Noise Properties of Saturated Raman Amplifiers

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Abstract *:* We present an analytical model and numerical simulations describing the unique noise properties of saturated Raman amplifiers. The calculations are confirmed in experiments for a Raman amplifier employing a 12km long dispersion compensating fiber.

The noise accompanying optical amplification plays a major role in determining the signal quality and hence its detectability while at the same time it represents an inherent property of a fundamental nature. The noise of any optical amplifier type operating in the linear regime is well understood and widely documented. For an amplifier operating in the non – linear regime, the situation is significantly more complicated. In Erbium doped fiber amplifier (EDFA) as well as in semiconductor amplifiers (SOA), saturation causes a deterioration of the inversion and consequently a noise increase [1-2]. For powers larger than the saturation power, the noise spectral density (which in the linear regime is proportional to the gain) decreases slower than the gain. This means that the noise of a linear amplifier with a gain of G is smaller than that of an amplifier operating with the same gain G but in saturation [3].

Saturation of a Fiber Raman Amplifier (FRA) amounts to depletion of the pump power along the fiber with a resultant gain decrease and a modification of the noise. This paper demonstrates that unlike the cases in an EDFA or SOA, the noise accompanying the signal in a saturated FRA decreases either faster or slower than the gain according to the pumping direction. We present an analytical formalism and numerical simulation which describe the noise under saturation. The calculated predictions are confirmed by experiments for a discrete fiber FRA employing a 12 km long Dispersion Compensating Fiber (DCF) as the gain medium.

The pump, the signal and the noise powers undergo different values of attenuation as they propagate down the fiber. The coupled differential equations describing their propagation do not have therefore a closed form solution [4]. However, it is possible to develop an explicit analytical solution using a simple iteration method. The pump depletion is neglected in the first step in order to get approximate signal power profiles. These are used in the pump power equation to correct the pump power profile. The expressions for the pump power are used next to solve for the signal and noise power profiles. More iterations improve the results but the formulation becomes complicated while the improvements in accuracy are minor. Using only two iterations yield the following results for the forward Raman amplification of several WDM channels:

$$\begin{cases} P_p(z)=P_P(0)\exp\left[-\alpha_p z-\sum_i \beta_i\left(\Gamma\left(\frac{\alpha_{si}}{\alpha_p},q_i\right)-\Gamma\left(\frac{\alpha_{si}}{\alpha_p},q_i\exp(-\alpha_p z)\right)\right)\right] \\ P_{si}(z)=P_{si}(0)\exp\left(-\alpha_{si}z+q_i A\zeta\left(\exp(-\alpha_p z)\right)\right) \\ P_n^+(z)=\left(2\mathcal{M}n_{sp}hf_n\Delta f\int_{\exp(-\alpha_p z)}^{1} u^{\frac{-\alpha_n}{\alpha_p}}\frac{d\left(\exp\left(-q_n A\zeta(u)\right)\right)}{du}du\right) \\ \qquad \exp\left(-\alpha_n z+q_n A\zeta\left(\exp(-\alpha_p z)\right)\right) \\ P_n^-(z)=\left(2\mathcal{M}n_{sp}hf_n\Delta f\int_{\exp(-\alpha_p z)}^{\exp(-\alpha_p L)} u^{\frac{\alpha_n}{\alpha_p}}\frac{d\left(\exp\left(q_n A\zeta(u)\right)\right)}{du}du\right) \\ \qquad \exp\left(+\alpha_n z-q_n A\zeta\left(\exp(-\alpha_p z)\right)\right) \end{cases}$$

with :

$$q_i=\frac{g(f_p,f_i)P_p(0)}{2\alpha_p} \qquad \beta_i=\frac{f_p}{f_{si}}\frac{P_{si}(0)}{P_p(0)}\exp(q_i)\,q_i^{1-\frac{\alpha_{si}}{\alpha_p}}$$

$$\Gamma(\alpha,u)=\int_0^u t^{\alpha-1}\exp(-t)\,\mathrm{d}t \qquad A=\exp\left(-\sum_i \beta_i\,\Gamma\left(\frac{\alpha_{si}}{\alpha_p},q_i\right)\right)$$

$$n_{sp}=\frac{1}{1-e^{-h(f_p-f_n)/kT}} \qquad \zeta(u)=\int_u^1 \exp\left(\sum_i \beta_i\,\Gamma\left(\frac{\alpha_{si}}{\alpha_p},q_i u\right)\right)du$$

α_p, α_{si}, α_n are the fiber loss coefficients at the pump, the i[th] signal and noise frequencies (f_p,f_{si} and f_n), $g_r(f_{pk},f_{si})$, is the Raman gain at the signal frequency f_{si} when the pump frequency is f_p. $\mathcal{M}$ refers to the polarization mode number ($\mathcal{M}=1$ for the polarized noise and $\mathcal{M}=2$ for unpolarizated noise).

The n_{sp} equivalent factor in Raman amplifiers takes into account the thermal distribution of the optical phonons and is close to the unity at ambient temperature and for large detuning. The forward and backward noise powers are calculated using partial integrations. The noise power expressions inside the parenthesis can be described as the equivalent input noise power to the amplifier.

The analytical solutions were compared to numerical simulations. Forward pumping amplification in a 12 km long DCF was considered. Ten input signals spectrally placed around the Raman gain peak, each having an input power of 0 dBm were assumed. Fig 1 compares the analytical expressions with the simulation results and shows a very good agreement. For clarity reasons, only the noise and signal power evolution for the wavelength allocated at the peak gain are shown in addition to the pump power evolution. For each signal type, we also have added the power evolution predicted by the undepleted pump approximation.

The figure shows that the amplifier is indeed saturated. Pump depletion reduces the gain by 2.5 dB while the noise is reduced by 4.2 dB in the forward direction and by 2.4 dB in the backward directions. It is to note that, as in the unsaturated case, the backward ASE noise power is higher than the forward ASE noise power because the pump power is higher at the fiber input than at the fiber end.

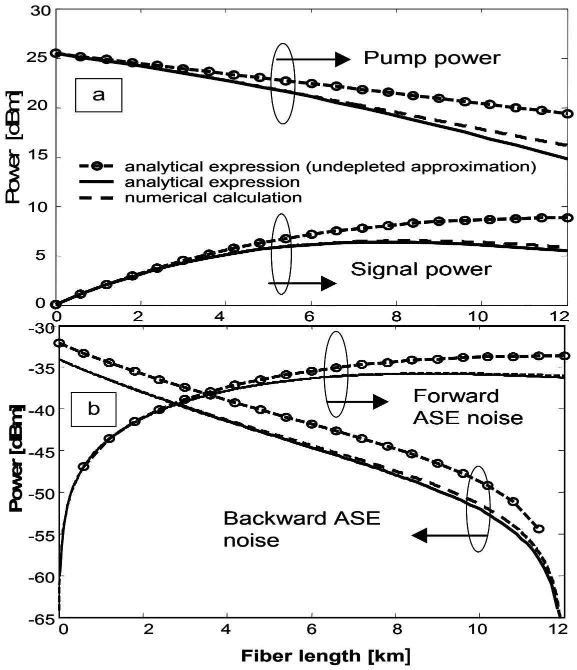

Figure 1 : Pump, signal (a) and forward and backward noise power profiles (b) using undepleted ,depleted and numerical approaches for forward pumped FRA in 12 km of DCF.

In the experimental set up depicted in Fig. 2, the amplifier pump is a 280 mW unpolarized source at 1460 nm which feeds a 12 km long DCF either in the forward or backward direction with respect the signal propagation. The gain in the linear regime was 13.3 dB at the Raman peak (~1560 nm). To produce significant pump depletion, we introduced a high power signal located at the gain peak and measured the changes in gain and in the noise using a weak (-20 dBm) probe signal located at 1542 nm. as a function of the pump depletion We define the induced depletion factors as the ratio of the gain, noise or pump power to their respective values in the linear regime.

Figure 3 exhibits the dependence of the measured gain and noise depletion as function of the pump power depletion for the two pumping schemes. The peak linear gain was 9.8 dB at the probe wavelength. The measurements show that in the forward pumping scheme the noise compression is faster than the gain compression as predicted by the theory. The gain is reduced by 2.7dB for a pump depletion of 4.4 dB while the noise power is reduced by 3.2 dB in the forward pumped FRA. In a similar experiment, we have demonstrated an opposite behaviour for a backwards pumped Raman amplifier. In that case, meaningful saturation requires larger signal powers but the noise spectral density (accompanying the signal) reduces slower than the gain when the amplifier saturates as expected from the model since higher forward ASE noise power levels are produced at the fiber end.

In conclusion, we have demonstrated theoretically and experimentally that a saturated fiber Raman amplifier exhibits a unique behaviour under saturation in that its noise reduces faster or slower than the gain according to the pumping direction unlike the case for an EDFA or a SOA.

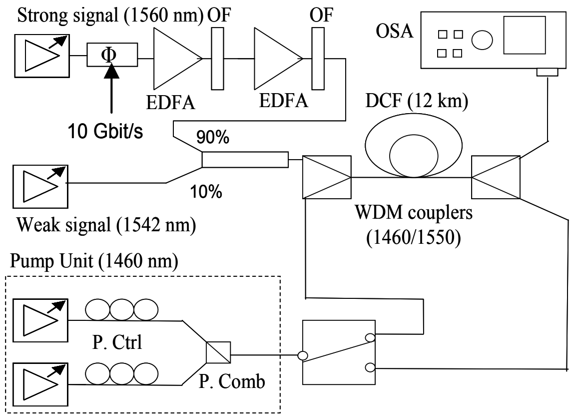

Figure 2 : Experimental set up for forward and backward Raman amplification. P.Ctrl=Polarization Controller, P.Comb=Polarization Combiner, Φ=Phase Modulator, OF=Optical Filter, OSA=Optical Spectrum Analyzer.

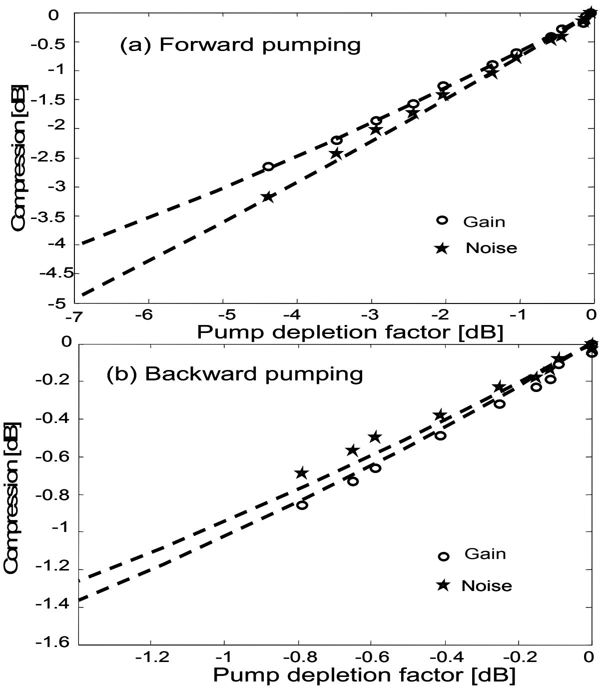

Figure 3 : Gain and noise compression as a function of pump depletion in 12 km long FRA for forward (a) and backward (b) pumping schemes. The theoretical predictions are described by the dashes curves.

Reference

1 J.F. Marcerou et al.,OAA'91 ,(1991), ThE1, p162.
2 M. Shtaif et al, J. Quantum Electron., 32, (1996), p 1801.
3 M. Shtaif et al., Opt. Lett., 21, (1996), p 1851.
4 D.Dahan et al, J. Light. Techn., 20, (2002), p 379.