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# Demonstration of Cascaded In-Line Single-Pump Fiber Optical Parametric Amplifiers in Recirculating Loop Transmission

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**Abstract** The performance of cascaded single-pump fiber optical parametric amplifiers (FOPAs) is experimentally studied for the first time using recirculating loop transmission with 80-km dispersion managed spans. Error-free performance has been achieved over 320 km for 40-Gbit/s CSRZ-OOK and CSRZ-DPSK modulated signals.

## Introduction

Fiber optical parametric amplifiers (FOPAs) are a promising choice for amplification of data signals outside the erbium-doped fiber amplifiers (EDFAs) band in long-distance optical transmission systems. The gain of FOPAs depends on pump power, fiber nonlinearity and fiber dispersion properties, and can therefore be tailored with respect to the wavelength configuration of the interacting waves and be centered at about any arbitrary wavelength<sup>1</sup>. Other unique aspects of FOPAs, such as the possibility for regeneration using gain saturation and frequency conversion make them even more attractive for multi-functional applications<sup>2,3</sup>. Until now, FOPAs have been mostly used as stand-alone amplifiers or all-optical signal processing elements, and only recently have studies on the implementation of these amplifiers in transmission links been under focus<sup>4-6</sup>. In Ref. 4 the performance of single-pump FOPAs in dense wavelength-division multiplexed systems was investigated using a recirculating loop with the FOPA actually

used outside of the loop, either as a booster amplifier or at the end of the transmission line. In Ref. 6, the reduction of nonlinear phase noise by an all-optical amplitude limiter using saturation of four-wave mixing in a fiber has been investigated in a recirculating loop transmission. However no gain was provided to the signal in the parametric amplitude regenerator. The use of FOPAs as in-line amplifiers in a multi-span link has, to the best of our knowledge, never been reported so far.

In this paper, we have experimentally investigated for the first time the performance of cascaded single-pump FOPAs using a multi-span recirculating loop transmission where a FOPA with 20 dB on-off gain is located in the transmission line. The cascadability of the FOPA is demonstrated for 40-Gbit/s carrier-suppressed return-to-zero (CSRZ) on-off keying (CSRZ-OOK) and CSRZ differential-phase shift keying (CSRZ-DPSK) modulated signals. Error-free performance is achieved for both modulation formats over a 320 km dispersion managed link, thus demonstrating a first step towards the

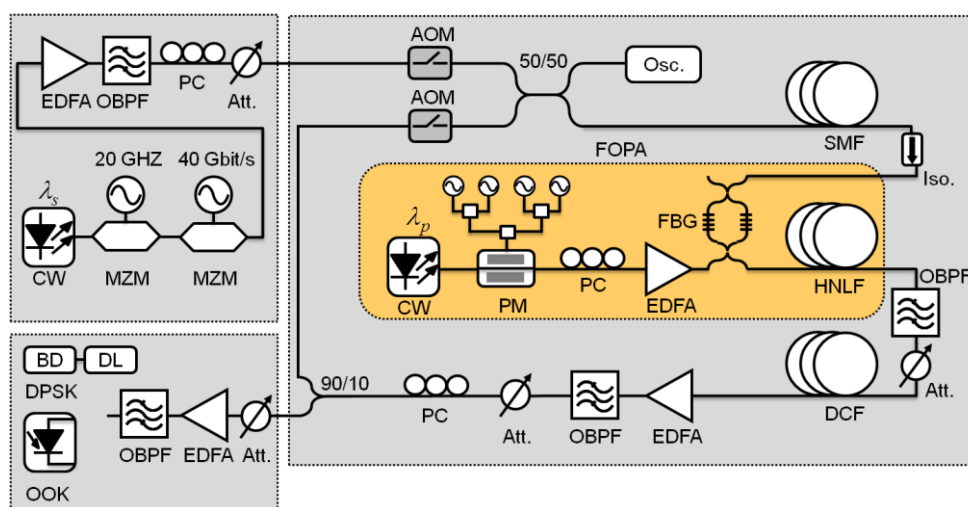


Fig. 1: Experimental setup

implementation of FOPAs as in-line amplifiers.

### Experimental setup

The experimental setup is shown in Fig. 1. A recirculating loop is used to realize the cascading investigation of FOPAs. At the transmitter, a 67% RZ-OOK or RZ-DPSK signal is generated from a continuous wave (CW) laser at 1545 nm using cascaded Mach-Zehnder modulators (MZMs) used as pulse carver and data modulator, respectively. The data modulator is driven with a  $2^{31}-1$  pseudo-random binary sequence (PRBS) at 40 Gbit/s. The modulation format is selected by adjusting the bias and peak-to-peak voltage applied to the data modulator. The modulated signal is then amplified by an EDFA followed by an optical bandpass filter (OBPF) with 3 nm bandwidth and its power at the loop input is adjusted by an optical variable attenuator (OVA).

The circulations in the loop are controlled by two acousto-optic modulators (AOMs). Data is continuously sent, via a 90/10% coupler, to the receiver. Gating of the bit-error ratio (BER) test-set and the oscilloscope enable the characterization of the signal after the last round-trip in the loop. The transmission link consists of an 80-km long standard single-mode fiber (SSMF) and a matching length of 13 km dispersion compensating fiber (DCF).

The FOPA, placed between the SSMF and the DCF, is realized by combining the signal with a CW pump that has been phase modulated with four radio-frequency (RF) tones of frequencies 111 MHz, 675 MHz, 1 GHz and 2.25 GHz for stimulated Brillouin scattering (SBS) mitigation, before being amplified by a high-power EDFA. The pump and signal are combined in a Mach-Zehnder interferometer add/drop multiplexer with fiber Bragg gratings (FBGs) reflective at the pump wavelength in each arm. This solution enables to simultaneously achieve less than 1 dB coupling loss for the transmitted signal/reflected pump and to filter the out-of-band amplified

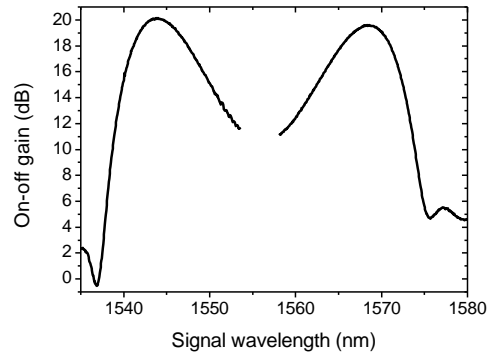


Fig. 2: Measured on-off signal gain spectrum.

spontaneous emission noise from the pump. The parametric amplification, with 20-dB on-off small signal gain at 1545 nm, takes place in a 500-m long highly nonlinear fiber (HNLf) with zero-dispersion wavelength at 1550.4 nm, nonlinear coefficient of  $10.7 \text{ W}^{-1} \cdot \text{km}^{-1}$ , dispersion slope of  $0.0185 \text{ ps}/(\text{nm}^2 \cdot \text{km})$ , and attenuation of  $0.7 \text{ dB}/\text{km}$ . The pump and signal power at the HNLf input are 28 dBm and -18 dBm, respectively. The measured on-off gain of the FOPA is represented in Fig. 2. The amplified signal is then filtered out by two cascaded thin-film OBPFs with 3-nm and 5-nm bandwidths in order to sufficiently suppress the pump. An EDFA with 28-dB gain and 15-dBm saturated output power is used after the DCF in order to compensate the loss of the rest of the elements in the loop, such as filters, loop switch and couplers. Finally the power in the loop is balanced with an OVA.

The FOPA design used in the present demonstration is polarization sensitive. Therefore it is ensured that a stable principal state of polarization is found for the recirculating loop thanks to polarization controllers (PCs) placed before the loop switch. Polarization matching between the signal and pump is ensured in order to provide maximum parametric gain. This is achieved thanks to another PC placed in the pump path within the FOPA. The receiver consists of an EDFA preamplifier, and a photodiode with 45-GHz bandwidth in the case of OOK, or a 1-bit fiber

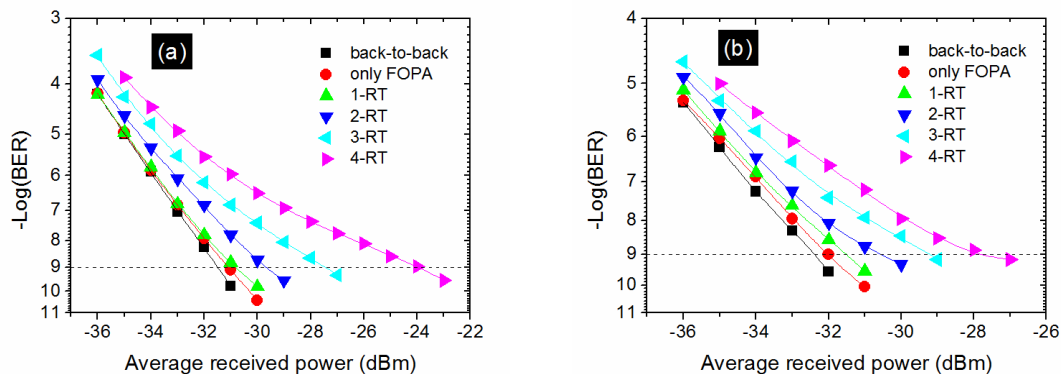
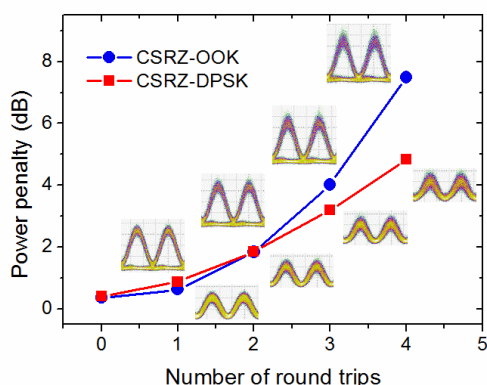


Fig. 3: BER characteristics of 40-Gbit/s CSRZ-OOK (a) and CSRZ-DPSK (b).



**Fig. 4:** Power penalty as a function of number of round trips and corresponding eye diagrams for 40-Gbit/s CSRZ-OOK and CSRZ-DPSK signals.

delay interferometer (DI) followed by a balanced detector (BD), also with 45-GHz bandwidth, for DPSK. A loop-compatible clock recovery circuit is also employed at the receiver.

### Experimental results

The performance of the cascaded FOPA is studied for CSRZ-OOK and CSRZ-DPSK modulation at 40 Gbit/s. The optimized average signal power at the input of the SSMF and DCF are 1.4 dBm and -5 dBm, respectively.

BER measurements are carried out as a function of the average received power. The BER performance of the cascaded FOPA for several round trips (RTs) as well as for the FOPA alone (without transmission span) is presented in Fig. 3. Error-free performance is achieved for both modulation formats up to four round trips (RTs), corresponding to 320 km transmission.

The power penalty as a function of the number of RTs has been extracted for a BER of  $10^{-9}$ , as shown in Fig. 4. The eye diagrams, taken at the input of the receiver, are also illustrated in the insets of the figure. '0' round trip corresponds to the penalty of the FOPA itself when placed between the transmitter and the receiver, which is less than 0.5 dB. When increasing the transmission distance by increasing the number of round trips, the power penalty increases while the pulse shape is well preserved, which suggests that noise accumulation is responsible for signal degradation for both modulation formats. For longer transmission distances the CSRZ-DPSK format shows a lower power penalty thanks to its well known robustness. The difference compared with the CSRZ-OOK format is 2.7 dB after 4 round trips.

### Discussion

Even though the first cascability of in-line FOPAs has been demonstrated in the reported experiment, it is clear that further practical

advances are needed to make the scheme comparable with EDFAs. Unavoidable phase modulation (PM) of the CW pump in order to suppress stimulated Brillouin scattering impacts the OOK modulated signals more than the DPSK signals. The pump PM affects the phase matching-condition, resulting in modulation of the gain. Moreover, optical filters and HNLf, as dispersive media, may transfer the pump PM into intensity modulation, which further causes signal gain variations through the pump power dependence of the gain. Efficient suppression of the pump and idler requires OBPFs with large extinction ratios to circumvent crosstalk and good cascability. Multichannel crosstalk mitigation needs to be implemented. Such effects may be negligible for well-designed single FOPAs, but are of an accumulative nature if those are cascaded as in-line amplifiers. Most importantly, polarization-independent configurations using either polarization diversity<sup>7</sup> or dual-pump FOPAs with orthogonally-polarized pumps<sup>8</sup> should be implemented to overcome polarization-induced gain changes while providing sufficient signal gain.

### Conclusion

The performance of cascaded single-pump FOPAs has been experimentally investigated for the first time using recirculating loop transmission. The feasibility of exploiting FOPAs as in-line amplifiers was investigated for 40 Gbit/s CSRZ-OOK and CSRZ-DPSK signals. Both modulation formats show error-free performance up to 320 km. The choice of CSRZ-DPSK signals allows to reduce the power penalty by 2.7 dB compared to CSRZ-OOK. Possible sources of impairments and possible ways to improve the performance of FOPAs as in-line amplifiers have also been discussed.

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