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# Design and Performance Evaluation of an OPC Device Using a Dual-Pump Polarization-Independent FOPA

I. Sackey<sup>(1,2)</sup>, F. Da Ros<sup>(2,3)</sup>, T. Richter<sup>(2)</sup>, R. Elschner<sup>(2)</sup>, M. Jazayerifar<sup>(1)</sup>, C. Meuer<sup>(1,2)</sup>,  
C. Peucheret<sup>(4)</sup>, K. Petermann<sup>(1)</sup>, and C. Schubert<sup>(2)</sup>

- (1) Technische Universität Berlin, Fachgebiet Hochfrequenztechnik, Einsteinufer 25, 10587 Berlin,
- (2) Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Einsteinufer 37, 10587 Berlin Germany (Email: isaac.sackey@hhi-extern.fraunhofer.de)
- (3) Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, DK.
- (4) FOTON Laboratory, CNRS UMR 6082, ENSSAT, University of Rennes 1, F-22305 Lannion, France.

**Abstract.** *The performance of a polarization-independent fiber-based optical parametric amplifier is experimentally investigated in terms of amplification and wavelength conversion for optical phase conjugation applications using 5×28-GBd PDM 16-QAM signals. Good conjugated signal quality up to 13-dB gain is obtained.*

## Introduction

The nonlinear Shannon limit represents one of the most critical challenges optical networks will have to address in the near future<sup>1</sup>. In this context, a renewed interest for nonlinear compensation has led to several demonstrations both in the digital and the optical domains<sup>2-4</sup>. Optical phase conjugation (OPC) is a well-known technique allowing inverting the signal spectrum, therefore enabling the compensation of dispersion and Kerr effect accumulated through propagation by further transmission of the conjugated signal. For practical application, an OPC device should provide broadband operation as well as modulation-format transparency and polarization independence. Towards this aim, nonlinear compensation was demonstrated in Ref. 5 for 16-quadrature amplitude modulation (QAM) signals. However, operation was restricted to single polarization and limited by the penalty introduced by the OPC itself. In Ref. 2, polarization-independence was achieved, but only quadrature phase-shift keying (QPSK) operation was reported.

In this work, we investigate the potential of using a broadband dual-pump fiber optical parametric amplifier (FOPA) to provide polarization-independent and low penalty OPC opera-

tion for a 5-channel wavelength-division multiplexed (WDM) 28-GBd polarization division multiplexed (PDM) 16-QAM signal. The relative performances of the amplified signal and idler are evaluated in terms of polarization sensitivity and bit-error ratio (BER), highlighting the key optimization aspects for the successful design of a black-box OPC device.

## Experimental setup

The experimental setup is presented in Fig. 1. The setup consists of a 5-channel 28-GBd PDM 16-QAM transmitter, the FOPA, and a coherent receiver. Five continuous wave (cw) external cavity lasers (ECLs) on a 50-GHz grid centered at 1550.12 nm were modulated with 16-QAM at 28 GBd using an IQ modulator driven by two channels of a 56-GS/s arbitrary waveform generator (AWG). A polarization emulator (PolMux) was then used to generate a PDM signal, followed by a decorrelation stage to fully decorrelate all five channels<sup>6</sup>. Before entering the FOPA, a scrambler was used to randomize the state-of-polarization (SOP) of the signal.

The FOPA consists of two ECLs serving as cw pump sources at 1534 nm and 1574 nm with linewidths of 25 kHz and 100 kHz, respectively. The pumps were separately modulated using phase modulators (PMs) driven in a coun-

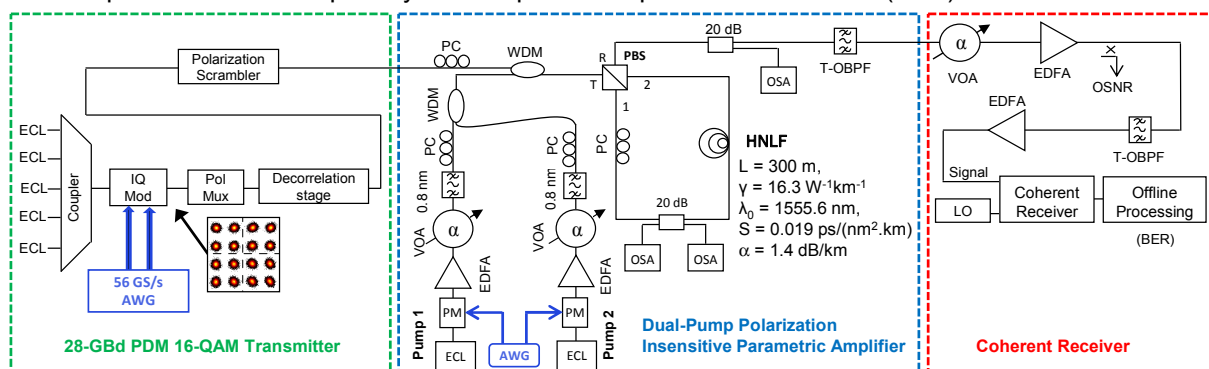


Fig. 1: Experimental setup.

ter-phasing fashion by two sinusoidal tones (69 MHz and 253 MHz; modulation index of 1.4 radians) generated by another two-channel AWG in order to increase the stimulated Brillouin scattering (SBS) threshold and to minimize the transfer of pump phase modulation to the generated idlers<sup>7</sup>. The pumps were amplified by EDFAs (output optical signal-to-noise ratio (OSNR) of 59 dB and 56 dB for the C- and L-band pumps, respectively) and combined with a WDM coupler. The pump power levels were controlled via variable optical attenuators (VOAs) thus ensuring constant pumps OSNR values. Optical band-pass filters (OBPFs) with a full-width at half-maximum (FWHM) bandwidth of 0.8 nm suppress the out-of-band amplified spontaneous emission (ASE). Pumps and signal were combined using a WDM coupler before being sent to the diversity loop consisting of a polarization beam splitter (PBS) and a piece of highly nonlinear fiber (HNLF) (length 300 m, zero dispersion wavelength 1555.6 nm, nonlinear coefficient 16.3/W/km, attenuation 1.4 dB/km, dispersion slope 0.019 ps/nm<sup>2</sup>/km). The total signal power at the PBS was kept constant at -5 dBm throughout the evaluation except for the saturation analysis. In order to match the gain in both loop directions, the SOP of the pumps was tuned via two polarization controllers (PCs) and the SOP of the signal was randomized using the polarization scrambler. A 20-dB coupler in the loop was used to monitor the pumps power levels in both directions of the loop. A PC in the loop was used to ensure that the waves at the output of the HNL exit at port-R of the PBS. The output spectra after the diversity loop were monitored by an optical spectrum analyzer (OSA) via a 20-dB coupler. At the FOPA output a tunable (T) OBPF with 4-nm FWHM bandwidth was used to select either the amplified signal or the idler bands and to suppress the pumps.

At the receiver, the signal was noise-loaded, the channel under test was selected by a T-OBPF and injected together with a local oscillator (LO) with 100-kHz linewidth in a coherent receiver consisting of a 90° optical hybrid, balanced photodiodes (BPD) and a 40 GS/s real-time sampling scope (RTO). Offline processing was then performed, including frequency-offset estimation, adaptive equalization, carrier phase estimation and error counting<sup>6</sup>.

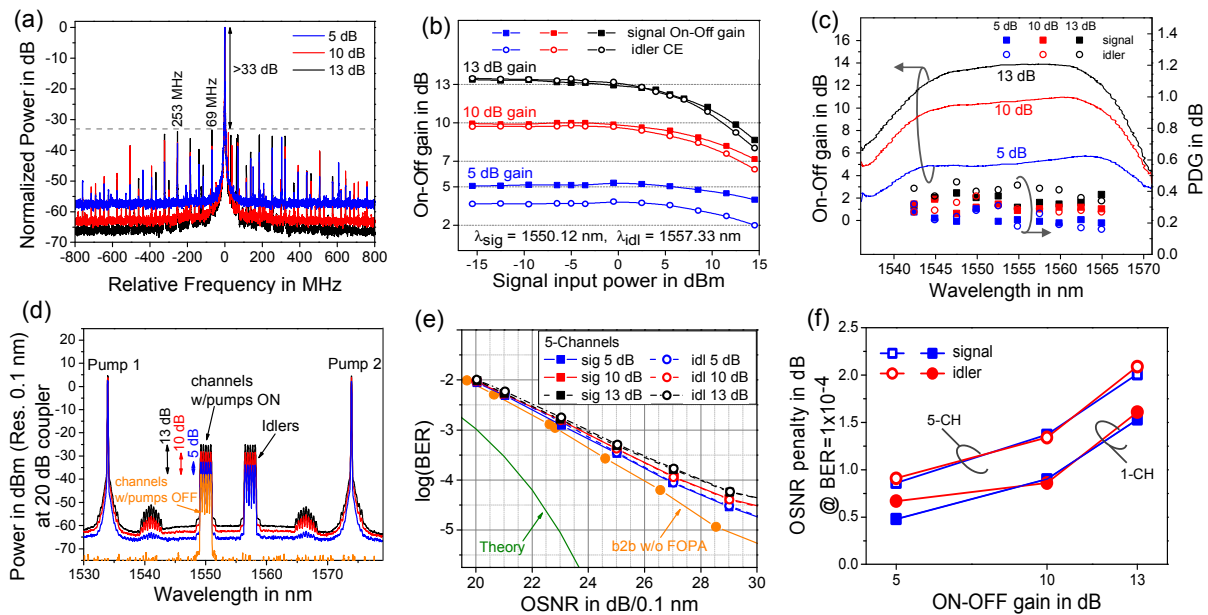
### Results and Discussions

The transfer of pump phase noise to the idler strongly degrades the quality of the idler. Therefore the counter-phasing was optimized using a single channel cw signal at 1550.12 nm

injected into the FOPA. The generated idler was detected using the RTO and its spectrum was monitored to assess the amount of phase modulation at 69 MHz and 253 MHz being transferred from the pumps. As shown in Fig. 2a, regardless of the On-Off gain values (5 dB, 10 dB and 13 dB were considered in this investigation), the suppression ratio between the carrier and the two tones and their harmonics was higher than 33 dB, showing that low phase modulation was transferred to the idler<sup>7</sup>.

Fig. 2b shows the On-Off gain and conversion efficiency (CE) as functions of the signal power at the PBS input. The CE is defined as the ratio of idler to signal powers with pumps off measured at the FOPA output. This particular characterization was done in a polarization dependent configuration. The polarizations of the pumps and a cw signal at 1550.12 nm were aligned to propagate in one direction of the diversity loop without polarization scrambling. As expected, the difference between gain and CE decreases with increasing the gain. Higher gains begin to saturate at lower input powers than lower gain levels. However, gain reduction of 1 dB is obtained at a signal input power of +5 dBm even when the gain is 13 dB.

For the gain bandwidth measurement, the WDM coupler (signal-pump combiner) was temporarily replaced with a 10-dB coupler. This characterization was performed with the pumps SOPs set for polarization-independent operation, and polarization-scrambling of the cw-probe signal, whose wavelength was swept from 1535 nm to 1572 nm. The total pump power into the loop was set to 28.2 dBm, 29.9 dBm, and 30.8 dBm for 5 dB, 10 dB, and 13 dB On-Off gain, respectively. The results are summarized in Fig. 2c and show a flat gain with 1-dB bandwidth of 24 nm at 5-dB On-Off gain which reduces to 18 nm at 13 dB. A slight gain tilt resulting from the Raman effect is also visible though its impact was kept low by setting the C-band pump power ~ 1.8 dB higher than the L-band pump power. Fig. 2c also illustrates the PDG for the modulated signal and its idler measured using the zero-span function of the OSA while scrambling a single-channel 28-GBd 16-QAM signal with the PDM emulator bypassed. Averaging effects in the PDG measurement are minimized by the use of a low scrambling rate. The signal wavelength varied from 1542.5 nm to 1565 nm, i.e. the flat region of the gain profile. The measurement was done for 5-dB, 10-dB, and 13-dB gain showing low PDG values ranging from 0.2 dB to 0.5 dB with similar signal/idler values. Note that at higher gain, the pump-power splitting is more critical



**Fig. 2:** (a) Spectra of RTO-acquisition showing suppression of pump phase modulation tones on the generated idler. (b) Gain saturation characteristics. (c) Gain bandwidth and PDG for the amplified signals and the idlers. (d) Spectra at the HNLF output for the different gain levels showing the 5-channel DWDM signal and the generated idlers. (e) 5-channel BER curves for signal and idler at different gain levels. (f) OSNR penalties at a BER of  $1 \times 10^{-4}$  for both signal and idler as functions of On-Off gain.

due to the exponential gain regime, resulting in slightly higher PDG values.

Fig. 2d shows the WDM spectra after the diversity loop with pumps On and Off for 5-dB, 10-dB, and 13-dB gain with a total WDM-signal input power into the loop of -5 dBm. This power was used to operate the FOPA in the linear regime<sup>8</sup>. The wavelengths of the WDM channels have been selected to be within the flat range of the gain spectra. The BER performance for the amplified signals and the generated idlers were measured for the 5-channel WDM input as well as for a single-channel input (WDM center-channel). The WDM results are shown in Fig. 2e in which the average BER of the five channels is plotted as a function of the OSNR (in 0.1 nm reference bandwidth). Very small BER differences were identified between the channels. A summary of the measured OSNR penalties for both single and WDM scenarios at a BER of  $1 \times 10^{-4}$  is depicted in Fig. 2f for the selected On-Off gain values. Signal and idler show similar BER performances, demonstrating the effectiveness of the scheme for OPC operation. However, the distortion experienced in the FOPA increases with gain and is stronger in the WDM case, indicating that a limited gain of 5 dB would be more beneficial for practical implementation.

The degradation is attributed to distortions such as self phase modulation in the case of the single-channel and cross phase modulation, cross gain modulation, and inter-channel four-wave mixing in the case of WDM<sup>8</sup>. Additionally, the diversity loop operation introduces extra penalty compared to a

polarization dependent scheme<sup>8</sup> limiting the gain. Further studies are therefore required.

**Conclusion**

A polarization-independent FOPA for OPC was experimentally demonstrated at 5 dB, 10 dB, and 13 dB On-Off gain for 28-GBd PDM 16-QAM signals in a 5-channel WDM system. Signal and idler investigations showed OSNR penalties below 1 dB for both single channel and a 5-channel WDM cases at 5-dB On-Off gain and at a BER of  $1 \times 10^{-4}$ . The maximum polarization dependent gain was also measured to be below 0.5 dB across a 22.5-nm wavelength range (1542.5 nm to 1565 nm). The scheme is well suited for in-line OPC applications at 5-dB gain for gain-transparent operation with minimal penalty from the FOPA.

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