# Mach-Zehnder FOPA for Dual Polarization Wavelength-Division-Multiplexed 100G Signal Amplification

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**Abstract:** We demonstrate amplification of 17x100 GHz-spaced channel in C-band by a PI-FOPA based on Mach-Zehnder architecture with net gain >10 dB and confirmed its robustness over time. A commercial 100G-PDM-QPSK transponder was used to measure/compare the bit-error-rate versus received power with a commercial EDFA. 

## 1. Introduction

These last 30 years, fiber optical parametric amplifiers (FOPA) have attracted a lot of attention due to their abilities to provide high gain, ultra-low noise figure [1], wide bandwidth flat gain, and arbitrary wavelength range operation [2]. Although its potential for next generation of optical communication amplifier is undoubted, practical applications of FOPA remain an issue due to their polarization dependent gain (PDG). Different approaches have been investigated to overcome this issue, like the half-pass-loop FOPA (HL-FOPA) [3], were both polarization components of the input signal propagate and are amplified independently in opposite direction. However, in such a design the signal polarization components pass through a gain section and then a loss section accumulating a strong nonlinear crosstalk or *vice-versa*, resulting in an increasing of the noise figure [4].

In this paper, we developed a polarization insensitive (PI)-FOPA based on Mach-Zehnder (MZ) architecture that gets rid of these loss sections leading to noise figure and/or nonlinear crosstalk degradation. Indeed, in such a disposal, input signal is split into two single-polarization components, each one propagating and being amplified independently in one of the two MZ arms and then recombined. We characterized this amplifier with a 100G PDM-QPSK signal and neighboring DWDM channels in C-band and measured the net gain and bit-error rate.

## 2. Experimental setup

Figure 1 shows our experimental setup. This is an in-line transmission arrangement test bed with a transmitter (blue box), our MZ PI-FOPA (yellow box), a receiver (red box) and a gain measurement setup (green box).

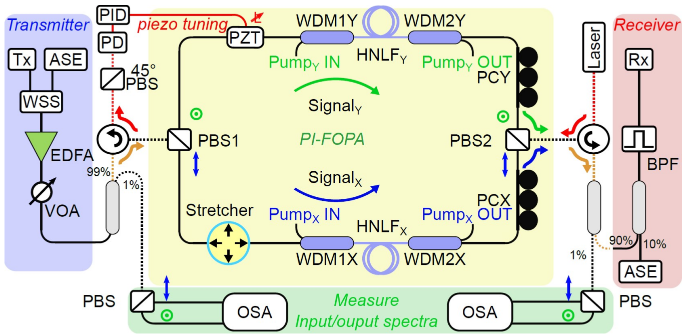


Fig. 1. Experimental setup.

The PI-FOPA was built on a Mach-Zehnder configuration. The input signal to amplify first goes through a polarization beam splitter (PBS1), splitting the signal into two single polarization components. Then, each polarization component was amplified through a four-wave mixing (FWM) process between the signal polarization component and a co-propagating pump ($\lambda$p=1553.33 nm, coupled and decoupled *via* wavelength-division-multiplexing filters, $WDM_{X/Y}$) in a highly nonlinear fiber (HNLF) of about 100 m ($\lambda_{ZDW}$~1551 nm, $\gamma$~14 $W^{-1}.km^{-1}$). Finally, both amplified polarization components were efficiently recombined *via* a second polarization beam splitter (PBS2) and polarization controllers ($PC_{X/Y}$).

Unlike HL-FOPA, delay between polarization components may occur at the output of MZ-FOPA because of optical path differences between MZ arms. To prevent this effect leading to signal distortions, we cut/added pieces of fiber in the longest/shortest arm with a precision of few centimeters and then embedded in the shortest arm a fiber stretcher to match the length between arms very accurately. Since external perturbations can modify the optical path between arms, we also developed an active system similar to Ref. [5] to compensate these variations of length.

The transmitter (Tx) was a commercial Ciena transponder Wavelogic 3 providing a 100G PM-QPSK signal at 1534.25 nm. Sixteen 100 GHz-spaced neighboring DWDM channels, copies of the transponder, were emulated and combined with the Tx data by shaping a broadband amplified spontaneous emission (ASE) source with a programmable filter (WSS). An EDFA and a variable optical attenuator (VOA) were used to tune the Rx power (received power) per channel between ~ -28 and -4 dBm.

The receiver coupled the DWDM channels amplified with a broadband ASE *via* a 90/10 coupler to tune the optical signal noise ratio. A band-pass filter (BPF) was used to get rid of residual pump power and emulated channels. The remaining transponder signal was then coherently detected by the Ciena transponder Wavelogic 3.

Note that dotted lines in Fig. 1 correspond to polarization maintaining fiber (PM), thus adding 99:1 PM tap couplers and PBSs at FOPA input/output we were able to record input and output spectra with an optical spectrum analyzer (OSA) and calculate the net gain for each polarization component.

## 3. Results

Figure 2(a-b) show the input/output optical power spectra (red/blue curves, respectively) for the X/Y signal polarization components, respectively. The power per channel was set to -23 dBm at the FOPA input and amplified

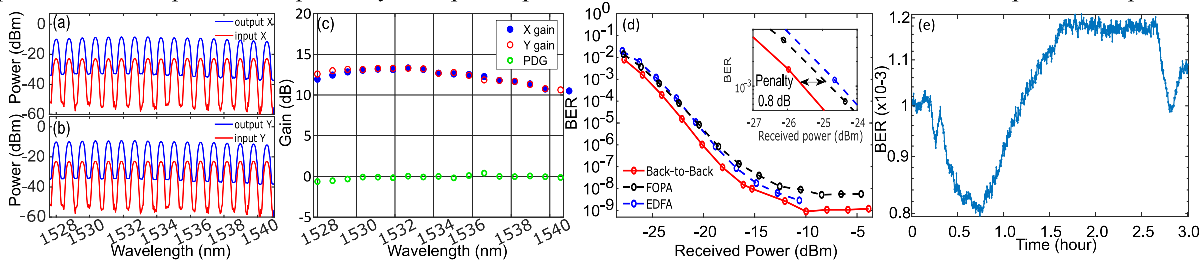


Fig. 2. (a)-(b) Signal input (red curves) and output (blue curves) power spectra for X/Y polarization components, respectively. (c) Net gain (blue and red dots) and PDG for each channel (blue dots). (d) BER vs received power. The red, blue and green curves stand for back-to back, FOPA and EDFA measurements. (e) BER vs time.

up to -8.6 dBm at the FOPA output. Figure 2(c) shows the net gain for each channel for X/Y polarization components, respectively (blue/red dots). A gain per channel >10 dB was obtained with a polarization dependent gain <1 dB (see green dots in Fig. 2(c)). Figure 2(d) depicts the BER vs Rx power. The red and black dots correspond to the back-to-back measurements and to measurements obtained with our in-line FOPA, respectively. We note a low BER of $10^{-8}$ at a Rx power >-10 dBm and a power penalty ~0.8 dB at a fixed BER of $10^{-3}$ (see thumbnail in Fig. 2(d)). This measurement are similar to performances of a commercial EDFA (blue dots in Fig. 2(d)) providing the same gain. At higher receiver power, the EDFA shows better performances in terms of BER but it is still of the same order than measurements obtained with our FOPA.

Finally, we investigate the reliability of this system with time by studying the stability of the BER for a given Rx power of -25 dBm. These results are depicted in Fig. 2(e) and show a low BER fluctuations <$0.4 \times 10^{-3}$ over three hours showing that this system is quite stable.

## 4. Conclusion

We gave a first proof of concept that PI-FOPA based on a Mach-Zehnder configuration can be used to amplify 100G PDM-QPSK signals in a DWDM arrangement in C-band with a net gain >10 dB and low PDG (<1 dB). Our MZ FOPA shows performances similar to commercial EDFA in terms of BER. Finally, measurements of the BER fluctuations <$0.4 \times 10^{-3}$ over 3 hours demonstrate the reliability/stability of such an amplifier for longtime use.


## 5. Acknowledgment

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