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Raman and loss induced quantum noise in a depleted phase-sensitive parametric amplifier

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We study the quantum noise properties of phase-sensitive fiber optical parametric amplifiers in deep pump depletion using a semi-classical approach. Amplified spontaneous emission and spontaneous Raman scattering are included in the analysis.

Keywords: Optical parametric amplifier, quantum noise, pump depletion

CVIII. INTRODUCTION

Fiber optical parametric amplifiers (FOPAs) have many potential applications in future all-optical communication networks. Their most distinct properties compared to EDFA and Raman amplifiers are the inherent generation of a frequency-shifted copy of the signal (the idler), which enables e.g. transparent frequency conversion, and the ability to operate phase-sensitively (PS) [1]. Continuous wave (CW) FOPAs have unique quantum noise (QN) properties: operated phase-insensitively they have a 3 dB quantum limited noise figure (NF), but operated phase-sensitively (PS), a 6 dB NF improvement has been predicted and a 5.5 dB NF improvement has been demonstrated [2]. In this work, we analyze the QN properties of the pump, signal and idler in CW FOPAs using a semi-classical approach. Existing full quantum approaches [3] neglect all but first-order dispersion and assume a constant pump and are thus only valid in the linear gain regime. Our semi-classical approach is valid also with pump depletion.

CIX. METHOD AND RESULTS

A classical FOPA with one pump (p), a signal (s) and an idler (i) is described in [1], and we include Raman scattering in the equation for wave k with terms on the form $g_r(\Omega_{kl})|A_l|^2A_k/2$, where $g_r(\Omega_{kl})$ is the Raman gain coefficient, to describe the interaction between waves k and l for $\{l,k\} = \{p,s,i\}$. We include nonlinear phase modulation and Raman interaction terms among all wave components so that the equations remain valid in depletion. We introduce quantum fluctuations to all fields by adding fluctuation variables, δa, to the real and imaginary parts of the amplitude of each field. The fluctuations have the properties $\langle\delta a\rangle=0$ and $\langle(\Delta\delta a)^2\rangle=1/4$ in units of photons. Thus we create ensembles that resemble coherent states. The signal-to-noise ratio (SNR) is evaluated as the mean photon number squared divided by the photon number variance, i.e. $SNR=\langle n\rangle^2/\langle(\Delta n)^2\rangle$, where $n=n_s+n_i$ is the total photon number and n_k is proportional to the field amplitude norm squared of wave k. The NF is then $SNR_{\mathrm{in}}/SNR_{\mathrm{out}}$. The amplifier gain is $G=n_{\mathrm{s,out}}/n_{\mathrm{s,in}}$. Spontaneous emission from the vacuum state and spontaneous Raman scattering are included by adding fluctuations after each numerical in the fiber; they have the properties $\langle\delta a_{vac}\rangle = \langle\delta a_{Ram}\rangle = 0$ and $\langle(\Delta\delta a_{vac})^2\rangle=\alpha\Delta z/4$ and $\langle(\Delta\delta a_{Ram})^2\rangle= (1+n_T(\Omega_{kl}))g_R(\Omega_{kl})|A_l|^2\Delta z/2$, where α is the loss coefficient, $n_T(\Omega_{kl}) = (\exp(\hbar\Omega_{kl}/k_BT)-1)^{-1}$ is the phonon equilibrium number, Δz is the step size, $\hbar$ is Planck's constant, k_B is Boltzmann's constant and T is the temperature.

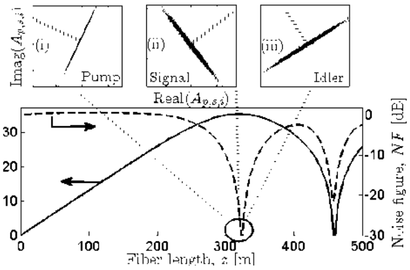

Fig. 1: Gain (solid) and NF (dashed) of a PS FOPA. Insets show constellation diagrams of (i) pump, (ii) signal and (iii) idler at the point of full depletion.

Figure 1 shows simulation results of a PS FOPA including loss and Raman scattering. In the linear gain regime (G increases linearly with z) the NF increases slightly above 0 dB due to spontaneous Raman scattering; then as the pump depletes, the NF decreases to -30 dB. Plots (i)-(iii) show constellation diagrams of the ensembles at full depletion, z=325 m (the dotted line points toward the origos of the respective phase-spaces). The plots (ii) and (iii) explain the NF behavior; the signal and idler ensembles are squeezed in amplitude, so that the photon number variance decreased, and hence, the SNR increases. Plot (i) shows that the pump takes active part in the four-wave-mixing process that generates the squeezed ensembles. Our results are similar to demonstrations of optical amplitude regeneration in depleted PS amplifiers [4].

In summary, we have analyzed the QN noise properties of a realistic PS FOPA in the depleted pump regime.

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