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Crosstalk in double-pumped fiber optic parametric amplifiers for wavelength division multiplexing systems

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Abstract

We study experimentally inter-channel crosstalk in double-pumped fiber optic parametric amplifiers constructed with conventional dispersion shifted fibers (DSFs) having different lengths ($L_A = 13.8$, $L_B = 6.8$, $L_C = 4.3$, and $L_D = 0.8$ km). For long fibers (L_A and L_B), eye diagram measurements in a 5-channel (100 GHz spacing) system show that in order to have negligible crosstalk, the output signal power per channel, P_s, should be limited to $P_s < 0$ dBm. By decreasing the fiber length (to L_C) it is possible to increase the output signal power and/or the number of signals while keeping the crosstalk on negligible levels. This trend was further confirmed by using a very short DSF ($L_D = 0.8$ km).

Finally, we experimentally demonstrate that a general trend in 2P-FOPAs is that spurious FWM increases with the number of signal channels up to a given number of channels when a saturation regime is reached. This saturation of the generation of spurious tones occurs when the bandwidth occupied by the signals exceeds ~4–5 nm.

Keywords: Optical parametric amplifier; Crosstalk; Wavelength division multiplexing

1. Introduction

The fiber optic parametric amplifier (FOPA) is a promising device for all-optical signal processing in future optical networks [1–26]. FOPAs have been demonstrated having high gain and low noise figure at arbitrary wavelengths by using a proper fiber design and tuning adequately one or two pump lasers. One important issue in FOPAs for wavelength division multiplexing (WDM) applications is inter-channel crosstalk, which arises principally from two fonts: cross-gain saturation (XGS) and spurious four wave mixing (FWM).

XGS is due to the instantaneous gain saturation experienced by a signal due to pump depletion, which is proportional to the number of signals transmitting simultaneously the bit one. The deleterious effects of XGS on FOPA performance have been investigated in detail in [27] and also in [28,29]. The other limiting effect arises from spurious FWM processes involving signals, idlers, and pumps. These processes can be very efficient in FOPAs due to the low dispersion fiber used as nonlinear medium, i.e., the proximity of the signals and idlers to the zero dispersion wavelength (λ_0). The first study on inter-channel crosstalk in FOPAs was reported by Krastev and Rothman in [29]. They studied a two-channel WDM system being amplified by a single-pumped FOPA (1P-FOPA) and showed that XGS and spurious FWM involving two signals (and two idlers) and the pump could lead to signal eye closure. In [30] it was predicted, through numerical simulations with double-pumped FOPAs (2P-FOPAs), that crosstalk from spurious FWM and XGS can be alleviated if the 2P-FOPA is constructed with shorter fibers and pumped at higher powers. In [31,32] it was presented a systematic numerical study of crosstalk by spurious FWM in 1P-FOPAs in terms of the output signal power, fiber length, nonlinear coefficient,

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and the number of amplified signals. In [33], it was characterized experimentally the spurious FWM generated by two WDM signal channels amplified in 2P-FOPAs having different lengths of fiber. It was found that for a fixed gain (G) and output signal power (P_s), the intensity of the generated tones grows with the length of the fiber (L). Essentially, the same results were obtained for the case of 1P-FOPAs through a numerical analysis in [32]. Recently, we have shown that variations of λ_0 strongly increase the generation of spurious FWM [28]. Since highly nonlinear fibers are known to suffer of stronger variations of λ_0 than conventional dispersion shifted fibers (DSFs), then conventional DSFs could be an interesting choice to minimize crosstalk. Numerical simulations using this type of fibers reported error free amplification of 64 signal channels [18].

In this paper, we experimentally analyze crosstalk due to spurious FWM and cross-gain saturation in 2P-FOPAs for WDM systems. The 2P-FOPA was constructed with conventional DSFs having different lengths. In Section 2, we present the basic concepts to analyze crosstalk arising from both spurious FWM and cross-gain saturation. In Section 3, we describe the experimental setup used for the measurements of signal eye diagrams in the presence of crosstalk. In Section 4, we show the results and discuss the contribution of both XGS and FWM to the observed crosstalk. In Section 5, we present a detailed investigation of spurious FWM generation in short fibers with very small variations of the zero dispersion wavelength. Limits in terms of the number of amplified signal channels and output signal power per channel are studied and discussed. Finally, in Section 6, we draw our conclusions.

2. Cross-talk in 2P-FOPAs due to spurious FWM and XGS

In a WDM system with equally spaced channels, with frequency spacing Δv, the nonlinearity induces a modulation in the refractive index at frequencies Δv, $2\Delta v$, $3\Delta v$,... (the beating among the idlers also reinforces this index grating). Each signal channel (or idler channel) at frequency v_{sm} (or v_{im}, where $m = 1, 2, 3, \ldots, N$, with N the number of channels) can scatter in such moving grating at frequencies $v_{sm} \pm \Delta v$, $v_{sm} \pm 2\Delta v$, $v_{sm} \pm 3\Delta v, \ldots$ (or at $v_{im} \pm \Delta v$, $v_{im} \pm 2\Delta v$, $v_{im} \pm 3\Delta v, \ldots$) producing crosstalk if channels are present at such frequencies. We shall refer these new tones as becoming from spurious FWM processes of type a. The presence of the pumps at v_{p1} and v_{p2} generate FWM tones at frequencies $v_{p1,2} \pm \Delta v$, $v_{p1,2} \pm 2\Delta v$, $v_{p1,2} \pm 3\Delta v$, ... (spurious FWM processes of type b). In addition, each pump mixes with signals or idlers, whichever are nearest, generating spurious tones at $2v_{p1} - v_{sm}$ and $2v_{p2} - v_{im}$ (spurious FWM processes of type c). Finally, each signal and idler mixes with one of the pumps, whichever is nearest, generating spurious tones at $2v_{sm} - v_{p1}$ and $2v_{sm} - v_{p1}$ (spurious FWM processes of type d). In fact, cascaded FWM processes along the fiber give a complicated 'cacophony' where all Fourier components become coupled to each other. Fig. 1 shows the simple situation where two signals, two idlers and the two pumps are present and mixes between them through FWM processes of the type a, b, c, and d. We calculated the wave-vector mismatch, $\Delta\beta_k$ (k = a, b, c, or d), for these spurious processes and our results are plotted in Fig. 2. A given FWM process is efficient if the phase mismatch over a length L of fiber is $\Delta\beta L < \pi$. The results in Fig. 2 are for a fiber having dispersion parameters and nonlinear coefficient as in the DSF used in the experiments (see Section 3) and for a pump power $P_1 = P_2 = 1$ W. Fig. 2(a) shows $\Delta\beta_a$ as a function of the signal wavelength λ_{s2} for three signal spacing ($\Delta\lambda = \lambda_{s2} - \lambda_{s1} \cong 0.4$, 0.8, and 1.6 nm). As expected, $\Delta\beta$ is larger as the signals are farther from λ_0 and as we increase the signal spacing. Fig. 2(b) shows $\Delta\beta_b$ as a function of the signal wavelength λ_{s2} for three channel spacing ($\Delta\lambda = \lambda_{s2} - \lambda_{s1} \cong 0.4$, 0.8, and 1.6 nm) and for two pump separations ($\Delta\lambda_{pumps} = 30$ and 60 nm). The mismatch decreases as the signals are closer to the pump. Note also that by increasing the signal spacing (or the pumps separation) the mismatch increases. In comparison with the spurious process a, $\Delta\beta_b$ is 10–100 times larger; however, since in process b the pump is involved while in process a only signals are involved the generated tones due to spurious tones a and b should be comparable. Fig. 2(c) shows $\Delta\beta_c$ as a function of the signal wavelength λ_{s2} for three pump separations ($\Delta\lambda_{pumps} = 20$, 40, and 60 nm). Note that as the pumps are closer to λ_0 phase matching is maintained for a broader range of signal wavelengths around the pumps. Fig. 2(d) shows $\Delta\beta_d$ as a function of the signal wavelength λ_{s2} for three locations of the pumps ($\Delta\lambda_{pumps} = 20$, 40, and 60 nm). Note the strong dependence of $\Delta\beta$ with the pump proximity to λ_0.

From the results presented in Fig. 2 we can conclude that spurious FWM processes a and b should be the strongest. However, the spurious processes of type a generate tones at the signal channels and crosstalk is induced, while processes of type b generate tones around the pumps with decreasing intensity for locations farther from the pumps. Crosstalk induced by process b is unlikely since usually the signal channels are accommodated far from the pumps.

To analyze the crosstalk arising from spurious FWM we consider a signal wave at v_s beating with a spurious FWM tone at the same frequency. The field amplitudes of these waves are, respectively,

$$E_s = A_s \cos(2\pi v_s t + \phi_s), \tag{1a}$$

$$E_{FWM} = A_{FWM} \cos(2\pi v_s t + \phi_{FWM}), \tag{1b}$$

where ϕ_s and ϕ_{FWM} are the corresponding phases. We consider the worst-case of parallel linearly polarized signals. In addition, we ignore the effect of signal spectral spread due to the intensity modulation.

The total power in the signal channel at v_s is proportional to $P_T = \langle \|E_s + E_{FWM}\|^2 \rangle$, where the brackets denote a temporal average over an optical period. If we consider that $\|E_{FWM}\|^2 \ll \|E_S\|^2$, then

$$P_T = P_s + 2A_s A_{FWM} \cos(\Delta\phi), \tag{2}$$