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Investigation of Fiber Optical Parametric Amplifier Performance in DWDM Transmission Systems

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***Abstract*—During the last decade, due to the growing demand on high capacity transmission, the evolution of optical transmission systems is moving into the focus of dense and cost-effective solutions. This has resulted in stricter requirements for the elements used in optical transmission systems, including optical amplifiers (FOPAs). One of the innovative and most promising types of amplifiers is fiber optical parametric amplifiers. In this article the authors implement a lumped single pump FOPA in a 8 channel DWDM transmission system and investigate the performance of the FOPA in order to obtain a configuration that would ensure higher level of amplification coped with less amplifier produced signal impairments.**

***Index Terms*—Dense wavelength division multiplexing, fiber optical parametric amplifiers, stimulated Brillouin scattering.**

I. INTRODUCTION

During the last decade the constantly growing number of worldwide users of multimedia services and the increasing amount of data per user has induced continuously growing demand on deployment and optimization of high capacity optical networks [1], [2]. The evolution of such systems is moving into the focus of dense and cost-efficient solutions, such as Dense Wavelength Division Multiplexing (DWDM) systems [3], [4]. It is highly important to maintain a certain level of system performance over a longer transmission distance, and therefore often optical signal amplification is deployed [1], [5].

Fiber optical parametric amplifiers (FOPA) are an innovative type of amplifiers, with many promising applications [6]. This type of amplifiers is based on four-wave mixing (FWM) that occurs inside an optical fiber. The main advantages of FOPAs are the ability to provide signal gain for the entire wavelength band used in optical communication systems, and generation of phase conjugated idler harmonics, that can be used for wavelength conversion [7].

The performance of FOPAs is considerably affected by several factors: Stimulated Brillouin scattering, related intensity noise (RIN), transferred from the pump to the amplified optical signal, and polarization dependence of the gain. Mostly all research on FOPAs has been done as on stand-alone amplifiers or all-optical signal processing elements, and only in the past couple of years the focus has moved towards implementation of this type of amplifiers in transmission systems [8].

The main goal of this article is to investigate the performance of a lumped single pump in-line FOPA in an 8 channel DWDM transmission system. During this research the amplifier was adjusted so that the frequencies of all 8 channels of the system would correspond to the peak of the provided gain spectrum. Phase modulation of the pump was used in order to mitigate the unwanted impact of Stimulated Brillouin Scattering (SBS) [8].

II. SIMULATION MODEL

Experimental results were obtained by introducing a simulation model of a system with the in-line single pump FOPA. For this purpose OptSim 5.2 was used, because this mathematical tool allows obtaining high accuracy results without acquiring high requirements to the hardware. The time domain split-step (TDSS) method was used to solve the fiber propagation equation

$$\frac{\partial A(t,z)}{\partial z} = \{L + N\}\, A(t,z), \tag{1}$$

where $A(t,z)$ is the optical field, L is the linear operator responsible for the calculation of the impact of such linear effects as attenuation and dispersion, and N is the nonlinear operator, which reflects fiber nonlinearity. The calculation is processed dividing the link into small spans of fiber, with length equal to Δz, and obtaining the L and N operators separately in the time domain.

For investigation of FOPA performance a simulation model of a 9.953 Gbit/s 8 channel DWDM transmission system with non-return-to-zero encoding technique, intensity on-off keying modulation format, and 50 GHz channel spacing has been introduced. This simulation model is shown in Fig. 1. The radiation of the continuous wave optical laser of each transmitter is externally modulated by NRZ coded electrical pulses via a Mach-Zehnder Modulator (MZM).

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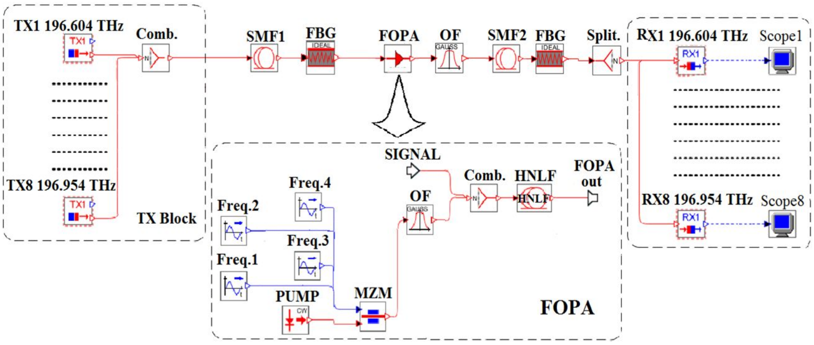

Fig. 1. Simulation model of the 9.953 Gbps 8 channel DWDM transmission system with an in-line FOPA.

The frequencies of channel carriers were chosen to be according to the ITU-T standardization in the region from 196.6 THz to 196.95 THz, corresponding to wavelengths of the optical S band. Later in the process of optimization of system parameters the carrier frequencies were slightly adjusted in order to minimize the crosstalk that occurs due topump-channel FWM interactions. These interactions produce parasitic spectral components (PC FWM harmonics), causing signal distortions. For this the pump-channel spacing needs to be chosen as odd multiple of the channel-channel spacing, so the frequencies of the PC FWM harmonics would be placed exactly in between the channels [9]. The carrier frequencies were upshifted by 4 GHz, so that the configuration would exactly match the condition mentioned above, so frequencies from 196.604 THz to 196.954 THz were used as carriers. The optical power of each transmitter was chosen to be 1 mW.

The 8 generated optical signals are combined and transmitted over a 100 km long standard single mode fiber (SMF). The attenuation, dispersion and dispersion slope parameters of the fiber at reference wavelength of 1550 nm are 0.2 dB/km, 16 ps/nm/km and 0.07 ps/nm^2/km respectively. After processing through this SMF the attenuated signal passes through a Fiber Brag Grating (FBG) in order to compensate dispersion that has accumulated through 100 km of SMF. This was required to ensure the phase matching condition for the FOPA. The amount of compensated dispersion at reference frequency of 196.78 THz was 1414 ps/nm.

The single pump FOPA is represented by an optical combiner, a 1 km long high non-linearity fiber (HNLF) and a powerful CW phase modulated pump. The parameters of the HNLF are shown in Table I.

TABLE I. HNLF PARAMETERS [10].

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

The power and the wavelength of the pump were selected in order to obtain higher amplification coped with less amplifier produced signal impairments. Phase modulation of the pump was required in order to broaden the spectrum of the pumping radiation, in such a way mitigating the impact of stimulated Brillouin scattering.

At the output of the FOPA the amplified signal passes through a 5 nm bandpass optical filter with center frequency of 196.78 THz, in order to suppress the pumping radiation and the idler spectral components that were produced in the HNLF during the process of amplification. After processing through the optical filter the transmitted signal was launched into a second SMF, the length of which was varied in order to obtain the achievable transmission distance for the system with the chosen FOPA configuration. At the input of the receiver block the signal was sent through a second FBG and its optical power was divided among 8 receivers via an optical splitter with 10.5 dB attenuation.

In order to assess the performance of the FOPA bit error rate (BER) values were obtained for each of the 8 channels. For optimization of parameters of the amplifier a simplified model of the system with optical gain suppression was introduced. In this simplified system the obtained gain spectrum and FOPA produced signal impairments were analyzed. Gain suppression was required to keep the level of the transmitted signal constant at the input of the received block, so that the increase of amplification would have minor impact on the quality of the received signal, and amplifier produced signal distortions would have direct impact on BER values.

III. Results and Discussions

The aim of this section is to analyse the results obtained while configuring the parameters of the amplifier, and to assess performance of the system with the obtained configuration of the single pump FOPA.

In order to estimate the benefit of applying the FOPA it was necessary to obtain the maximal transmission distance for the system without amplification. The maximal length of the optical line was obtained, for which the required quality of the signal was ensured, namely for which BER values of all 8 channels were below the 10^{-12} mark. Experimental results show that the maximal transmission distance for which this condition was true was 46 km with the amount of compensated dispersion of 650 ps/nm at reference frequency 196.78 THz.

Gain spectrum bandwidth and the achievable level of amplification are highly dependent on phase mismatch between the pump and the signals to be amplified, so at first the optimal pump wavelength for the given HNLF parameters and optical signal carriers needed to be chosen. This phase mismatch is not only contributed by system parameters and fiber dispersion, but is also affected by such nonlinear effects as self-phase modulation (SPM) and cross-phase modulation (XPM), so after choosing the final pump power it was required to readjust the wavelength of the pump one more time [6].

As already mentioned before, the optimization of FOPA parameters was performed using a simplified model of the system, in which the SMF fibers were replaced by optical attenuators. This allowed configuring the FOPA without taking into account the impact of dispersion of the SMF, polarization state changes of the amplified signal along the fiber, and polarization mode dispersion (PMD) of the SMF that has a random distribution along the fiber. Thus this has helped to obtain configuration of the FOPA, for which phase mismatch that occurred due to linear and nonlinear effects in the HNLF was minimized.

The first estimation of pump power and wavelength was 700 mW and 1553.92 nm respectively. Such amplifier configuration was used in order to configure phase modulation of the pump for SBS suppression. The obtained results have shown that the highest level of amplification with a constant power of the CW pump was observed when the pump was modulated by four radio-frequency tones with the following frequencies: 180 MHz, 420 MHz, 1.087 GHz and 2.133 GHz. Of course the usage of a phase modulator has lowered the pump power level at the input of the HNLF by about 3 dB, but this has significantly raised the total level of pumping power that could be launched into the HNLF without scattering a significant part of it on generation of SBS parasitic harmonics.

The same pump wavelength as mentioned above was used to find the most appropriate power of the pumping radiation. It is very important to note, that even though higher pumping powers can ensure higher level of amplification, excessive pumping of the FOPA may result in serious degradation of quality of the amplified signal and hence also will cause severe power penalty at the receiver. It is mostly caused by the fact that the impact of FWM produced inter-channel crosstalk also increases together with the power of the pump.

To find balance between the obtained level of amplification and signal impairments, produced by fiber non-linearity, BER values were obtained at the receiver end for all 8 channels of the system for pumping power in range from 400 mW to 800 mW. The optical attenuator that was placed between the amplifier and the receiver blocks was set to 13 dB to simulate insertion loss of a 50 km long SMF and a part of the gain reduction caused by polarization state changes and phase mismatch that occurred due to PMD. The obtained results are shown in Fig. 2.

As can be seen from Fig. 2 the minimal BER value of all 8 channels is observed at pumping power of 660 mW. Higher BER values for pumping power less than 660 mW occur due to low signal power at the receiver part, therefore can be explained by the lack of amplification. The growth of BER values for pumping powers higher than 660 mW is associated with the increase of inter-channel crosstalk. The chosen pump power was 660 mW, for which the wavelength of the pump was readjusted to 1553.9 nm.

To get a clear view on the amount of signal impairments produced by the amplifier, BER values of the received signal were observed for the same power level, that is required to satisfy the quality condition in the system with no amplification (for fixed level of signal power at the receiver end of -24 dBm). The obtained results are shown in Fig. 3.

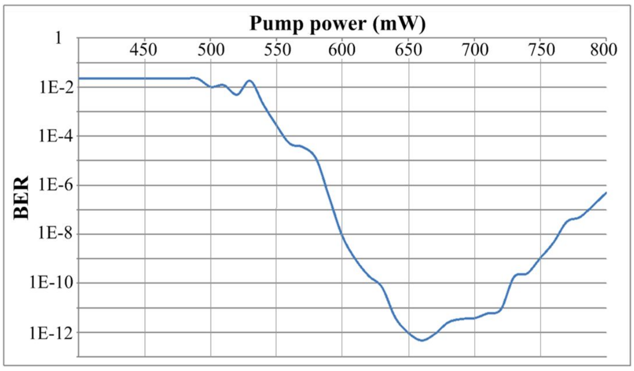

Fig. 2. System BER value dependence on the pumping power of the FOPA.

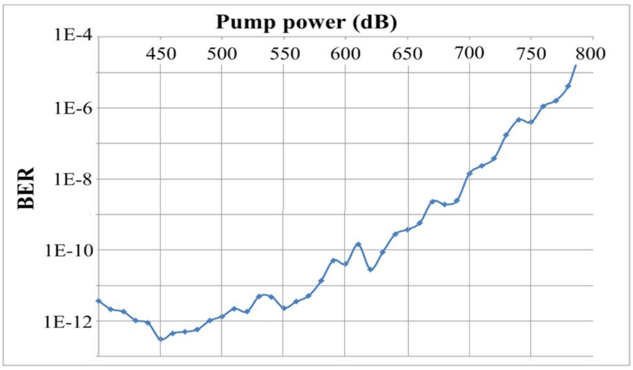

Fig. 3. System BER dependence on the pumping power for a fixed level of signal at the receiver end of -24 dBm.

Figure 3 shows, that the maximal level of pumping power, for which BER values of all 8 channels stay below 10^{-12} at a fixed level of the received signal of -24 dBm, was 480 mW. Higher BER values at lover signal powers are associated with the change of shape of the amplification spectrum due to phase mismatch between the pump and the amplified signals. This mismatch occurred because at lower pumping powers SPM and XPM had less impact on the pump and the amplified signal. As result of this the carriers with higher frequencies received less amplification; hence the quality of the signal for these channels was lower. The elevation of BER values for pump powers higher that 480 mW clearly represents the growth of impact of fiber non-linearity, which in its turn results in dramatic increase of BER values. It also can be seen from Fig. 3 that for the chosen amplifier configuration to ensure the required transmission quality, the power level of the signal at the receiver needs to be high enough to compensate about three orders of BER.

After the analysis of amplifier produced signal impairments, FOPA with the above described configuration was implemented into the simulation model of the system under test.

Gain spectrum, provided by the chosen FOPA configuration, is displayed in Fig. 4. Figure 4 shows that the maximum of the obtained gain spectrum coincides with the frequencies used for transmission in the system under attention. The chosen FOPA configuration provides up to 22.8 dB of on-off gain, which varies by 0.5 dB in the frequency region used for transmission. It has been found that the usage of phase modulation has ensured gain improvement up to 5.2 dB in comparison with the system with no SBS mitigation for the same level of pump power at the input of the HNLF.

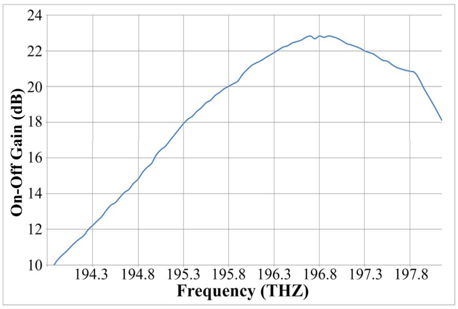

Fig. 4. Dependence on the 660 mW 1553.9 nm single pump FOPA provided on-off gain on the frequency of the 8 transmission channels.

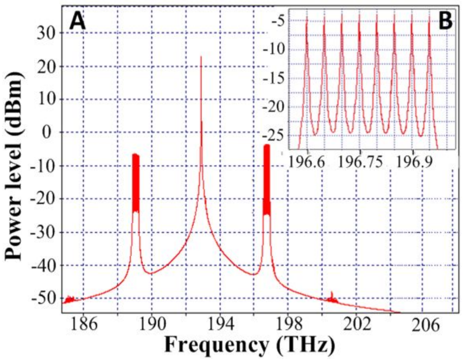

Fig. 5. Total optical spectrum (A) and spectrum of the amplified signal (B) at the output of the amplifier.

The optical spectrum at the output of the amplifier is given in Fig. 5(A). Power level of the amplified signal at the output of the FOPA has reached -3.7 dBm (4_{th} channel, Fig. 5(B)). As can be seen in Fig. 5(A) the frequencies of the generated phase conjugated idler spectral components are exactly symmetrical to the amplified signal in respect to the pumping radiation, but the obtained power level of these spectral components is 2.5 dB lower than of the amplified signal. It also can be seen, that the level of the pumping power is high enough to generate third order spectral components, so a small part of the pumping radiation was lost due to generation of these parasitic harmonics.

To estimate the benefit of implementing the FOPA the maximal transmission distance was found for the system with the obtained FOPA configuration. It was found that the usage of the amplifier has increased transmission distance from 46 km to 141 km, therefore a 95 km benefit in transmission distance was ensured. The optical power level at the receiver, that corresponded to the channel with the highest BER value (1_{st} channel, BER = $6.56 \cdot 10^{-12}$) has reached -23.1 dBm. Therefore power penalty for the chosen FOPA configuration was 0.9 dB.

IV. CONCLUSIONS

The goal of this article was to obtain such configuration of a lumped in-line single pump FOPA, that would ensure higher level of amplification coped with less amplifier produced signal distortions in a 8 channel DWDM transmission system, and to obtain the maximal transmission distance for this particular solution.

The FOPA was based on a 1 km long HNLF fiber. From the results obtained it was decided to the FOPA with 660 mW 1553.9 nm pumping radiation that was phase modulated by four radio-frequency tones of 180 MHz, 420 MHz, 1.087 GHz and 2.133 GHz. Phase modulation of the pump has helped to improve the on-off gain of the system by 5.2 dB for the same power level at the input of the amplifier. This has shown that broadening of the pumping radiation spectrum has significantly increased the SBS threshold and therefore improved the efficiency of amplification. The obtained FOPA configuration has insured on-off gain of 22.8 dB. The implementation of the FOPA described above has enlarged the maximal transmission distance of the system under test from 46 km to 141 km, so a benefit of 95 km was obtained.

It was found that for pumping powers larger than 480 mW it was not possible to ensure the required transmission quality with the same power level of the detected signal as in the system with no amplification. So the detected signal power needed to be higher to ensure BER values below the 10^{-12} mark. It was found that for the system with the obtained FOPA configuration power penalty of 0.9 dB needed to be compensated in order to ensure the required quality of the received signal. Signal impairments that were generated by the amplifier were mostly represented by fiber non-linearity produced signal distortions, especially by FWM produced inter-channel crosstalk.

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