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Modelling of noise suppression in gain-saturated fiber optical parametric amplifiers

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ABSTRACT

Noise properties of both one-pump (1-P) and two-pump (2-P) fiber optical parametric amplifiers (FOPAs) are theoretically investigated and particularly the unique feature of FOPAs for the noise suppression in the gain-saturated regime is modeled. For the 1-P FOPAs, the simulation results are compared with the available experimental data and a very good agreement is obtained. Also, for the 2-P FOPA where no experimental work has been reported regarding their noise properties in the saturation regime, the noise behavior of the amplified signal is simulated for the first time. It is shown that for a specific power in the deep saturation regime, the signal noise is suppressed; and with further increase of the signal power when the gain saturation reaches its new cycle, a periodic behavior of noise suppression is observed originating from the phase-matching condition. The existence of a negative feedback mechanism which is responsible to the suppression of the excess noise in the first cycle of the gain saturation is confirmed both for 1-P and 2-P FOPAs. Generally, it is shown that the noise suppression can be observed for several specific powers at which the slope of the output signal power versus the input one is zero. The results of this paper may have some applications in signal processing, e.g., cleaning noisy signals.

1. Introduction

Fiber optical parametric amplifiers (FOPAs) relying on four-wave mixing (FWM), exhibit great potentials for various applications such as high gain amplification, signal processing, regeneration, etc[1–4]. These versatile devices can be classified as one-pump (1-P) and two-pump (2-P) FOPAs [5,6]. 1-P FOPAs use one pump wave which is injected together with the signal wave into the fiber input, whereas in 2-P FOPAs two pump waves are first combined together and then with the signal wave are input into the fiber. The fiber which is usually used for the FOPA setup is a highly nonlinear fiber (HNLF) possessing a high nonlinear coefficient and a zero-dispersion wavelength (ZDW) in the telecom region [7]. Although a 2-P FOPA has a more complex architecture in comparison with a 1-P FOPA, it offers a flatter and broader gain spectrum [8]; for example, a very wide bandwidth and smooth amplification over 155 nm has been recorded in a 2-P FOPA [9].

Especially in the gain-saturated regime, FOPAs have found important applications in signal processing [2,3]. Gain-saturated FOPAs can be employed to remove the excess noise of noisy signals. Kylemark et al. [10,11] and Bogris et al. [12] have investigated noise characteristics of 1-P and 2-P FOPAs, but for the case of an undepleted pump and a lossless fiber. The models presented in [10–12] fail when a FOPA operates in the saturation regime and whenever the loss of the fiber is considered. Recently, there have been some studies on noise in both 1-P and 2-P FOPAs, albeit for the noise transfer from pump to signal [13–15] where the input signal is assumed to be almost very clean and the input pump is considered noisy owing to the intensity modulation. In this work however we investigate different aspect of the noise in FOPAs, i.e., the suppression of the noise in the saturation regime when the input signal wave is initially very noisy for example due to the amplified spontaneous emission (ASE), and the input pump is almost clean. By now, the noise suppression in the gain-saturated 1-P FOPAs has been only investigated experimentally without any theoretical model to simulate the experimental data [16]. Also, no theoretical and/or experimental work has been reported to investigate the noise suppression in 2-P FOPAs when they operate in the saturation regime.

In this paper, we investigate for the first time the noise suppression properties of both 1-P and 2-P FOPAs when the signal power is high enough to saturate the parametric gain. We show that for both 1-P and 2-P FOPAs there exists a specific signal power in the deep saturation regime at which the excess noise of the amplified signal is suppressed. Moreover, we show that when the input signal power is increased continuously, the FOPA experiences a new cycle of the gain saturation and the noise suppression are repeated at new signal powers. The periodic behavior of the

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noise suppression as a function of input signal power refers to the phase-matching condition which is specific to parametric phenomena. It should be noted that although the noise suppression can be observed in other types of optical amplifiers, e.g., semiconductor optical amplifiers (SOAs) [17,18], the existence of such a specific power with a periodic behavior is a unique feature of FOPAs. Our results confirm the existence of a negative feedback mechanism which had been already proved experimentally for 1-P FOPAs by Inoue et al. [16]. The negative feedback mechanism that is responsible for the noise suppression of the signal wave in the deep saturation regime is predicted in our work for 2-P FOPAs as well.

2. Theory

Pump, signal and idler are there interacting waves in a 1-P FOPA with the angular frequencies of, ω_s, and, respectively. The frequency assignments of the pump, signal and the idler are shown in Fig. 1(a). Due to the four-wave mixing (FWM) phenomenon and the phase-matching condition, the power flows periodically from the pump wave to the signal and idler waves, as they propagate down the fiber. The evolution of the waves power is described by the three coupled amplitude equations which can be found in many references [4,5,19]. For example, the equation for the signal amplitude A_s, is given by

$$\frac{\partial A_s}{\partial z} = i\gamma\left(|A_s|^2 + 2|A_i|^2 + 2|A_p|^2\right)A_s + i\gamma A_i^* A_p^2 \exp(-i\Delta\beta z) - \frac{1}{2}\alpha A_s \tag{1}$$

where and A_p are the amplitude of the idler and the pump waves, respectively. $\gamma$and $\alpha$are respectively the nonlinear coefficient and the loss of the fiber. Moreover, the wave-vector mismatch of the interacting waves is

$$\Delta\beta = -\frac{2\pi c}{\lambda_0^2} S_0(\lambda_p - \lambda_0)(\lambda_p - \lambda_s)^2 \tag{2}$$

where c is the light speed and S_0 is the dispersion slope of the fiber calculated at the zero-dispersion wavelength, λ_0 λ_p and λ_S are the pump and the signal wavelengths, respectively.

For 2-P FOPAs one can simply consider four interacting waves propagating along the fiber known as: pump 1, pump 2, signal and idler. However, it has been shown that for a better description of the gain properties of 2-P FOPAs, especially in the wavelength region between the two pumps, six interacting waves (which is referred to as six-wave model) should be considered [4,14]. The frequency assignments of the six-wave model are shown in Fig. 1 (b). Here, ω_1 and ω_2 denote the angular frequencies of the pumps 1 and 2, respectively. The center frequency is defined as $\omega_c = \frac{\omega_1+\omega_2}{2}$ and the signal is injected at the angular frequency ω_4 close to the pump 1. Three new sidebands known as idler 1, 2, and 3 can be generated due to the FWM among the interacting waves. The frequencies of these idlers denoted by ω_5, ω_3, and ω_6 are also shown in Fig. 1(b).

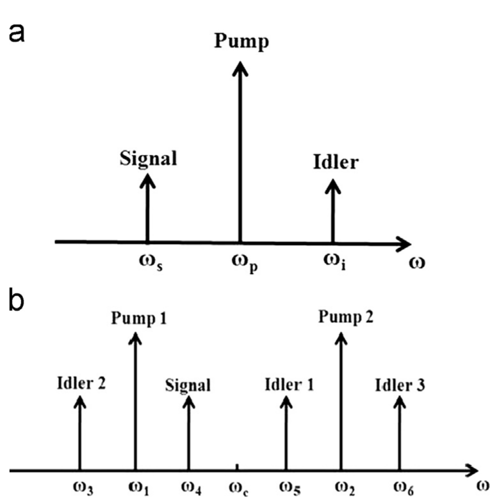

Fig. 1. Frequency assignments of a 1-P FOPA (a); and a 2-P FOPA based on six-wave model (b).

To simulate the parametric gain (in dB units) which is defined as G$=P_s(L)/P_s(0)$, one should solve six coupled equations governing the amplitude evolution of the two pumps (waves 1 and 2), one signal (wave 4), and three generated idlers (waves 3, 5, and 6) along the fiber. Here, $P_s(0)$ and $P_s(L)$ are the signal powers at the FOPA input ($z=0$) and output ($z=$L), respectively. For brevity, we only give the equation regarding the amplitude evolution of the signal as below [14]:

$$\begin{aligned}\frac{\partial A_4}{\partial z} &= i\gamma\Big\{2(|A_1|^2 + |A_2|^2)A_4 - |A_4|^2 A_4 + A_1^2 A_3^* \exp(-i\Delta\beta_{3411} z) \\ &+2A_1A_2A_5^* \exp(-i\Delta\beta_{4512}\, z) + 2A_1A_2^*A_6 \exp(-i\Delta\beta_{2416} z) \\ &+2A_3A_6A_5^* \exp(-i\Delta\beta_{4536} z)\Big\} - \frac{1}{2}\alpha A_4\end{aligned} \tag{3}$$

whereA_i (i=1–6) is the amplitude of each wave and $\Delta\beta_{ijkl} = \beta(\omega_k) + \beta(\omega_l) - \beta(\omega_i) - \beta(\omega_j)$ is the linear wave-vector mismatch of the six interacting waves: i, j, k, and l (i, j, k, l=1, 2, 3, 4, 5, 6). $\beta(\omega_i)$, $\beta(\omega_j)$, $\beta(\omega_k)$and $\beta(\omega_k)$ are the mode propagation constant of each lightwave calculated at its frequency, and $*$ represents complex conjugate. $\beta(\omega_i)$ can be expanded in a Taylor series about the center frequency ω_c as:

$$\begin{aligned}\beta(\omega_i) &= \beta(\omega_c) + \beta^{(1)}(\omega_i - \omega_c) + \frac{1}{2}\beta^{(2)}(\omega_i - \omega_c)^2 \\ &+ \frac{1}{6}\beta^{(3)}(\omega_i - \omega_c)^3 + \frac{1}{24}\beta^{(4)}(\omega_i - \omega_c)^4\end{aligned} \tag{4}$$

where $\beta^{(1)}$, $\beta^{(2)}$, $\beta^{(3)}$, and $\beta^{(4)}$ are the first, second, third, and the fourth-order dispersion coefficients of the fiber calculated at center frequency ω_c, respectively.

When the signal wave gets amplified in the FOPA, its quantum noise is also amplified simultaneously, which degrades the signal. In addition to the quantum noise, there is also some excess noise due to the beating between the Amplified Spontaneous Emission (ASE) of the pump and the signal wave. ASE noise originates from the preamplifiers, for example Erbium-doped fiber amplifiers (EDFAs), which are usually used in the FOPA setup to increase the pump power level injected into the fiber. This noise which is more significant compared to the quantum noise, modulates the signal and leads to the fluctuations of its amplitude.

When the noise is added to the signal wave, the resulting signal amplitude can be written as $A_s(z) = \overline{A}_s(z) + \Delta A_s(z)$, where$\overline{A}_s(z)$ is the mean signal amplitude (the solution of signal equation together with other coupled equations) and ΔA_s(z) are the variations of the signal amplitude created by the excess noise. Owing to the very fast interactions among the waves which is originated from Kerr nonlinearity, the amplitude variations of the pump (ΔA_s(z)) and the signal (ΔA_s(z)) are transformed to other waves as well. Therefore, one obtains three/six coupled equations for the amplitude variations of the interacting waves for 1-P/2-P FOPAs, where the equation for the signal amplitude variations is given by

$$\begin{aligned}\frac{\partial \Delta A_s}{\partial z} &= i\gamma\overline{A}_s\Big\{\Delta A_s\overline{A}_s^* + \overline{A}_s\Delta A_s^* + 2\Big(\Delta A_i\overline{A}_i^* + \overline{A}_i\Delta A_i^* + \Delta A_p\overline{A}_p^* + \overline{A}_p\Delta A_p^*\Big)\Big\} \\ &+ i\gamma\Big(|\overline{A}_s|^2 + 2|\overline{A}_i|^2 + 2|\overline{A}_p|^2\Big)\Delta A_s \\ &+ i\gamma\exp(-i\Delta\beta z)\Big(\Delta A_i^*\overline{A}_p^{\,2} + 2\overline{A}_i^*\overline{A}_p\Delta A_p\Big) - \frac{1}{2}\alpha\Delta A_s\end{aligned} \tag{5}$$