_{RS} - \alpha_S + g_R P_P(z)\right] N_S(z) dz + g_R (2P_P(z) N_P(z))^{1/2} P_S(z) dz}_{\textit{Attenuated and amplified input fluctuations}}$$

$$+ \underbrace{\left[\alpha_{RS} + \alpha_S + g_R P_P(z)\right]\left(h\nu_S/2\right) B_0 dz}_{\textit{Fluctuations induced by the amplifier}} . \tag{3.2}$$

Similarly the signal power P_P and the associated intensity power noise N_P are written as:

$$P_P(z+dz) = P_P(z) - \left[\alpha_{RP} + \alpha_P\right] P_P(z) dz - (\nu_P/\nu_S) g_R \left[P_S(z) + N_S(z) + (h\nu_S/2) B_0\right] P_P(z) dz \tag{3.3}$$

$$N_P(z+dz) = N_P(z) - \left[\alpha_{RP} + \alpha_P\right] N_P(z) dz - \left[(\nu_P/\nu_S) g_R P_S(z)\right] (2P_P(z) N_P(z))^{1/2} dz$$

$$+ \left[\alpha_P + \alpha_{RP}\right](h\nu_P/2) B_0 dz + \left[(\nu_P/\nu_S) g_R P_S(z)\right] (2P_P(z)(h\nu_P/2) B_0)^{1/2} dz . \tag{3.4}$$

Equations (3.1) and (3.3) are the well-known propagation equations [24] in which depletion induced by signal P_S and associated noise N_S are added. In (3.2) and (3.4) the two first terms express the common propagation of noise components, to which are added the contributions of amplification and partition noise at signal and pump frequency respectively (last terms). In equation (3.2), the third term in the right hand side is the contribution of pump fluctuations in generation of the intensity noise which accompanies the signal in an optical bandwidth B_0.

4. COMPARISON OF RAMAN CONFIGURATIONS : RESULTS ON THE INFLUENCE OF THE GAIN DISTRIBUTION

Using equations (3.1) to (3.4), the total gain and the optical output Signal-to-Noise Ratio (SNR) are first numerically evaluated. The noise figure F defined according to the IEEE standard [18] is directly deduced from the output SNR since the initial incident signal and associated noise are constant at the input. Then a more inquisitive study on the origin of noise power is performed by numerically and separatedly evaluating noise powers linked, on the one hand, to field fluctuations which are here zero-point fluctuations associated to signal and pump (first bracketed part in equation (3.2)), and, on the other hand, to amplifier properties (second bracketed part).

4.1 Gain performances

The total gain *G* of Raman amplifiers is performed for different loss coefficients and for different amplification lengths in backward (Figure 3) and forward configuration (Figure 4). The obtained results are close to experimental observations.
So whichever the chosen configuration, gain factors reach a maximum value when signal is propagating along the amplification length due to pump depletion mechanism. This parameter depends on the importance of loss processes and its value is decreasing with an increasing loss amount. As illustrated on figures 1 and 2, the amplification process is spatially distributed on a long length varying with the attenuation coefficient. For all attenuation coefficient and configuration, gain evolution is the same : to a rapid growing of *G* value up to the maximum gain value succeeds a slow decrease whose rate depends on loss amounts.

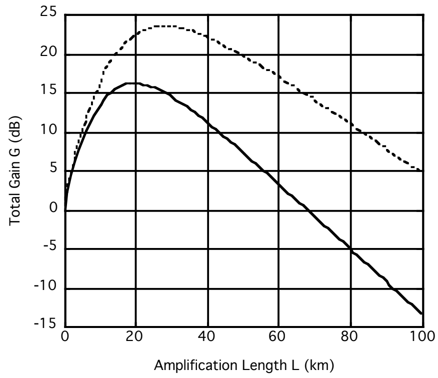


Figure 3: Gain performances in Raman amplifiers in backward configuration for different fiber lengths and loss coefficients. (□p=206THz, □S=192THz, $g_R=8.10^{-14}$m/W, $A=70.10^{-12}m^2$, $□_{RP}=□_{RS}$=0.7dB.□m^4/km, B_0=12.5GHz, $P_P(0)$=0.6W, $P_S(0)=3.10^{-6}$W). $□_P=□_S$=0.2dB/km (dashed line), $□_P=□_S$=0.3dB/km (solid line).

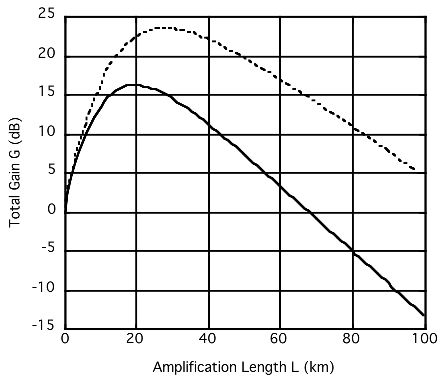


Figure 4: Gain performances in Raman amplifiers in forward configuration for different fiber lengths and loss coefficients. (□p=206THz, □S=192THz, $g_R=8.10^{-14}$m/W, $A=70.10^{-12}m^2$, $□_{RP}=□_{RS}$=0.7dB.□m^4/km, B_0=12.5GHz, $P_P(0)$=0.6W, $P_S(0)=3.10^{-6}$W). $□_P=□_S$=0.2dB/km (dashed line), $□_P=□_S$=0.3dB/km (solid line).

4.2 Noise performances

The output SNR is performed for different loss coefficients and for different amplification lengths in backward (Figure 5) and forward configuration (Figure 6).
Assuming shot-noise limited pump condition, i.e. a pump Relative-Intensity-Noise (RIN) equal to 1, and comparing both configurations, noise performances are always worse in backward configuration and degrade as loss amounts are

higher and amplification length are longer. It has also to be noticed the difference of SNR evolution between forward and backward configuration. It is a first illustration of the effects of gain distribution. Indeed in forward configuration signal is very sensitive to pump characteristics such as the power and noise intensity since signal and pump propagate simultaneously and conjointly. So the output noise is small as far as the pump RIN is low. On the other hand in backward configuration signal experiments a pump whose characteristics are time-averaged due to its propagation along the amplification length, smoothing and increasing noise characteristics. In backward configuration, because signal and pump counterpropagate, their respective intensities have to be chosen sufficient so that pump can overlap and feed signal. Otherwise SNR decreases rapidly since signal is no more amplified and noise contributions are added. For short amplification lengths, SNR is better since pump intensity is sufficient to feed signal and to counteract signal internal losses.

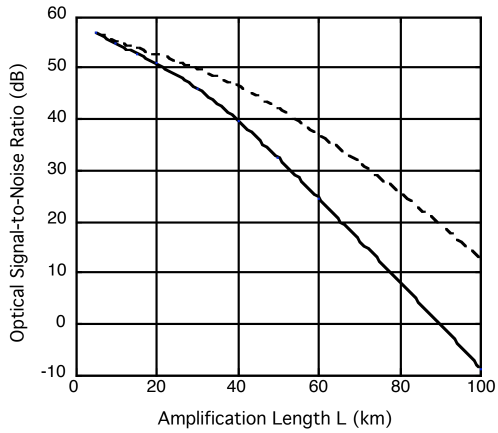


Figure 5: Noise performances in Raman amplifiers in backward configuration for different fiber lengths and loss coefficients. (□$_p$=206THz, □$_S$=192THz, g_R=8.10^{-14}m/W, A=70.10^{-12}m^2, □$_{RP}$=□$_{RS}$=0.7dB.□m^4/km, B_0=12.5GHz, $P_P(0)$=0.6W, $P_S(0)$=3.10^{-6}W). □$_P$=□$_S$=0.2dB/km (dashed line), □$_P$=□$_S$=0.3dB/km (solid line).

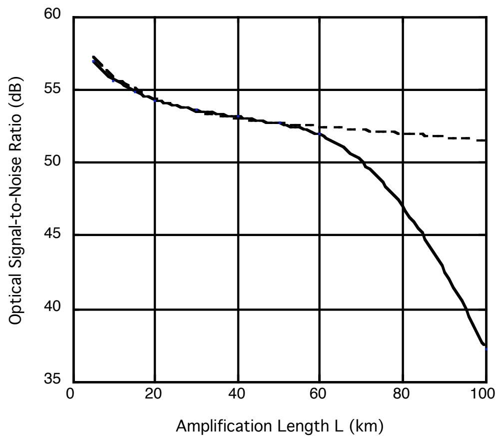


Figure 6: Noise performances in Raman amplifiers in forward configuration for different fiber lengths and loss coefficients. (□$_p$=206THz, □$_S$=192THz, g_R=8.10^{-14}m/W, A=70.10^{-12}m^2, □$_{RP}$=□$_{RS}$=0.7dB.□m^4/km, B_0=12.5GHz, $P_P(0)$=0.6W, $P_S(0)$=3.10^{-6}W). □$_P$=□$_S$=0.2dB/km (dashed line), □$_P$=□$_S$=0.3dB/km (solid line).

To explain such noise performances, a complementary study on the origin of total noise power associated to signal is performed. The different noise powers linked, on the one hand, to field fluctuations (first bracketed part in equation (3.2)) and, on the other hand, to amplifier properties (second bracketed part) are separately and numerically evaluated in backward (cf. figure 7) and forward configuration (cf. figure 8).

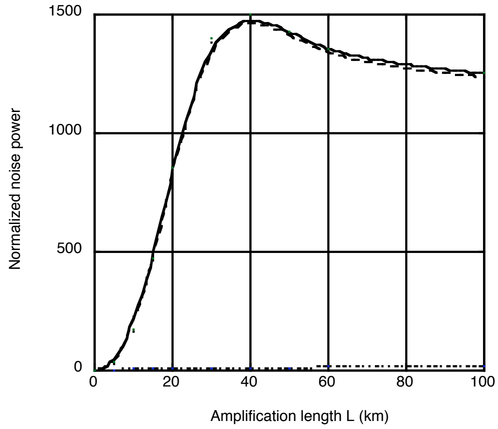


Figure 7: Noise powers in Raman amplifiers in backward configuration for different fiber lengths. (ν_p=206THz, ν_S=192THz, g_R=8.10^{-14}m/W, A=70.10^{-12}m^2, α_P=α_S=0.3dB/km, β_{RP}=β_{RS}=0.7dB.μm^4/km, B_0=12.5GHz, $P_P(0)$=0.6W, $P_S(0)$=3.10^{-6}W). Noise power linked to field fluctuations (dashed line), Noise power linked to amplifier properties (dotted line), Total noise power (solid line).

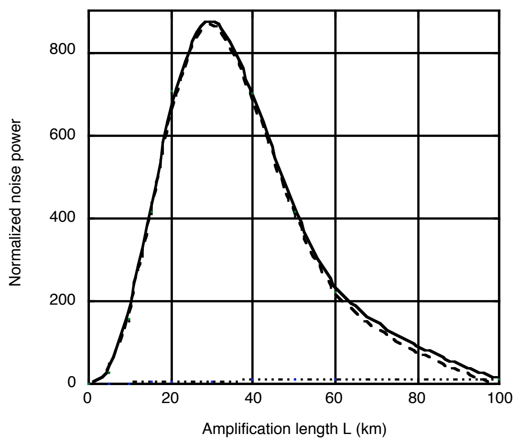


Figure 8 : Noise powers in Raman amplifiers in forward configuration for different fiber lengths. (ν_p=206THz, ν_S=192THz, g_R=8.10^{-14}m/W, A=70.10^{-12}m^2, α_P=α_S=0.3dB/km, β_{RP}=β_{RS}=0.7dB.μm^4/km, B_0=12.5GHz, $P_P(0)$=0.6W, $P_S(0)$=3.10^{-6}W). Noise power linked to field fluctuations (dashed line), Noise power linked to amplifier properties (dotted line), Total noise power (solid line).

These figures show that the origin of noise power associated to signal varies according to the chosen configuration and to the amplification length. In backward configuration, because of gain distribution, noise contribution brought by incident signal and pump fluctuations is always preponderant as compared to noise power originated from amplifier properties, and is almost the unique source of noise for it is ten times as large as its counterpart. However the noise intensity only increases with propagation length until a maximum value before slowly decreasing with length. This behaviour is also encountered in forward configuration but on a shorter amplification length range. In this configuration, the origin of noise powers turns more rapidly with propagation length : for lengths smaller than a characteristic length ($\approx$ 90 km) increasing with pump power as have shown complementary studies, noise power results mainly from amplified incident signal and pump fluctuations and beyond it, comes mostly from amplifier properties. Comparing gain and noise evolution, it appears that this characteristic length coincides with the length beyond which pump is highly depleted and so insufficient to feed signal amplification. These different behaviours are explained by the fact that in forward configuration the results obtained along the amplification length are both a temporal and a spatial description of the phenomenon occurring in the amplifying fiber since pump and signal propagate at the same time in the same direction. The signal is then only a reproduction of pump whose power is rapidly depleted along the fibre. On the other hand in backward Raman amplifiers, due to gain distribution along the fibre, the instantaneous fluctuations are time averaged and noise power is spatially distributed. Therefore such amplifiers are strong noise generators. In order to verify the influence of pump noise in noise generation, another study of generated noise power in backward and forward configuration is made for a pump which is accompanied by different initial noise power (cf. figure 9 and 10).

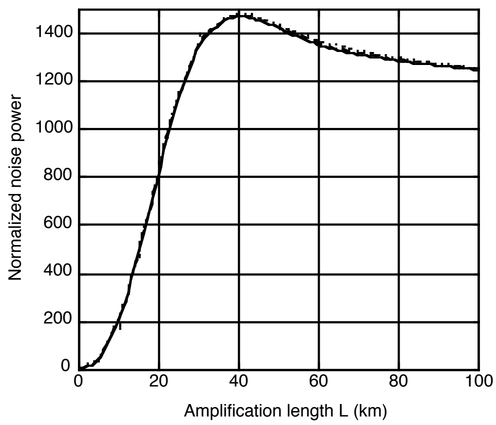


Figure 9: Noise performances in backward Raman amplifiers for different pump noise values vs. amplification length. (□$_p$=206THz, □$_S$=192THz, g_R=8.10^{-14}m/W, A=70.10^{-12}m^2, □$_P$=□$_S$=0.2dB/km, □$_{RP}$=□$_{RS}$=0.7dB.□m^4/km, B_0=12.5GHz, $P_P(0)$=0.6W, $P_S(0)$=3.10^{-6}W). SNL - 0dB (plain line), 7dB (dashed line), 10dB (dotted line).

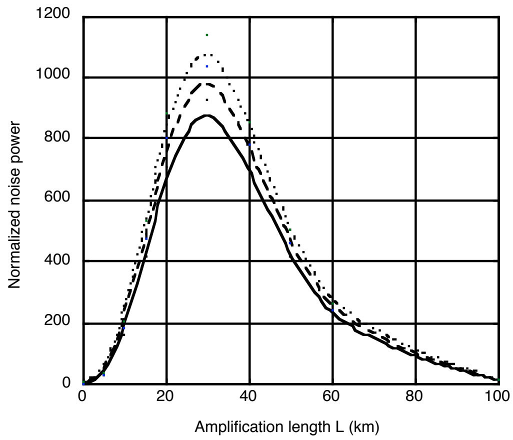


Figure 10: Noise performances in forward Raman amplifiers for different pump noise values vs. amplification length. (□$_p$=206THz, □$_S$=192THz, g_R=8.10^{-14}m/W, A=70.10^{-12}m^2, □$_P$=□$_S$=0.2dB/km, □$_{RP}$=□$_{RS}$=0.7dB.□m^4/km, B_0=12.5GHz, $P_P(0)$=0.6W, $P_S(0)$=3.10^{-6}W). SNL - 0dB (plain line), 7dB (dashed line), 10dB (dotted line).

Figure 9 and 10 show that whichever the initial pump noise value is, the evolution of signal noise power at the output of Raman amplifiers in backward and forward configuration versus the amplification length is similar as this shown in figure 7 and 8. Moreover and obviously, the main effect of increasing initial pump noise value is to increase noise power at the output of the amplifier and so to degrade the performance of the latter. Comparing figure 9 and 10, the effects of gain distribution on smoothing pump fluctuations are underlined. Indeed as it is shown on figure 10, Raman amplifiers in forward configuration are very sensitive to pump fluctuations except on very short lengths (□ 10km) and long lengths (> 60km) where fluctuations tend toward shot noise level (SNL) and so are sufficiently weak. On the other hand, in Raman amplifiers in backward configuration, due to gain distribution, pump fluctuations are smoothed and have a weak influence on output signal noise power values which are relatively constant.
So Raman amplifiers in backward configuration seem particularly adapted for long length amplification processes and when a noisy pump is used (noise > 10 dB) for in this case, gain is higher than in forward one and noise amount is minimized. On the other hand forward configuration is suitable for short amplification lengths where the signal-to-noise ratio and gain are better than in backward configuration when initial pump noise power is close to the SNL.

5. CONCLUSION

Using a classical formalism, the total gain and the signal noise power at the output of optical Raman amplifiers have been numerically calculated for both forward and backward configurations. The roles of signal and pump fluctuations and of loss coefficients as noise generators and as gain limiting elements have been shown. This work has also underlined the role of gain distribution as a parameter which determines the noise quantity produced in optical amplifiers. It has pointed out the importance of controlling such a parameter to achieve successfully the amplification process with reduced noise effects and the generation of squeezed-states at the output of amplifiers.

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