First Experimental Mach-Zehnder FOPA for Polarization- and Wavelength-Division-Multiplexed Signals

Florent Bessin [1], Vladimir Gordienko[1], Filipe M. Ferreira[2], Nick Doran[1]

[1] Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET, England,

[2] Optical Networks Group, University College London, London, WC1E 6BT, UK

bessinf@aston.ac.uk

Abstract *We demonstrate and characterize a polarization insensitive fiber optical parametric amplifier based on a Mach-Zehnder configuration using a commercial 100G PDM-QPSK transponder. A net gain >10 dB is obtained for 17 channels in C-band, 100 GHz spaced.*

Introduction

Fiber optical parametric amplifiers (FOPA) have been widely studied for a few decades due to their abilities to provide wide bandwidth gain [1], ultra-low noise figure [2] and arbitrary wavelength range operation [3]. However, one of the major issues of FOPA is their polarization dependent gain. To overcome this issue, different technics have been investigated such as half pass loop FOPA that as demonstrate great results [4]. In this configuration both polarization components of the input signal propagate in opposite direction in the FOPA loop. Thus, each polarization of the input signal can be amplified independently. Nevertheless, these signal components pass first through a loss section accumulating small nonlinear crosstalk and then through a gain section, or *vice-versa* – with stronger nonlinear crosstalk limiting the FOPA performance [5]-[6].

In this paper, we demonstrate for the first time to our knowledge a promising polarization insensitive (PI-)FOPA based on a Mach-Zehnder (MZ) architecture that gets rid of these passive sections, inherent to half pass loop FOPA and responsible for losses and crosstalk. Indeed, in MZ configuration an input signal is first split into two single-polarization components, each one propagating in one of the two arms of the MZ (each containing an independent gain section), and finally recombined. We show in particular that we can amplify DWDM signals in C-band with a gain >10 dB, using signal amplification of 100G PDM-QPSK signals supplied by a Ciena transponder WaveLogic 3.

Experimantal setup

Figure 1 shows the in line transmission arrangement test bed that consists in a transmitter (a commercial transponder plus ASE-shaped channels), a variable optical attenuator to set input power, our PI-FOPA and a receiver.

The PI-FOPA is based on Mach-Zehnder interferometer architecture. The signal is firstly guided through a polarisation beam splitter (PBS1) that separates input signal into two single polarization components ($Signal_{X/Y}$). Each component then undergoes a gain section of highly nonlinear fiber ($HNLF_{X/Y}$, respectively)

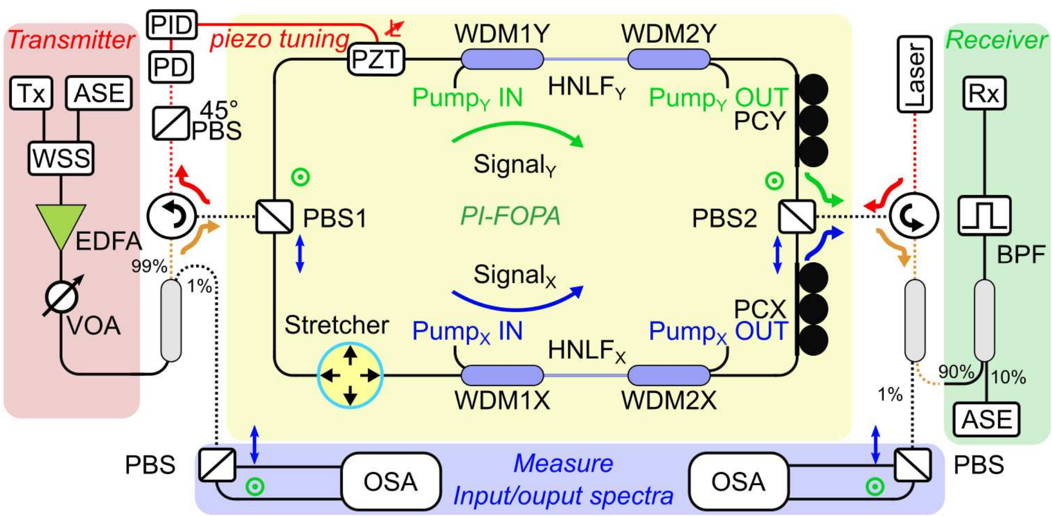

Fig. 1: Experimental setup of a polarization insensitive Mach-Zehnder FOPA. OSA: optical spectrum analyzer; PD, photodetector; PBS, polarization beam splitter; PID, proportional-integrate-derivative; ASE, amplified spontaneous emission; PZT, piezo-electric acuator; HNLF, highly nonlinear fiber; EDFA, erbium doped fiber; VOA, variable optical attenuator.

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provided coupling with a 34.5 dBm and 34.2 dBm co-propagating pump, for $Signal_{X/Y}$ respectively ($Pump_{X/Y}$, respectively). Each HNLF length is 100m long with zero-dispersion wavelength of ~1551nm and nonlinearity coefficient of ~14 $W^{-1}.km^{-1}$. Coupling of pumps and signals into HNLFs are performed by 200 GHz-wide wavelength division multiplexing filters ($WDM1_{X/Y}$) centered at 1553.33 nm. In the same way, we use at the output of HNLFs $WDM2_{X/Y}$ to remove pumps. $Pump_{X/Y}$ are obtained from a 100 kHz-linewidth tuneable laser source set to λ_p=1553.38 nm and phase modulated to mitigate stimulated Brillouin scattering in the HNLF – high power is achieved using two erbium doped fiber amplifiers ($EDFA_{X/Y}$) after a 50/50 splitter. Electronically addressable polarization controllers are used to align the pump and signal field polarizations to maximize the coupling efficiency. Finally, signal components are recombined by PBS2. We added in each arm a polarization controller (PCX and PCY) used to align $Signal_{X/Y}$ with PBS2 polarization axis for an efficient recombination.

An optical path difference between arms may cause a delay between $Signal_{X/Y}$ at the output of MZ-FOPA and leads to signal distortion. To match the optical paths, we cut-back fiber from the longer MZ arm to a precision of a few centimeters. A mechanical stretcher embedded in arm-X allows to finely tune its length and match the optical paths between both arms. Due to the interferometric nature of this device, this system is extremely sensitive to external perturbations such as a change in pressure or temperature that induces variations of length between arms. To overcome this issue we added circulators at each sides of MZ-FOPA similar to Ref. [7] allowing us to use independently both direction of propagation. While data signal propagates from left to right, a reference signal at λ_{ref}=1567 nm propagates in the other direction. This reference signal, also affected by external perturbations, passes through a PBS with polarization axis at 45 ° from those of PBS1. This arrangement ensures to observe the interference behavior of the reference signal with a high visibility via a photodetector. Then, we use this detected signal as an error signal for a feedback loop system (proportional integrate derivative) that drives a piezo-electric fiber stretcher embedded in arm-Y and compensate for length fluctuations.

The optical transmitter of the test bed consisted of 17x 100 GHz spaced channels in a wavelength range of 1528.0-1540.56 nm. The channel at 1534.25 nm was a 100G PDM-QPSK signal sourced from a Ciena transponder WaveLogic 3. Other channels were emulated copies of the transponder sourced from amplified spontaneous emission (ASE) shaped by a wavelength selective switch (WSS). A VOA after transmitter was used to sweep power per channel between -27 dBm and 0 dBm.

The receiver coupled broadband ASE with signal via a 90/10 coupler allowing to sweep OSNR, and selected the 100G channel using a band-pass filter (BPF). This filtered channel was then coherently detected by a Ciena transponder WaveLogic 3.

Note that in order to measure input and ouput spectra of both signal polarization components, cirulators and third ports of PBS1 and PBS2 are made of polarization maintening (PM) fibers (dotted lines in Fig. 1). Thus, adding 99/1 PM tap couplers before and after FOPA, we can obtain these spectra through 1% ports thanks to PBS.

Experimental Results

Figure 2 (a) and (b) show the FOPA input and ouput DWDM spectra for X and Y signal polarization components respectively, when power per channel was set to -23 dBm at FOPA input and we observed a power per channel >-12 dBm at FOPA output. We also noted a residual pump power (not shown here) of about 10 dBm which was not detrimental in our experiment since it was filtered before receiver by the BPF tuned to the 100G channel wavelength.

Figure 3 depicts the net gain for each channel

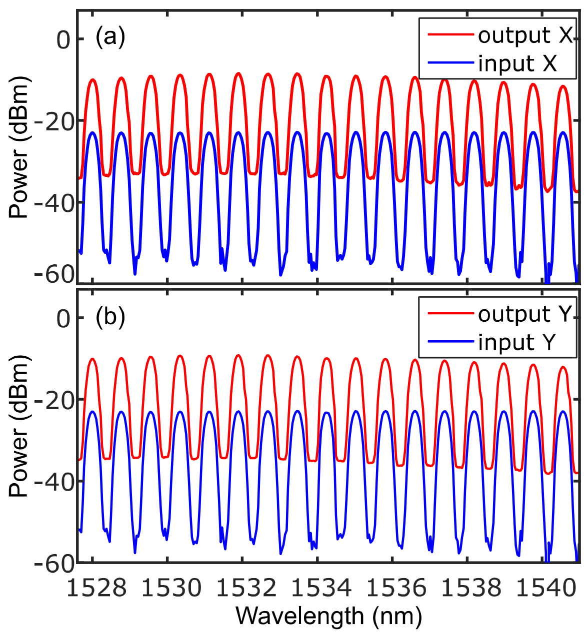

Fig. 2: The blue and red curves depict the signal input and output power for X and Y polarization components in (a) and (b), respectively.

in blue and red for X and Y components, respectively. The net gain for polarization components for the 100G channel at 1534.25 nm is about 12.6 dB and in a range of 10.5 and 13.3 dB for other channels. The black dots in Fig. 3 correspond to the polarization dependent gain (PDG) of each channel. It is about 0.01 dB for 100G channel and in a range of ±0.5 dB for other channels.

In Fig. 4, we display the bit error rate as

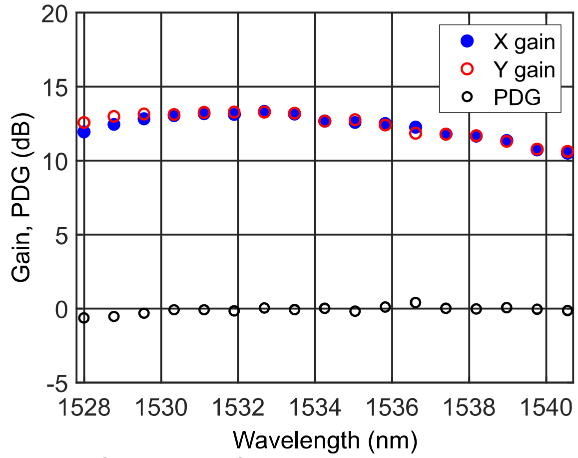

Fig. 3: FOPA net gain for each channel. The blue and red circles depict net gain of X and Y signal polarization components, respectively. The black circles depict the polarization dependence gain for each channel.

function of the optical power at the receiver for the 100G channel. These results show promising results with a BER of 10^{-8} for a received power of -3 dBm. We also note for a fixed received BER of 10^{-3}, that penalty on the receiver sensitivity is about 1.9 dB.

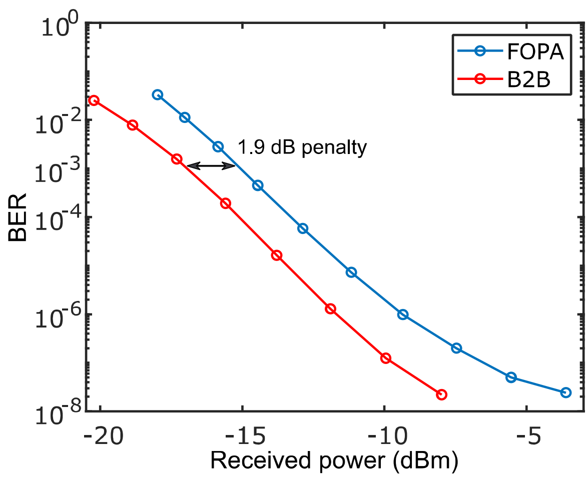

Fig. 4: Bit error rate versus received power. The red curve stands for back to back measurements and the blue curve for FOPA measurements.

Conclusions

We provide the first experimental demonstration of a PI-FOPA based on a Mach-Zehnder configuration to amplify 100G PDM-QPSK signal. We obtained a net gain >10 dB for both signal polarization components for emulated DWDM from 1528.0 to 1540.56 nm. These results provide a proof of concept of such amplifier architecture and open the way to future improvement about crosstalk and losses in FOPA.

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