Low-Noise Phase-Sensitive Optical Parametric Amplifier with Local Pump Generation using Digital Frequency and Phase Control

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Abstract: We demonstrate a novel, lossless approach, eliminating the need to co-propagate pumps in phase-sensitive parametric amplifier-based links, by control loops creating a locked pump within the amplifier. Gain, noise and BER measurements validate the performance.

1. Introduction

Phase-sensitive amplifiers (PSAs) offer several advantages over phase-insensitive amplifiers (PIAs) like the EDFA; they exhibit a theoretical 0 dB noise figure, can mitigate transmission nonlinearities and are wavelength flexible with a potentially large gain bandwidth [1]. These appealing aspects of PSAs make them attractive for applications such as preamplification in free-space [2]- and fiber-optical transmission links [3], all-optical phase and amplitude regeneration [4] and all-optical sampling [5,6].

PSAs, like other parametric amplifiers, rely on nonlinear interaction in either a three- [7] or four-wave mixing (FWM) process where one or several pump waves exchange energy to weaker signal and idler waves. A common and practical setup for a PSA is the two-mode, degenerate pump configuration [1], where signal and idler waves are equally spaced apart in frequency around a central degenerate pump wave. The relative phase between these three waves determines the exchange of energy between them. The gain of such an amplifier can be written as [1]

$$G_{\text{PSA}}(\phi) = |\mu|^2 + |\nu|^2 + 2|\mu||\nu|\cos\phi, \quad \phi = \phi_s + \phi_i - 2\phi_p + \phi_c. \tag{1}$$

Here, $|\mu|^2 = G_{\text{PIA}}$ is the PIA gain the signal wave experiences should the idler be absent at the amplifier input, $|\nu|^2 = G_{\text{PIA}} - 1$, $\phi_{s,i,p}$ is the phase of the signal, idler and pump waves respectively and ϕ_c is a constant phase.

To achieve phase-sensitive gain and reach the attractive < 3 dB NF (lowest measured fiber-PSA NF: 1.1 dB [8]) the three waves need to be locked in phase at the PSA input. In the case of an optical link, while correlated signal, idler and pump waves are commonly produced in the transmitter (Tx), usually by employing a copier scheme [1], it is practically difficult to create a correlated receiver (Rx)-side, high- power and quality, pump wave.

In previous demonstrations, the pump was regenerated for the PSA, either by co-propagating the Tx pump in the link along with the signal and idler for injection-locking to a Rx-side slave laser [2] or by tapping part of the received signal as carrier reference for an optical phase-locked loop (OPLL) [7]. In addition, another OPLL has been used to maintain the phase locking. Here we demonstrate a method that eliminates the need for co-propagating a pump or tapping the received signal before amplification, using phase dithering and a field-programmable gate array (FPGA) to control the phase and frequency of a Rx-side pump laser.

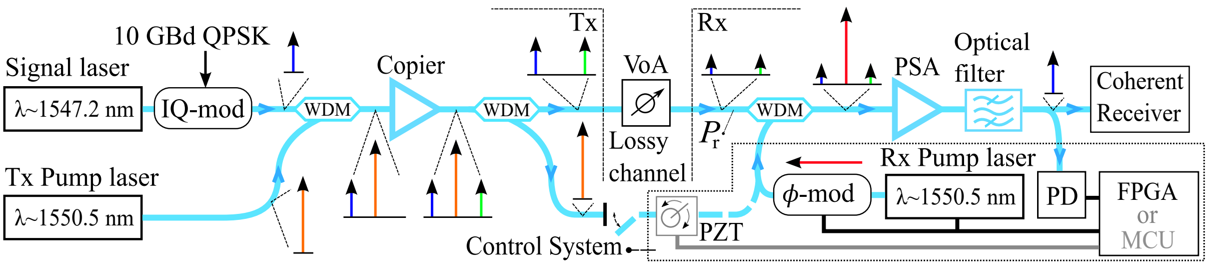
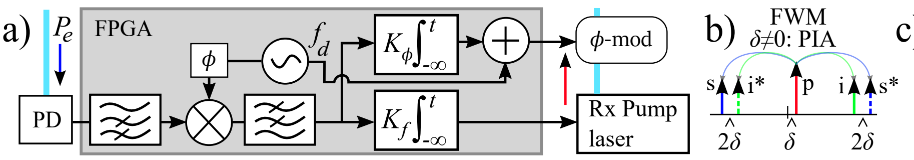


Fig. 1. A transmission system with a Tx-side copier stage, a lossy channel and a Rx-side PSA with either a loop-controlled Rx- or recycled Tx pump. PZT: Piezo-electric transducer, VoA: Variable optical attenuator, WDM: Wavelength multiplexer, PD: Photo detection, MCU: Micro-control unit.

2. Experiment

The experimental setup is depicted in Fig. 1. A signal wave carrying a 10 GBaud QPSK data signal is combined in a WDM with a high-power pump wave from an NKT fiber laser. The signal is copied onto a conjugated idler wave (of equal power) in a highly nonlinear fiber, denoted copier. After, the pump wave is filtered away using a WDM before signal and idler waves are sent through a VoA, representing a lossy channel. At the Rx side, the signal and idler are combined with a high-power pump wave (29 dBm) from a Thorlabs ULN external fiber-Bragg grating cavity laser. The signal and idler experience gain in the 600 m long highly nonlinear fiber-PSA according to Eq. (1). The signal is then separated using an optical filter before detection in an intradyne coherent receiver and sampling in a real-time oscilloscope for offline processing. Note that this approach is, in principle, lossless since no signal or idler power needs to be tapped at the input of the amplifier, which would degrade the "black-box" NF.

To continuously maximise the PSA gain, the control system dithers the pump phase using an electro-optic phase modulator at the output of the pump laser. The PSA gain-phase relation in Eq. (1) is near identical to that of interference in a 50/50 coupler. As such the dither creates an optical error signal P_e at the PSA output which is proportional to the phase error at the input of the PSA and oscillating at the dither frequency, as described in [9]. The PSA output power, containing P_e, is then tapped, detected in a photo-receiver, fed into a low-cost 125 MS/s, 14-bit Red Pitaya FPGA [10] and processed using pre-built IQ and PID modules found in the software Pyrpl [11]. The FPGA, see Fig. 2 a), demodulates the error signal before passing it to two separate integrators, one with loop gain K_ϕ for phase compensation in the electro-optic phase modulator and the other with gain K_f for current control of the Rx pump laser for compensating relative frequency drifts.



c)

	G [dB]	NF [dB]
PIA	11.2 ± 0.5	4.4 ± 0.3
PSA_{LP}	16.4 ± 0.4	2.2 ± 0.1
PSA_{REF}	17.2 ± 0.3	1.6 ± 0.3

Fig. 2. a) The FPGA high-pass filters the error signal, then demodulates it before low-pass filtering and splitting to two separate integrators, one for phase-compensation (to which the dither is added) and one for frequency-compensation. b) FWM of misaligned signal, idler and pump, "*" is the complex conjugate. c) Measured parametric amplifier performance.

For each received power P_r (Fig. 1), K_ϕ and K_f were changed and the Rx-side pump was brought into phase-lock manually by tuning the laser current control to minimise the PD-beat signal frequency 2δ that arises from FWM with a misaligned (δ) pump wave, as illustrated in Fig. 2 b). Both a 1 MHz and a 31.25 MHz dither frequency were used for different measurement batches and the dither phase magnitude was tuned in the range $[0.22, 0.45]$ rad to maintain P_e signal-to-noise ratio (SNR).

For comparison, PIA measurements were performed where the idler was removed from the PSA input. Similarly, to compare with an ideal PSA, a reference measurement was performed where the correlated pump wave from the Tx was phase-aligned using a PZT (controlled by an MCU) and used to pump the PSA.

3. Results and discussion

In Fig.2 c) we present the measured gain G and NF for the local pump-locked PSA (PSA_{LP}), the reference PSA (PSA_{REF}) and the PIA. The values were calculated from the total received power P_r ($P_r \in [-59, -46]$ dBm) and the resulting optical spectrum and optical SNR (OSNR), measured with an optical spectrum analyser (OSA) at the PSA output. In terms of gain, PSA_{LP} exhibits a 5.2 dB increase over the PIA while having 0.8 dB less gain than PSA_{REF}. The PSA_{LP} NF is 2.2 dB lower than the PIA NF and is 0.6 dB higher than for PSA_{REF}.

Phase-sensitive operation is shown by the < 3 dB NF and the performance improvement over the PIA. The bit-error-rate (BER) curves in Fig. 3 a) and the amplifier output spectrum in Fig. 3 b) further support this result. P_r was swept and the BER was calculated as shown in Fig. 3 a). At 10^{-2} BER, compared with theory, there is a power penalty of 3.1 dB and 2 dB for PSA_{LP} and PIA respectively. Here the PSA_{LP} exhibits a 2 dB sensitivity improvement in P_r w.r.t the PIA while having 0.9 dB worse sensitivity than PSA_{REF}. In Fig. 3 b), the measured OSNR improvement for the PSA over the PIA also confirms the phase-sensitive operation.

The performance difference between PSA_{REF} and PSA_{LP} indicates that loop gains and dither parameters can be further optimised. The error signal SNR and the frequency drifts (< 1 MHz/s) and phase noises, among Tx and Rx pump waves all impact the locking. The delay imposed by the 600 m PSA, combined with the effective pump drift and phase noise doubling ($2\phi_p$) in Eq. (1), contributes to further instability. Also, due to the limited output voltage range to the phase modulator, 2π-phase jumps need to be made occasionally for tracking to pursue.

Although there is room for improvement w.r.t. the locking efficiency the dither will always cause a small penalty

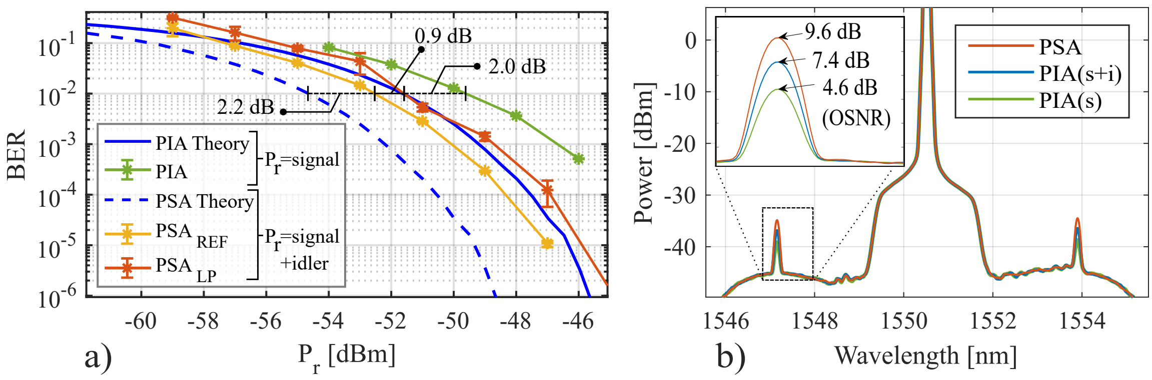


Fig. 3. a) Theoretical and measured BER curves, including standard deviation error bars, versus received power. b) A captured spectrum of the PSA output at $P_r = -49$ dBm (-52 dBm for PIA).

to the PSA operation, akin to that of dither-based coherent combining in a 50/50-coupler, as described in [9]. In fact, applying the demonstrated system on a 50/50-coupler, instead of a PSA, will lock two uncorrelated waves, achieving 0 Hz offset-locking without optical injection locking. While this has been achieved previously to some extent in the active phase alignment of a local oscillator for homodyne detection, as demonstrated in [12], the digital solution used here is more versatile thanks to the powerful Red Pitaya FPGA [10] and Pyrpl software [11].

4. Conclusions and future outlook

Using a dither-based local pump locking scheme we have demonstrated phase-sensitive amplification with a 5.2 dB and 2.2 dB gain and noise figure improvement respectively versus the phase-insensitive case.

The phase dithering, although comprising a small penalty to the PSA performance, still poses an attractive solution to the practical dilemma of PSA pump-phase alignment. It circumvents transmitter pump wave injection-locking or the need to tap the received signal prior to amplification, only relying on an error signal produced at the PSA output. Not needing to transmit a weak pump wave enables other signal and idler-transmitting schemes such as optical frequency combs and makes PSAs more attractive in fiber- and space communication links.

4.1. Acknowledgements

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References

1. P. A. Andrekson and M. Karlsson, “Fiber-based phase-sensitive optical amplifiers and their applications,” Adv. Opt. Photon. **12**, 367–428 (2020).
2. R. Kakarla, J. Schröder, and P. A. Andrekson, “One photon-per-bit receiver using near-noiseless phase-sensitive amplification,” Light Sci. Appl. **9**, 153 (2020).
3. S. L. I. Olsson, B. Corcoran, C. Lundström, T. A. Eriksson, M. Karlsson, and P. A. Andrekson, “Phase-sensitive amplified transmission links for improved sensitivity and nonlinearity tolerance,” J. Light. Technol. **33**, 710–721 (2015).
4. R. Slavík *et al.*, “All-optical phase and amplitude regenerator for next-generation telecommunications systems,” Nat. Photonics **4**, 690–695 (2010).
5. A. Tersigni *et al.*, “Polarisation independent optical sampling using four- wave mixing,” in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference,* (Optica Publishing Group, 2003), p. CMR2.
6. P. Andrekson and M. Westlund, “Nonlinear optical fiber based high resolution all-optical waveform sampling,” Laser & Photonics Rev. **1**, 231–248 (2007).
7. S. Shimizu *et al.*, “Non-degenerate phase-sensitive amplification scheme using digital dispersion pre-equalization for unrepeated transmission,” Opt. Express **29**, 8451–8461 (2021).
8. Z. Tong *et al.*, “Towards ultrasensitive optical links enabled by low-noise phase-sensitive amplifiers,” Nat. Photonics **5**, 430–436 (2011).
9. R. Larsson, J. Schröder, M. Karlsson, and P. A. Andrekson, “Coherent combining of low-power optical signals based on optically amplified error feedback,” Opt. Express **30**, 19441–19455 (2022).
10. “RedPitaya, Swiss Army Knife For Engineers,” (2022).
11. L. Neuhaus, “Lneuhaus/pyrpl: Pyrpl turns your Redpitaya into a powerful DSP device, especially suitable as a lockbox in quantum optics experiments.” (2016).
12. M. L. Stevens, D. O. Caplan, B. Robinson, D. M. Boroson, and A. L. Kachelmyer, “Optical homodyne psk demonstration of 1.5 photons per bit at 156 mbps with rate-$\frac{1}{2}$ turbo coding,” Opt. Express **16**, 10412–10420 (2008).