Experimental Comparison of Gain and Saturation Characteristics of a Parametric Amplifier in Phase-sensitive and Phase-insensitive Mode

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Abstract *We demonstrate a parametric amplifier with precise control of the in-going waves and study gain and saturation properties in both PSA and PIA mode. A PSA gain of 33 dB is achieved.*

Introduction

Phase-sensitive amplifiers (PSAs) offer several intriguing applications such as amplification with a noise figure below the 3 dB quantum limit of phase insensitive amplifiers (PIAs)[1], dispersion compensation[2], and the possibility of optical phase regeneration of phase encoded signals[3]. An interesting prospect is simultaneous phase and amplitude regeneration by using a saturated PSA[3].

In order for phase-sensitive interaction to occur phase-locking among the interacting waves is required. While this can be achieved in an interferometric loop configuration[4], this approach is frequency degenerate and thus inherently single-channel. Another way of implementing a PSA is by using nondegenerate four-wave mixing (FWM) in a fiber-optic parametric amplifier (FOPA)[5]. This requires injecting three (or four) waves; pump, signal and idler with a fixed phase relation into the fiber. In order to prepare these phase-locked waves one can generate them by means of electro-optic modulation, but the modulator then limits the bandwidth. A wideband PSA can be created with two FOPAs in cascade, generating a phase-locked but conjugated idler in the first FOPA, and, with a mechanism for changing the relative phase among the waves in between, achieving PSA operation in the second FOPA[6].

In this paper we demonstrate a way of implementing a PSA with an advanced optical processor, allowing for precise amplitude and phase control, without the need for a complex external phase-locking control. We examine the PSA gain and are here presenting the first study of the saturation properties of a FOPA in PSA mode, and compare it with PIA mode. It is found to saturate for lower signal powers in PSA mode, whereas the parametric attenuation is not significantly affected. Moreover, for a PSA to be practically usable, sufficiently large gain is required. By operating in the exponential gain regime, a PSA gain of 33 dB was achieved.

Experimental setup

The experimental setup is shown in Fig. 1. A tuneable laser (TL) set at 1553.0 nm was used as a pump source and was phase modulated with four RF tones

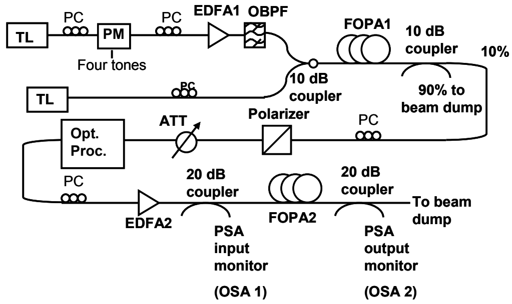

Fig. 1: Experimental setup of two FOPAs in cascade.

to suppress Stimulated Brillouin Scattering (SBS). The pump wavelength was chosen to contain the gain bandwidths of the two FOPAs within the operating bandwidths of the optical processor and the EDFAs. The pump was amplified to 3.8 W by a high-power erbium-doped fiber amplifier (EDFA1), and filtered by an optical bandpass filter (OBPF). A second tuneable laser was used as signal source. The pump and signal were then coupled via a 10 dB coupler into FOPA1, implemented with a 150 m long highly nonlinear fiber (HNLF) with a nonlinearity coefficient γ=10 (W·km)$^{-1}$, and a zero-dispersion wavelength λ_0=1542 nm. The output was passed through a 10 dB coupler, a polarizer, and a variable attenuator (ATT) with a built-in power monitor. The purpose of the polarizer was to align all three waves, and then, with a polarization controller, align them with a principal axis of EDFA2, to minimize the impact of DGD. The waves were subsequently passed through an optical processor (Finisar Waveshaper 4000E) that allowed for individual filtering, attenuation, and phase-shift of the three waves. The three waves were amplified by EDFA2 to up to 2 W, with the pump wave completely dominating the power, and injected into FOPA2, which was implemented with a 250 m HNLF with γ=11.7 (W·km)$^{-1}$, and λ_0=1542 nm. The input into and output from FOPA2 were monitored on two optical spectrum analyzers (OSAs) via two 20 dB couplers.

Results

PSA operation requires that the signal and idler powers are equalized, which was realized to within 0.5 dB. The PSA gain or attenuation is governed by the relative phase among the three waves. It is defined as $\theta_{rel}=2\theta_p-\theta_s-\theta_i$, with θ_p, θ_s and θ_i being the phases of the pump, signal and idler waves, respectively. θ_{rel} is zero after FOPA1, and modified by dispersion between FOPA1 and 2. By changing the phase of one or more of the waves with the optical processor, θ_{rel} at the input of FOPA2 can be set to an arbitrary value. The idler can also be blocked in the optical processor, changing FOPA2 to PIA operation.

In Fig. 2, the measured PSA gain and attenuation, defined as output signal power/input signal power (not on-off gain), as well as the PIA gain using a pump power of 1.2 W are plotted versus signal wavelength. The difference beween maximum PSA and PIA gain was very close to 6 dB. The difference in minimum and maximum PSA gain, was found to be maximal when the signal is close to the pump, and decreasing from there. From theory, one expects the minimum gain to be equal to the negative maximum gain. It is believed that the observed discrepancy is related to the dispersion between FOPA1 and 2, which complicates setting the proper phase, as the pump and idler have linewidths of several GHz, due to the pump phase modulation. Moreover, the region of minimum gain is quite narrow, and increasingly so as the maximum gain increases, which due to the limited resolution of the optical processor, makes it more difficult to optimize for.

In Fig. 3, the PSA gain versus θ_{rel}, measured at a signal wavelength of 1553.9 nm, is shown for three different pump powers with the corresponding theoretical curves. At the lowest pump power, experiments and theory agree very well. At higher pump powers, the minimum gain deviates from the theory, for the same reasons as discussed above.

By increasing the signal/idler power, while keeping the input pump power constant at 1.2 W we reached the gain saturation regime. The gain of FOPA2 in PIA and PSA mode with varying input signal/idler power at a signal wavelength of 1553.9 nm is shown in Fig. 4. The maximum PSA gain saturates before the PIA gain, owing to the higher gain of the PSA, while the parametric attenuation remain unaffected. The triangles represent the difference between maximum PSA and PIA gain, and follows the theoretical 6 dB line until the PSA reaches saturation. Finally, by

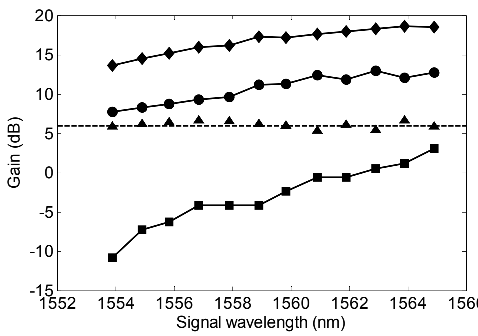

Fig. 2 : Measured PIA (circles), PSA max. (diamonds) and min. (squares) gain of FOPA2. The triangles show the gain difference between PIA and PSA.

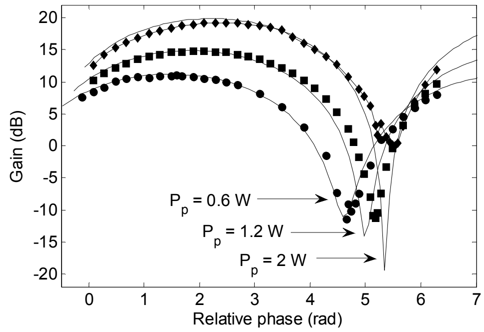

Fig. 3: PSA gain as function of relative phase.

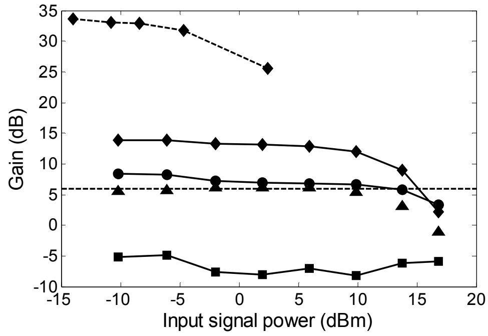

Fig. 4: Measured PIA (circles), PSA max. (diamonds) and min. (squares) gain of FOPA2 vs. input signal power. The triangles represent the difference between PIA and PSA gain, and the dashed line shows PSA gain in the exponential gain regime.

moving the signal wavelength to 1563.8 nm and increasing the pump power to 2 W, we were able to achieve 33 dB of PSA gain. Because the noise from EDFA2 imposes a lower limit on the input signal/idler powers, we could not achieve unsaturated gain. Therefore, the difference between PSA and PIA gain was less than 6 dB. Nevertheless, PSA behaviour was confirmed by changing the input phase and observing the difference in output signal power.

Conclusions

We have demonstrated a PSA that allows for precise control of the signal and idler powers, as well as the relative phase without the need for external phase locking. We measured a phase-sensitive gain of 33 dB, which we believe is the highest reported to date. We also performed the first investigation of the saturation properties of a PSA, and found that the PSA saturates for lower input signal powers, in accordance with theory.

Acknowledgment

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