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Amplification of 12 × 10 Gb/s WDM signals with negligible FWM crosstalk in a double-pumped fiber optical parametric amplifier

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Abstract

We report on the amplification of 12 × 10 Gb/s wavelength-division-multiplexed signals by a double-pumped fiber optic parametric amplifier (2P-FOPA). A gain of 10 dB is obtained using a 4.3 km-long conventional dispersion shifted fiber (DSF) as nonlinear medium. Our spectra show negligible generation of spurious FWM products, and we attribute this to the small variations of the zero-dispersion wavelength of the DSF. The 2P-FOPA performance is assessed through *Q*-factor measurements, and we show that for output powers per channel ranging from −15 to 3 dBm the power penalty is less than 0.5 dB.

Keywords: Optical parametric amplifier; Crosstalk; Wavelength division multiplexing

1. Introduction

Fiber optical parametric amplifiers (FOPAs) are potentially attractive for optical communication systems, as they can exhibit gain spectra wider than those of Erbium doped fiber amplifiers (EDFAs) and be centered anywhere in the low-loss window of silica fibers [1–9]. Recently, a double-pumped FOPA (2P-FOPA) having flat gain over a bandwidth of 115 nm has been reported [10]. The large bandwidth provided by 2P-FOPAs is desirable for amplification or wavelength conversion of a large number of wavelength division multiplexed (WDM) signals. However passing multiple signals through FOPAs results in nonlinear crosstalk, due to the generation of undesirable four-wave mixing (FWM) products, and to cross-gain modulation (XGM) induced by pump depletion [11–23]. The effect that this crosstalk has on FOPA performance has received increased attention in the past years. Numerical and experimental investigations of the generation of spurious FWM and the effect of XGM as a function of FOPA parameters such as the fiber length (L), the output signal power (P_s^{out}), the nonlinear coefficient (γ), and the pump power (P) have provided some design rules for crosstalk minimization. For example, it was shown that reducing the output signal power reduces both the impact of spurious FWM and XGM [12–18].

Simulations of a 2P-FOPA amplifying 32 modulated channels up to $P_s^{out} \sim 0$ dBm (with 20 dB gain) have demonstrated little signal degradation [14]. On the other hand, experiments have been reported only with 2-7 WDM modulated channels [15, 21–24]. This rather small number of channels may be due to the fact that with larger channels counts, nonlinear crosstalk can give rise to prohibitive degradation. In several of the reported experiments strong spurious FWM tones were present [18–20, 22,23]. One reason for this might be that the fibers used to construct the FOPA exhibited a non-negligible amount of fluctuations of the zero-dispersion wavelength (λ_0): it was experimentally shown that fibers with 1–2 nm of λ_0 fluctuations give rise to spurious FWM products which are 10–15 dB larger than

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in the case of FOPAs constructed with ideal fibers (i.e. without λ_0 fluctuations) [19].

Conventional dispersion shifted fibers (DSFs) are known to have, in general, smaller variations of λ_0 compared to highly nonlinear fibers (HNLFs). Recently, a 2P-FOPA constructed with a short length DSF was reported, and it was shown that low FWM was achievable when 10 unmodulated signals were amplified up to 10 dBm [21]. In this paper we report on the amplification of 12 signals, modulated at a bit rate of 10 Gb/s, by a 2P-FOPA constructed with a conventional DSF exhibiting very low variation of λ_0. We focussed on the impact of FWM-induced crosstalk, so we modulated all the signals with the same bit stream in order to avoid the effect of XGM. System performance was evaluated by means of Q-factor measurements. We find that for signal output powers per channel ranging from $P_s^{out} \cong -15$ dBm to $P_s^{out} \cong 3$ dBm, the power penalty is less than 0.5 dB.

2. Experimental setup

The experimental setup is shown in Fig. 1. Twelve signal lasers, with frequencies spaced by 100 GHz (except for channel #10, which could not be finely tuned), are combined by means of several 3 dB couplers (not shown), and then intensity-modulated at 10 Gb/s by a common Mach–Zehnder intensity modulator driven by a pseudo-random binary sequence (PRBS) of non-return-to-zero (NRZ) data with a word length of $2^{31} - 1$. The signals are then boosted by an EDFA and enter the 2P-FOPA (not shown). There they are combined with the two pumps by means of a 10/90 coupler, and pass through the gain medium. The pumps, with powers of $P_1 \cong P_2 \sim 250$ mW, are optically filtered with band-pass filters in order to remove amplified spontaneous emission (ASE) noise from EDFA boosters. The gain medium is a 4.3 km-long DSF, with nonlinear coefficient $\gamma \cong 2.1$ W^{-1}/km, dispersion slope $S_0 \cong 0.073$ ps/nm km, which exhibits low variation of λ_0 (estimated to be around 0.2 nm [16]). The measured polarization mode dispersion (PMD) parameter of the fiber is 0.03 ps$^{1/2}$/km. The 2P-FOPA output is then divided by a 1/99 coupler, with 1% being sent to an optical spectrum analyzer (OSA) with 0.1 nm resolution. The remaining power enters an arrayed waveguide grating (AWG) filter that selects one of the channels, which is then attenuated with a variable attenuator, optically pre-amplified, and filtered before reaching the oscilloscope which displays the signal eye pattern. The Q-factor was measured as a function of the signal power entering into the pre-amplifier. The sensitivity of the pre-amplifier was measured to be -35 dBm for $Q = 6$ (this corresponds to a bit error rate of 10^{-9}).

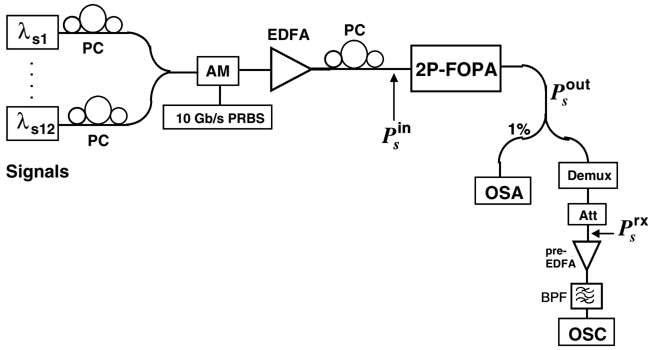

Fig. 1. Experimental setup. Each pump power was about 250 mW.

The pump polarizations were adjusted to be approximately perpendicular in order to minimize the polarization-dependent gain (PDG), which was measured to be of the order of 2–3 dB. To have roughly the same output power in all the channels we adjusted the input channel powers to compensate this PDG.

3. Experimental results

The FOPA performance was investigated as the output signal power was varied (we could change P_s^{out} by varying the gain of the EDFA, i.e. by varying P_s^{in}). Fig. 2a shows the output optical spectrum obtained for the case of $P_s^{out} \cong -3$ dBm. In the inset the eye pattern for channel #4 is shown: it was obtained by setting the attenuator in order to have $P_s^{rx} = -25$ dBm entering into the pre-ampli-

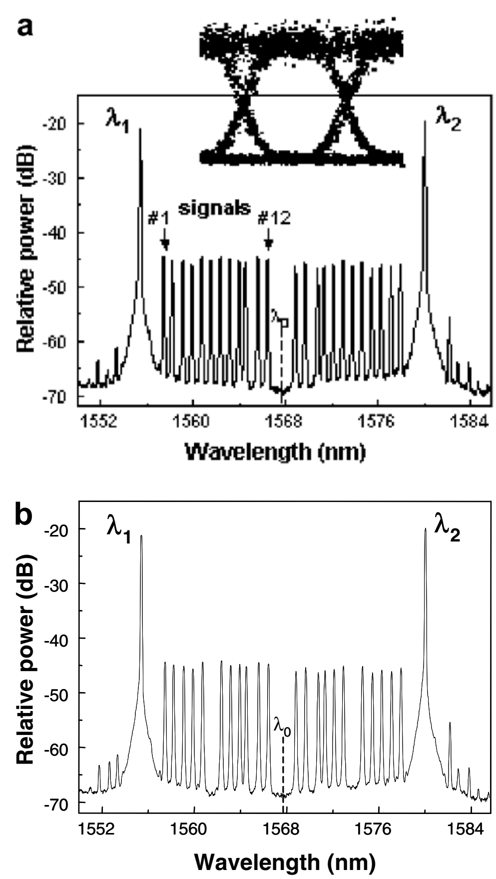

Fig. 2. Output optical spectrum for signal output powers of $P_s^{out} \cong -3$ dBm. The on–off gain of the 2P-FOPA varied from 9 to 12.5 dB (PDG of ~2.5 dB). (a) 12 channels present; the inset shows the eye pattern for channel 4 ($Q = 10.7$). (b) same as (a), but without channel #6.