Demonstration of Polarization Muiltiplexed Signals Division Using a Fiber Optical Parametric Amplifier

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Abstract— The main goal of this paper is to demonstrate the ability of a single pump parametric amplifier with linearly polarized pumping radiation to divide orthogonally polarized optical signals, by emphasizing a signal with certain state of polarization from a combination of orthogonally polarized signals. In the implemented solution two orthogonally polarized optical signals are placed on the same wavelength, and, after being highly attenuated, processed by the parametric amplifier in such a way, that only a signal with a certain state of polarization is amplified. Such additional application of parametric amplifiers has not been demonstrated so far.

1. INTRODUCTION

Due to development of high non-linearity fibers (HNLF) and efficient stimulated Brillouin scattering (SBS) suppression techniques, in recent years fiber optical parametric amplifiers (FOPAs) have received increased attention [1]. Due to the variety of potential applications parametric amplification is positioned as the future leading technique for ultrafast all-optical signal processing in optical communication systems [1, 2]. Additionally to providing optical signal amplification, FOPAs also offer a number of applications for all-optical signal processing, such as: wavelength conversion, 2R and 3R optical signal regeneration, tunable dispersion compensation, and also binary polarization shift keying (2PolSK) to intensity on-off keying (OOK) modulation format conversion [3–5].

The ability to ensure 2PolSK to OOK modulation format conversion is based on the high polarization dependency of the FOPA provided gain. This application requires to use linearly polarized pumping radiation, the state of polarization (SOP) of which should coincide with the SOP of the logical “1” component of the binary PolSK signal. In this case the logical “1” component will receive maximal amplification, and the orthogonally polarized logical “0” will not get amplified [5]. This feature of parametric amplifiers can also be used to ensure one more additional application: division of polarization multiplexed optical signals. Such additional application of parametric amplifiers can be very promising, as potentially it can lead to doubling of spectral efficiency in systems, where FOPAs are used for optical signal amplification.

The main goal of this article is to investigate the ability of FOPAs with linearly polarized pumping radiation to ensure division of two polarization multiplexed signals, placed on the same wavelength, by emphasizing the signal with a certain state of polarization from the overall optical flow.

2. SIMULATION MODEL

For investigation of the ability of the FOPA to emphasize a signal with a certain state of polarization, a simulation model of a 9.953 Gbit/s two channel optical transmission system with non-return to zero (NRZ) encoding technique and OOK modulation format was introduced. This simulation model is shown in Fig. 1. OptSim 5.3 simulation software was chosen as the experimental environment. Previous studies show that results obtained using OptSim simulation software have high correlation with results obtained in a real life experiment [6].

In the transmitter block the radiation of the continuous wave (CW) optical laser is externally modulated via a Mach-Zehnder Modulator, which in its turn is driven by a sequence of NRZ coded electrical pulses that are produced by a tandem of a logical data source and an NRZ coder. For each channel the optical power of the CW laser is 1 mW (0 dBm). Both channels were placed on the same carrier frequency: 196.5 THz (wavelength: 1554.537 nm), corresponding to the wavelength of the S optical band. To ensure that the channels are orthogonally polarized, at each channel the produced NRZ-OOK optical signal passes through an optical polarizer with the same state of polarization, and afterwards the polarized signal from the 2nd channel is processed by a polarization rotator. The state of polarization of the 2nd channel is turned in such a way obtaining such SOP that is orthogonal to the SOP of the signal in the 1st channel.

Afterwards both signals are combined and processed through an optical attenuator with optical signal attenuation of 36 dB. This optical attenuator is used to represent a 150 km long standard

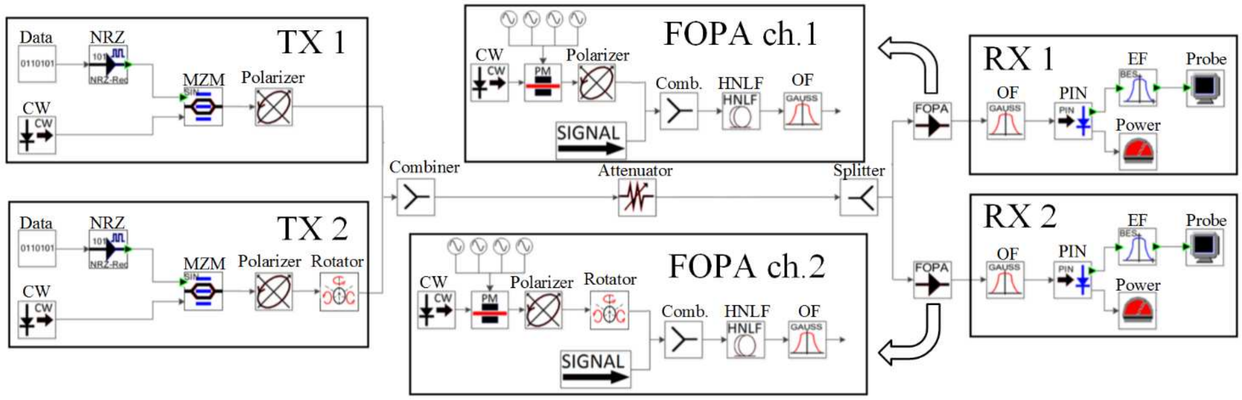


Figure 1: Simulation model of the two channel optical transmission system with FOPA for division and amplification of polarization multiplexed signals.

single mode fiber with attenuation of 0.2 dB/km, and to allocate a 6 dB margin, as it is advised to do during the design process of optical transmission systems [7]. Afterwards the signal is divided among two branches of the transmission system. Each branch represents a receiver block, containing a parametric preamplifier and two receivers: one for the signal at carrier frequency, and one for detection of the generated idler spectral component.

In each branch the FOPA consists of the following mainelements: an optical combiner (to combine the signal with the pump), a 1 kilometer long HNLF (the medium where amplification takes place), and a powerful CW optical laser, that represents the source of the pumping radiation. Parameters of the HNLF can be observed in Table 1.

Table 1: HNLF parameters [8].

Attenuation at 1550 nm, dB/km	0.96
Zero dispersion wavelength, nm	1553.35
Fiber non-linearity coefficient, $(\mathrm{W}\cdot\mathrm{km})^{-1}$	15
Core effective area, $\mu\mathrm{m}^2$	10

The pumping radiation, produced by the CW laser is phase modulated, to broaden its spectrum, and therefore suppress the unwanted impact of stimulated Brillouin scattering; and processed via an optical polarizer, to ensure that the SOP of the pump coincides with the SOP of the corresponding channel. For the same reason, in the case of the 2nd channel the polarized pumping radiation is also sent through a polarization rotator. The power and the wavelength was configured in a way to obtain such configuration of the amplifier that would ensure bit error rate (BER) below $1\cdot 10^{-12}$ mark, using as less pumping power as possible. To do so it was required for the peak of the gain spectrum to coincide with the frequency of the amplified channel.

At the output of the FOPA the combination of the amplified signal, the pump and the generated idler spectral component is divided among 2 via an optical splitter. At the input of each receiver this combination is processed via a cascade of two bandpass optical filters. It was required to implement double filtering because the extinction ratio of real life optical filters is not enough to filter out the powerful pumping radiation.

3. RESULTS AND DISCUSSIONS

The aim of this section is to analyze the results obtained while configuring the parameters of the amplifier for each of the two receiver blocks, and implement such amplifier configuration that would efficiently emphasize optical signal with a certain state of polarization from the overall optical flow, simultaneously ensuring the required quality of the emphasized signal.

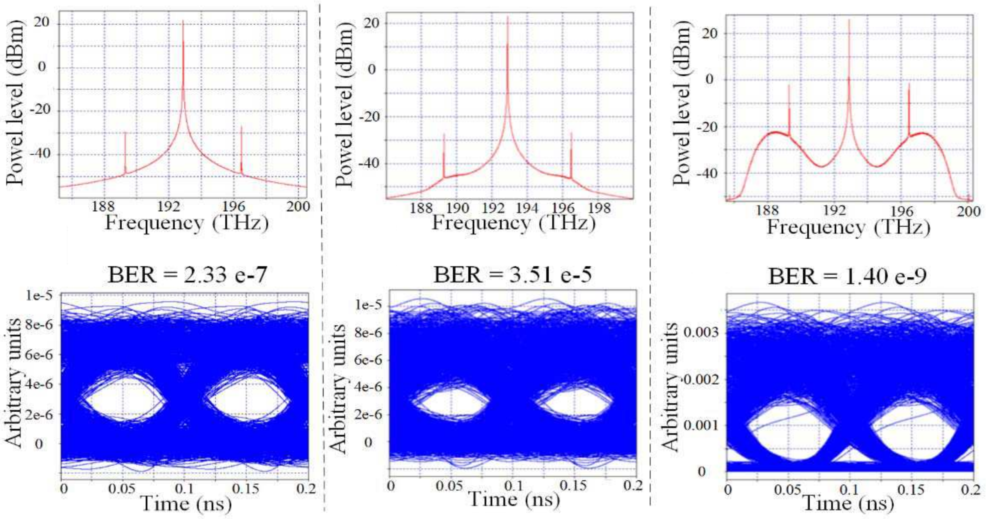
To meet the proposed requirement for efficient division of polarization multiplexed signals using as low pumping power as possible, simultaneously maintaining BER values below the 10^{-12} mark, it was required to configure the amplifier in such a way, that the peak of the gain spectrum would coincide with the frequency of the channel to be amplified. Due to the fact that the process of parametric amplification is highly dependent on the phase mismatch between the interacting optical fields, it is required to take into account not only the linear phase mismatch that occurs due to fiber dispersion, but also the non-linear phase mismatch that occurs as the consequence of such nonlinear effects as self-phase modulation (SPM) and cross-phase modulation (XPM). Therefore, while adjusting the power of the pumping radiation one must also simultaneously shift the wavelength of the pump in order to maintain the peak of the provided gain spectrum at the desired frequency.

But before seeking for the exact power and wavelength of the pumping radiation, it was required to configure the phase modulation of the pump in order to mitigate the unwanted impact of SBS. The first estimation Pump power and wavelength were chosen to be 550 mW and 1554.1 nm respectively. It was found that the highest optical gain and least amplified signal discrepancies were observed when the pump was phase modulated by four radio frequency tones of 0.13 GHz, 0.42 GHz, 1.087 GHz and 1.94 GHz.

On one hand the usage of phase modulation has decreased the power of the pumping radiation at the input of the HNLF, but on the other hand, this has significantly increased the maximal power of the pump, that could be launched into the HNLF without causing dramatic degradation of amplified signal quality. Eye diagrams of the detected signal and optical spectrum at the output of the FOPA with and without phase modulation of the pump are shown in Fig. 2. As can be seen in Fig. 2(a) and Fig. 2(b) when no action is performed for SBS mitigation even at low amplified signal power the amount of SBS produced signal discrepancies (the elevation of optical spectrum in Fig. 2(b) and Fig. 2(c) is enough to increase BER by at least two orders. If the pump power was 550 mW at the input of the HNLF (without the 3 dB attenuation, caused by phase modulation) even a -1.31 dBm optical signal isn't enough to insure BER below the 10^{-12} mark. It is clear that the peak of amplification is shifted from the desired value (elevation of spectrum in Fig. 2(c) and the obtained level of amplification is not high enough (BER value in Fig. 2(a), so the amplifier needs to be reconfigured. Therefore it was required to obtain the values of the power and wavelength of the pumping radiation, which would match the condition, mentioned at the beginning of this section. For this purpose the dependence of BER values of detected signal on the power of the pumping radiation was obtained (see Fig. 3(a).

In Fig. 3(a) it can be seen that for channel 2 BER values below 10^{-12} mark can be obtained at a slightly lower pump power than for channel 1. This might be related to polarization mode dispersion (PMD) that occurred in the HNLF. PMD caused additional phase mismatch between signal in channel 1 and the pump, therefore the level of amplification was slightly decreased.

Based on the results shown in Fig. 3 it was decided that 530 mW 1553.9 nm pumping radiation should be used. Eye diagrams of the detected signal at carrier frequencies in both receiver blocks



(a) (b) (c)

Figure 2: Optical spectrum at the output of the FOPA (to the left) and eye diagram of the detected signal in channel 2 at carrier frequency in the system (a) with pump phase modulation, (b) without pump phase modulation but with the same pump power at the input of the HNLF, (c) and without phase modulation with 550 mW pump power.

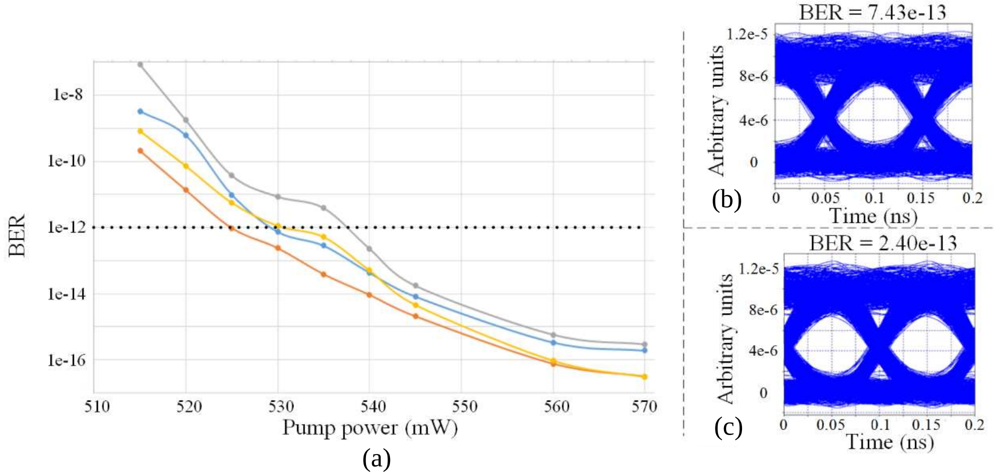


Figure 3: Dependence of BER values of the detected signal on the (a) pumping power of the amplifier at carrier frequencies in the 1st channel (blue), in the 2nd channel (red) and idler frequencies in the 1st channel (grey) and in the second channel (yellow); (b) and eye diagrams of the detected signal at carrier frequency at 530 mW pumping power in the 1st channel and (c) in the 2nd channel.

of the system with the chosen configuration are available in Fig. 3(b) and Fig. 3(c). Fig. 3(b) and Fig. 3(c) also show that even though the signal covered only 1 km of HNLF fiber, the transactions between the logical "1" and the logical "0" were broadened. This, in the absence of high amount of cumulated dispersion, clearly indicates that the signal was influenced by SPM and XPM. Gain spectrum that is provided by the chosen FOPA configuration can be observed in Fig. 4. Due to the fact that gain spectra in both branches were very alike, it was decided to show only the gain spectrum for the 1st channel.

It can be seen from Fig. 4 that the peak of amplification directly coincides with the frequency of the signal to be amplified. On-off gain of 19.95 dB and 20.05 dB was obtained for the 1st and the 2nd channel respectively. The power level of the idler spectral components at the output of the FOPA was about 0.7 dB lover than at carrier frequency. This explains why higher pumping power was required to ensure the desired quality of the signal at idler frequencies (Fig. 3(a)). To assess the produced signal distortions that occurred during the process of amplification, the power of the amplified signal that was required to ensure a certain BER value was compared to an ideal single channel NRZ-OOK system where no amplification is used. The obtained results are shown in Fig. 5.

Figure 5 shows that there is 0.75 dB of power penalty between the signal at carrier frequency and the ideal system. However, for the idler channel this penalty is just under 0.5 dB. This can

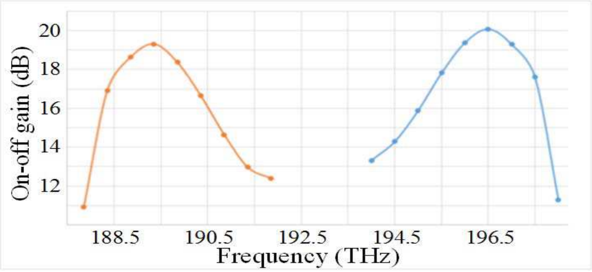


Figure 4: FOPA provided on-off gain at carrier (blue) and idler (orange) frequencies.

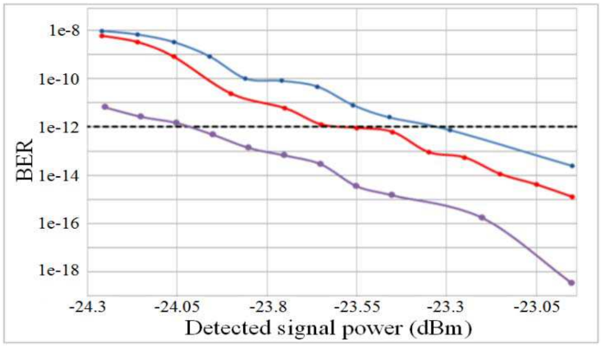


Figure 5: BER value dependence on the power of the detected signal in the ideal OOK system (violet) and in the 1st channel of the system with the chosen FOPA configuration at carrier (blue) and idler (red) frequencies in the system with modulation format conversion.

be explained by the fact that for each channel the orthogonally polarized spectral component was not involved in the process of parametric amplification and wavelength conversion, and, therefore, was not replicated in the idler. But this orthogonal spectral component, which in this case is interpreted as noise, still exists at carrier frequency, and therefore slightly influences the BER value of the detected signal.

4. CONCLUSIONS

In this article the authors have demonstrated the ability of FOPAs to efficiently emphasize a signal with a certain state of polarization, and, therefore, can be successfully used for division of polarization multiplexed signals. It was also shown that phase modulation of the pumping radiation can be successfully implemented to mitigate SBS also in cases where the pump of the FOPA is linearly polarized. In our case this has helped to gain about 2 orders of BER, even though at that time the configuration of the amplifier was not optimal.

It was found that even though signals in both channels were exactly in the same conditions, the difference in amplification has reached 0.1 dB. This can be related to fiber PMD that produced slight phase mismatch between the signal in channel 1 and the pump and, therefore, has caused slight decrease of amplification in comparison with channel 2. Due to the broadened transactions between the logical "1" and logical "0 levels", it was concluded that the emphasized signal has experienced influence of SMP and XPM. The thick logical "1" level in eye diagrams of the detected signal shows that optical noise also was produced during the process of amplification. The increase of the amount of this noise and the growing impact of SPM and XPM have decreased the progress of lowering BER values while increasing the pump power in Fig. 3(a).

It was found that power penalty of 0.75 dB exists between the provided solution and an ideal NRZ-OOK system. For the idler this penalty was by 0.25 dB lower, due to the fact that the orthogonally polarized component was not involved in the process of parametric amplification and, therefore, was not transferred to the idler spectral component.

ACKNOWLEDGMENT

This research has been supported by the European Social Fund within the project No. 2013/0008/1D P/1.1.1.2.0/13/APIA/VIAA/016.

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