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Investigation of Dual-Pump FOPA Performance in a 4-Channel 40 Gbps WDM Transmission System

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***Abstract*—Fiber-optical parametric amplifiers (FOPA) are positioned as the future leading technique for optical signal amplification. This type of amplifiers is highly appreciated due to their applications in all-optical signal processing. Signal amplification can be achieved using single-pump or dual-pump pumping schemes. Dual-pump FOPAs provide smoother gain over wider bandwidth than single-pump FOPAs, but it is harder to maintain high performance of dual-pump FOPAs due to the stimulated Raman scattering (SRS) induced energy transfer from one pump to another. In this paper the authors investigate the performance of a dual-pump FOPA under the influence of SRS in order to ensure higher gain using as low pump power as possible in a 4-channel 40 Gbps wavelength-division multiplexed transmission system.**

***Index Terms*—Fiber optical parametric amplifiers; four wave mixing; wavelength division multiplexing; stimulated Raman scattering.**

I. INTRODUCTION

Under the influence of the continuous development of multimedia services and their all-time growing availability, the demand for higher transmission system throughput has increased rapidly during the last two decades. According to the later Cisco Visual Networking Index (VNI) forecast, global IP traffic will reach 2.3 ZB per year, or 194 EB per month by the end of 2020 [1]. This trend has resulted in rapid development of fiber optical transmission systems with wavelength division multiplexing (WDM).

One of the possibilities to increase the total throughput of an optical WDM transmission system is by increasing the number of channels. The commonly used type of amplifiers in such systems is erbium-doped fiber amplifiers (EDFA), but the conventional EDFA solutions are able to operate only in C wavelength band (1530 n–1562 nm) [2]. This brings to attention the use of other amplification schemes. Even though S-band EDFA’s (1450 nm–1520 nm) and L-band EDFA’s (1570 nm–1605 nm) exist, the use of multiple EDFA’s is more complex and it can’t provide a combination of flat gain and low noise figure (NF) [3]. It is possible to achieve gain over wide bandwidth with low NF by using multi-pump Raman amplifiers [4]. Multi-pump configuration means 2 or more pumps – the number of required pumps increases together with the growth of the gain bandwidth. Contrary to Raman amplifiers, FOPAs can provide high flat gain over bandwidth of tens or hundreds of nanometers using only 2 pumps. Flat gain was achieved for over nearly 100 nm [5] in phase-insensitive mode and 170 nm in phase-sensitive mode [6]. In theory it is possible to achieve NF for FOPA as low as 3 dB in phase-insensitive mode and 0 dB in phase-sensitive mode [7]. FOPAs are mainly constructed using highly nonlinear fibers (HNLF) as gain medium and are able to operate at any wavelength, if the pump frequencies and HNLF properties such as zero dispersion wavelength (ZDWL) are chosen accordingly [8].

There are some limitations of performance of FOPAs. It is highly affected by stimulated Brillouin scattering (SBS), which limits the maximum pump power that can be used for amplification, so SBS threshold must be increased. It can be achieved by modulating the pumps phase at several fixed frequencies or over a broad range. This technique causes spectrum broadening and raises the SBS threshold [9]. Secondly, because the pumps are co-propagating with respect to the signal, the signal is affected by relative intensity noise (RIN). And finally, the gain provided by parametric amplifiers is highly polarization dependent. Polarization independent operation can be realized by using orthogonally polarized pumps [10]. Additionally, to the above mentioned factors, stimulated Raman scattering can severely impact the performance of a dual-pump FOPA. SRS induces energy transfer between the pumps. The efficiency of the four-wave-mixing is maximal when pump powers are equal, and significantly decreases together with increasing of the pump power difference [9].

The goal of this article is to investigate how the choice of pump frequency, total pump power and its initial proportion between the two pumps can affect the performance of a dual-pump FOPA under the influence of SRS. This research was performed in a 4-channel 40 Gbps WDM transmission system with binary differential phase shift keying (BDPSK) modulation.

II. SIMULATION SETUP

To achieve the above mentioned goal OptSim 5.2 simulation software was chosen. This specific simulation

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tool was chosen due to its ability to handle simulations of complex optical transmission systems without requiring powerful hardware and is in use by engineers in both academic and industrial organizations worldwide [2], [9]. To reach the goal of this research the simulation model of a WDM system with a dual-pump FOPA preamplifier was introduced. This model is displayed in Fig. 1. As can be seen in Fig. 1, it is a 39.813 Gbit/s (STM-256 without forward error correction) 4 channel WDM transmission system with non-return-to-zero encoding technique and binary differential phase-shift keying modulation format.

The centre frequencies used for transmission of the 4 channels were placed from 193.1 THz to 193.7 THz with 200 GHz channel spacing. Each transmitter consisted of an optical source with 9 dBm output power, the phase of the output radiation of which was modulated using a DPSK modulator, which in its turn was driven by a flow of non-return-to-zero (NRZ) coded electrical pulses. The output radiation of all 4 transmitters is being combined into a single optical flow using an arrayed waveguide grating (AWG) multiplexor with 3 dB insertion loss. This optical flow is sent through an optical attenuator with 23 dB insertion loss. This optical attenuator represented the insertion loss of a 100 km long standard single-mode fiber (SMF) and of a Fiber Bragg Grating. The use of the attenuator was required to exclude the impact of state of polarization changes of the signal in the SMF on the performance of the FOPA, which could lead to misinterpretation of the obtained results.

After being sent through the attenuator the optical flow enters a dual-pump FOPA. The FOPA consisted of 2 powerful optical sources, the output radiation of which was phase modulated by the following 4 frequency tones in order to mitigate SBS: 0.18 GHz, 0.42 GHz, 1.087 GHz and 2.133 GHz. These frequency tunes were chosen empirically during one of the previous researches [9]. The power and the frequency of the pumps were selected by obtaining bit-error-ratio values (BER) at the receiver end in all channels – the results are displayed in the next section.

The radiation of both pumps and of the input signal is combined and sent through a 800 meter long HNLF with 1553.35 nm zero dispersion wavelength (193 THz). This HNLF was used as the gain medium and its parameters are shown in Table I. The centre frequencies of the transmitted channels were put so close to the zero dispersion frequency of the HNLF to minimize dispersion impact on the quality of the signal.

TABLE I. HNLF PARAMETERS [11].

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

At the output of the amplifier a combination of the amplified signal, two pumps and the generated idler spectral components is obtained. The pumps are filtered out using a bandpass optical filter with 1 THz–3 dB bandwidth (8 nm) and 193.4 THz centre frequency (1550.116 nm). Afterwards, the optical flow is divided among 4 balanced receivers, each corresponding to a specific channel. It was required to implement double filtering (optical band pass filter and AWG) because the extinction ratio of real life optical filters is not enough to filter out the powerful pumping radiation.

III. RESULTS AND DISCUSSION

The main purpose of this section is to introduce and to analyse the results obtained while choosing the configuration of the dual-pump FOPA.

At first the frequencies of the two pumps need to be chosen. Because the parametric gain is extremely sensitive to any mutual phase mismatch that occurs between the interacting spectral components, the pumps need to be symmetrically placed with respect to the zero dispersion frequency (ZDF), which was equal to 193 THz (ZDWL = 1553.35 nm). If the pumps are placed symmetrically and relatively far from the ZDWL then the gain spectra of parametric amplifiers are relatively flat in its centre part, but amplification drops in the wavelength regions close to the pumps. Also the further the pumps are placed from the ZDWL the lower is the obtained gain coefficient. Therefore, it was required to select such pump frequencies that would represent the minimal spacing from the pumps to the ZDF of the HNLF, that could ensure that the signal is placed in the flat part of the gain spectrum with as high gain as possible. For this purpose the dependence of maximal BER values among all 4 channels (systems maximal BER values) on the spacing from the pumps to the ZDF of the HNLF was obtained. These results were obtained at equal pump powers and 1.3 W total pump power (650 mW each) and are shown in Fig. 2.

From Fig. 2 it can be seen that an explicit minimum of BER values is observed at 1.6 THz spacing from the pumps to the ZDF. Based on these results 191.4 THz (1566.314 nm) and 194.6 THz (1540.557 nm) frequencies were selected for the 1st and the 2nd pumps respectively. Afterwards it was required to select the power of the pumps.

Due to the presence of stimulated Raman Scattering (SRS) in the HNLF, it is possible that the optimal power distribution between the pumps may be obtained when their power is not equal. This is why it was decided at first to find such total pump power that would be capable to ensure BER values in all channels below the 10^{-12} value, and only afterwards to find the best power distribution between the two pumps. To find the preferred total pump power the power of the 2 pumps was varied from 500 mW till 850 mW and the systems maximal BER values were obtained for each pump power. The obtained dependence is displayed in Fig.3. As can be seen in Fig. 3, the minimal total pump power that could ensure BER values below the 10^{-12} threshold was 1350 mW (the power of both pumps was set to 650 mW).

After the total pump power was selected it was required to find the best power distribution between the two pumps. For this purpose the initial power of each pump was varied from 350 mW to 1050 mW in such a way that the total pump power remained 1350 mW, and systems maximal BER values were obtained for each combination of pump powers. The obtained results are shown in Fig. 4.

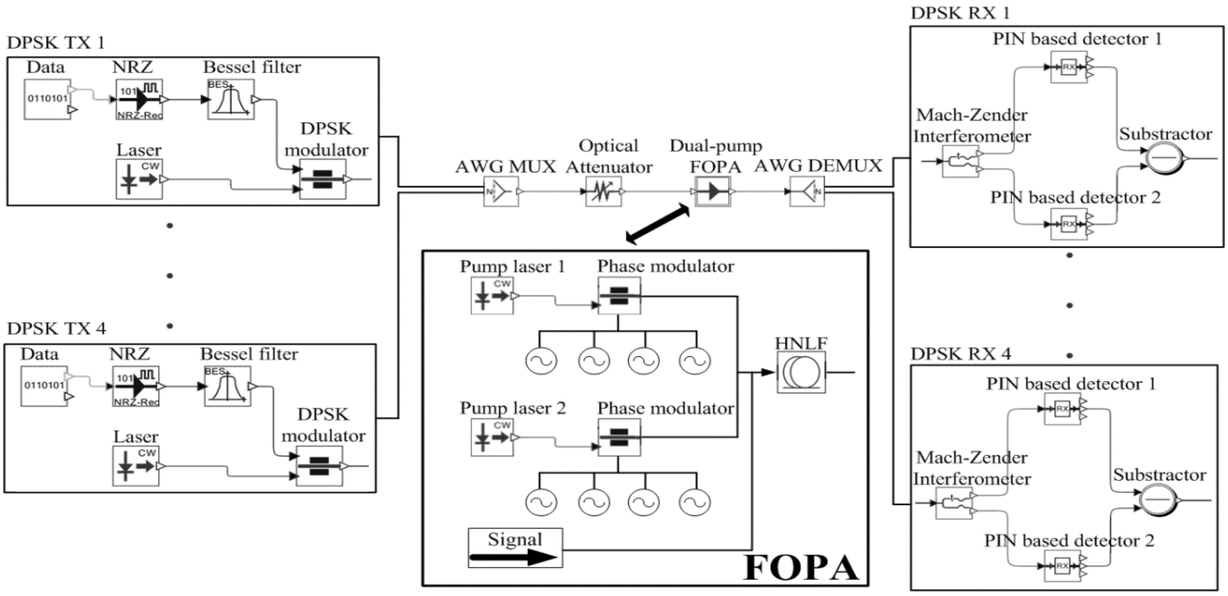

Fig. 1. Simulation model of 4-channel 40 Gbps WDM transmission system with BDPSK modulation format and dual-pump FOPA for loss compensation.

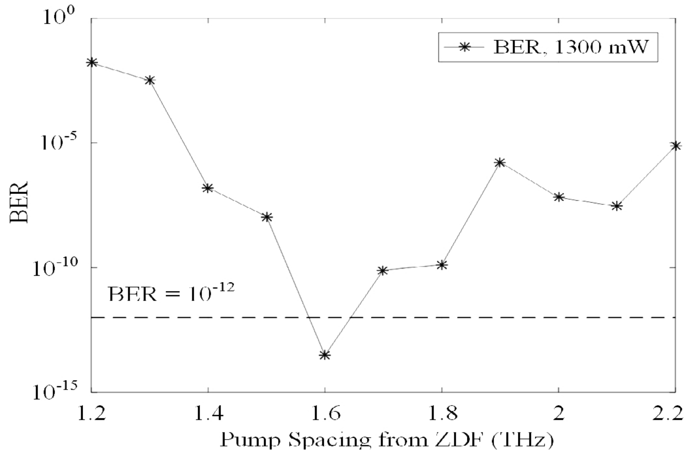

Fig. 2. Dependence of system maximal BER values on the spacing between the pumps and the zero dispersion frequency at equal pump powers and 1.3 W total pump power.

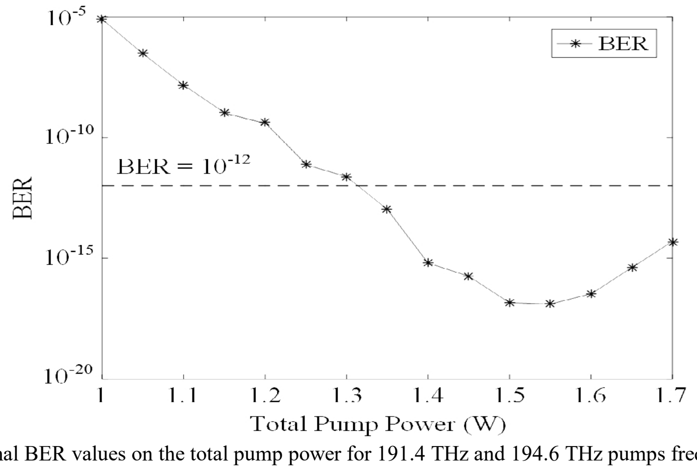

Fig. 3. Dependence of system maximal BER values on the total pump power for 191.4 THz and 194.6 THz pumps frequencies.

As can be seen in Fig. 4, the lowest BER values were obtained when the power of the 191.4 nm pump was equal to 825 mW and the power of the 194.6 THz pump was 525 mW. Such distribution of pump power can be explained in the following way: there are 2 main factors that impact FWM efficiency in this case – SRS induced power transfer and the phase mismatch between the interaction spectral components. SRS induces power transfer from the 191.4 THz pump to the 194.6 THz pump, therefore by making the 191.4 THz pump more powerful the power distribution is approximately equal over a longer span of HNLF. But if the 191.4 THz pump is more powerful than 825 mW, then the pump power equality would be obtained at a further point in the HNLF, where the efficiency of FWM would be limited by accumulated phase mismatch between the interacting optical fields.

Finding balance in distribution of pump powers has allowed to decrease the overall pump power by 24 % (by 324 mW), so the final configuration of the pumps is the following: 627 mW 191.4 THz and 399 mW 194.6 THz. The gain spectrum that was ensured by the FOPA with the configuration is displayed in Fig. 5.

As can be seen in Fig. 5, the FOPA with the chosen configuration has ensured from 15.6 dB to 15.8 dB gain for the 4 channels. To assess the performance of the FOPA the power of the signal at the input of the receiver, that was required to ensure a certain BER value in the channel with the highest BER, was compared to the same results that were obtained in the same system but without amplification. Power penalty was obtained with respect to this system. These results are displayed in Fig. 6.

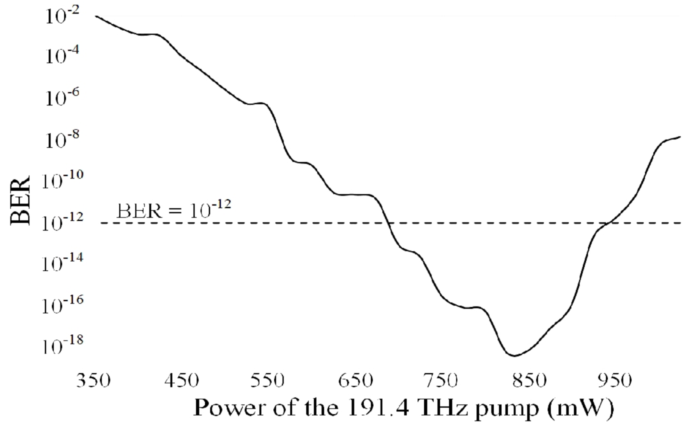

Fig. 4. Dependence of system maximal BER values on the power of the 191.4 THz pump at constant total pump power of 1350 mW.

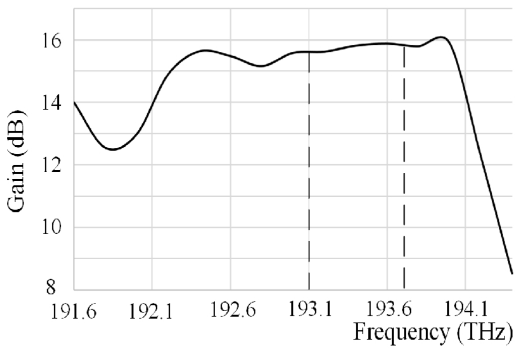

Fig. 5. Gain spectrum ensured by the dual-pump FOPA with the chosen configuration (191.4 THz 675 mW and 194.6 THz 675 mW pumps).

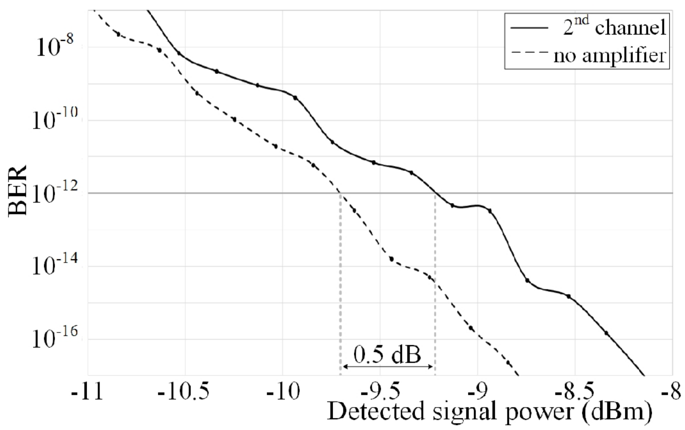

Fig. 6. Dependence BER values on the power of the received signal in the 2nd channel of the system with the dual-pump FOPA (solid line) and in the system without amplification (dashed line).

Figure 6 shows that there is 0.5 dB of power penalty observed between the system with the dual-pump FOPA and the system without amplification. This power penalty is related to the channel-channel four wave mixing produced inter-channel crosstalk and signal distortions that were produced under the influence of other fiber non-linear effects.

IV. CONCLUSIONS

The goal of this paper was to investigate the performance of the FOPA under the influence of SRS depending on the pumping parameters. The idea was to obtain such FOPA configuration that would ensure the required quality of the amplified signal (BER below 10^{-12}) using the least possible pump power. In the end it was found that in this specific case 627 mW 191.4 THz and 399 mW 194.6 THz pump configuration satisfies the above defined requirement.

The frequencies of the pumps were chosen symmetrically with respect to the ZDF to minimize the phase mismatch between the pumps. It was found that the minimal spacing from the pumps to the ZDF of the HNLF that could ensure that the signal is placed in the flat part of the gain spectrum with as high gain as possible was 1.6 THz (3.2 THz spacing between the pumps).

While choosing the pump power at first the approximate total pump power was estimated. Then, due to the presence of SRS, the distribution of power between the pumps was adjusted and the minimal pump power that was capable of ensuring BER below the 10^{-12} threshold was determined. This adjustment of pump power distribution has helped to severely improve the FWM efficiency, and therefore to increase the performance of the FOPA – approximately the same BER values were obtained in the amplified channels using by 24 % (by 324 mW) less pumping power in total.

Such amplifier performance increase at these specific pump powers is explained by the following two factors:

1. The obtained gain is highly dependent on the accumulated phase mismatch between the pumps and the signal. Even when the pumps are placed symmetrically with respect to the ZDF, this mismatch increases along the HNLF due to higher order dispersion and polarization mode dispersion (PMD). So the further into the HNLF, the less is the efficiency of FWM, the lower is the obtained gain.
2. Efficiency of the FWM is maximal when the power of the two pumps is equal. Due to the presence of SRS, the power of the pump with the lower frequency was partially transferred to the pump with the higher frequency (and also to the amplified signal and its idler spectral components).

Therefore, by making the 191.4 THz pump more powerful the power distribution is approximately equal over a longer span of HNLF. But if the 191.4 THz pump is more powerful than 825 mW, then the pump power equality would be obtained at a further point in the HNLF, where the efficiency of FWM would be limited by accumulated phase mismatch between the interacting optical fields.

It was also found that the usage of the FOPA resulted in 0.5 dB power penalty, which is mostly related to the channel-channel four wave mixing produced inter-channel crosstalk and signal distortions that were generated under the influence of other non-linear effects.

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