Chapter 10

# Evaluation of Parametric and Hybrid Amplifier Applications in WDM Transmission Systems

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Additional information is available at the end of the chapter

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**Abstract**

Over the past two decades, a rapid expansion of the amount of information to be transferred has been observed. This tendency is explained by the rapid increase of Internet and other service users, as well as with the increasing availability of these services. This rapid growth in the amount of globally transmitted data is also associated with the expansion of the range of services offered, including such resource-consuming services as high-resolution video transmission, videoconferencing, and cloud computing, as well as with increasing popularity of such services. To satisfy this constantly increasing demand for higher network capacity, fiber optical transmission systems have been studied and applied with a growing intensity. Currently, optical transmission systems with wavelength-division multiplexing (WDM) have attracted much attention, as this technology allows using the available optical fiber resources more effectively than alternative technologies.

**Keywords:** optical amplifiers, parametric amplifiers, hybrid amplifiers, fiber optics, EDFA, WDM

## 1. Introduction

According to the latest Cisco forecast, the total amount of global IP traffic in 2016 reached 1.1 zettabytes, whereas in 2018 it will reach 1.6 zettabytes. The forecasted increase in the monthly transferrable IP traffic over the period from 2013 to 2018 is shown in **Figure 1a**. Studies performed by Cisco show that in comparison with 2012 the amount of Internet traffic transferred in the peak hours in 2013 increased by 32%, whereas the average daily volume of transferrable Internet traffic increased by 25% [1]. If this tendency remains, then in 2018 the volume of

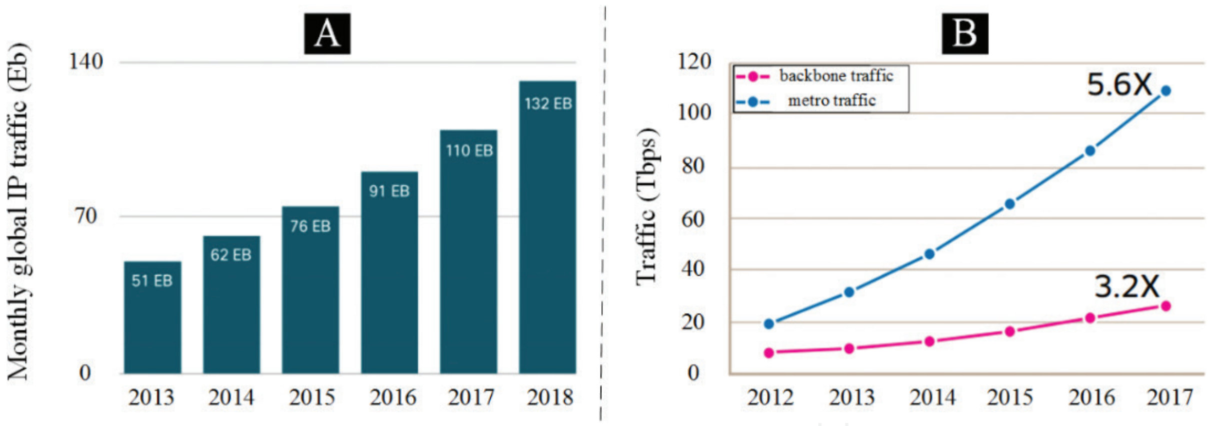


**Figure 1.** Cisco forecast of the monthly transferrable IP traffic (A) and Bell Labs forecast of the transferrable data amount in backbone and metro networks (B) [1, 2].

transferrable Internet traffic during the peak hours will reach 1 petabit per second, whereas the daily average will reach 311 terabits per second [1, 3]. According to the Bell Labs forecast, results of which are shown in **Figure 1b**, during the period from 2012 to 2017, the increase of traffic in backbone networks will reach 320%, whereas in metro networks, it will reach by 560% [2].

It is possible to increase the wavelength-division multiplexing (WDM) system throughput capacity either by increasing the data transmission speed in channels or the number of channels. The wavelength band that is used for transmission in WDM systems is limited due to the wavelength dependence of optical signal attenuation in optical fibers [4, 5]. In modern transmission systems, the minimum attenuation of single-mode optical fiber is 0.2 dB km$^{-1}$, and it is observed in the “C” wavelength band, which corresponds to wavelengths from 1530 to 1565 nm. Regardless of the fact that the attenuation value is so low, its impact accumulates with every next kilometer. In long-haul transmission systems, where transmission lines are several hundreds and even thousand kilometers long, the attenuation substantially degrades the quality of the received signal, as the photodetector sensitivity is limited [6–8]. As the number of channels increases, the attenuation caused by the optical signal division also increases, especially in cases where power splitters are used [9]. However, by increasing the speed of data transmission, it becomes necessary to reduce the optical noise produced by optical components (light sources, modulators, amplifiers, receivers, etc.), as higher transmission speed signals have lower noise immunity.

Therefore, solutions are needed for compensating the ever-increasing accumulated signal attenuation in an ever-broader wavelength range. Currently, erbium-doped fiber amplifiers (EDFAs) are most commonly used around the globe for compensation of optical signal attenuation. The amplification bandwidth of EDFAs is strictly limited (for conventional EDFA solutions, it is only 35 nm), which restricts the wavelength range used for the transmission in existing systems [10–12]. It is, thus, necessary to seek for new solutions to amplifying optical signals and for opportunities of expanding the range of amplified wavelengths and increasing the attainable amplification level for the already-existing optical signal amplification solutions. This can be achieved by combining amplifiers of various types. In such a way, it is possible to combine the positive properties and partly compensate the drawbacks of different types of amplifiers.

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During recent years, the need to increase transmission capacity of existing optical networks together with requirements for reducing the total cost of construction and maintenance of optical networks has induced increasing interest in all-optical signal processing [13–16]. In contrast to solutions with optical-electrical-optical (O/E/O) signal conversion, which induces the so-called bottlenecks in optical transmission systems, all-optical signal processing is performed in real time, whereas the signal is transmitted through a nonlinear medium [17]. Therefore, all-optical signal processing allows avoiding the part of transmission capacity limitation that is caused by O/E/O signal conversion.

The progress in nonlinear material research has resulted in commercial production of optical fibers and other components with high values of the nonlinear coefficient. Therefore, the optical power, required to initiate fiber nonlinearities, has become lower [15]. Fiber nonlinearity is the main mechanism that is used for all-optical signal processing. Optical amplifiers are the only optical devices capable of rising the power of optical signal high enough to induce manifestation of nonlinear effects during transmission. That is why the usage of optical amplifiers for all-optical signal processing purposes has been intensively studied all over the world during recent years, and various applications of optical amplifiers have been demonstrated [13–16, 18–20].

## 2. Main principles of optical amplification

Amplification of optical signals is based on the energy transfer from pumping optical radiation or another type of energy to the amplifiable optical signal. This process is implemented differently in various types of optical amplifiers. In general, the amplification process uses the stimulated emission phenomenon in the amplification environment, such as, for instance, semiconductor optical amplifiers or doped fiber optical amplifiers. Furthermore, such nonlinear optical effects such as Raman, Brillouin, and four-wave mixing (FWM) are used to amplify optical signals in cases of Raman, Brillouin, and parametric optical amplifiers, respectively [21].

The mechanism of amplifying optical signals is based on occurrence of stimulated light emission in the gain medium. The light emission phenomenon can be explained using the Rutherford-Bohr atomic model. Bohr has stated that atoms may jump from one energy state to another, by performing what is known as the quantum jumps, corresponding to a change of orbit. This orbit change requires a change in the energy level; therefore, if the atom jumps from the higher energy state to the lower energy state, it will produce a photon. A photon contains energy, which corresponds to the difference between the initial higher energy level and lower occupied level energy, as the overall energy of the process must remain unchanged. This assumption derives from the law of conservation of energy [22]. Thus, photon energy can be determined according to the following equation [23]:

$$E_{photon} = E_2 - E_1 = h\, v_{photon} \tag{1}$$

where $E_{photon}$ is the generated photon energy, $E_1$ and $E_2$ are the high and low energy level, h is the Planck constant, and $v_{photon}$ is the generated photon frequency.

Optical amplifiers can be classified according to the nature of the amplification process [23]:

**a.** Amplifiers, in which amplification is obtained, using linear properties of the material (semiconductor optical amplifiers (SOAs) and amplifiers on rare-earth element-doped fiber basis (xDFA))

**b.** Amplifiers, for which the principle of operations is based on nonlinear properties of the material (Raman optical amplifiers, Brillouin optical amplifiers, and fiber optical parametric amplifier (FOPA))

A second way of classifying optical amplifiers is according to the medium, in which amplification takes place:

- Amplifiers, in which semiconductor material is used (SOA)
- Amplifiers, which are produced on the basis of optical fibers

The main parameters that are used to characterize optical amplifiers are the level of amplification, the gain bandwidth, the saturation power of the amplifier, the polarization sensitivity of the produced gain, and the amount of signal impairments produced by the amplifier.

The achievable level of amplification is determined as the relation of the output signal power to the power of the same signal in the input of the amplifier. Amplifiers are sometimes also described with amplification efficiency, which describes the amplification as a function of the pumping power. The unit of measurement of efficiency of amplification is dB/mW [24].

The bandwidth of the amplifier produced gain is applied to the wavelength or frequency range, in which the use of the amplifier is effective, namely, where it can ensure an increase in signal power. This value is especially important in WDM transmission systems, as it limits the number of channels in such systems [23].

The saturation point for an optical amplifier is the maximum attainable output power value, namely, when the optical signal power in the amplifier output no longer increases while raising the signal power at the amplifier input. When the input power is increased above the saturation point, all carriers in the gain medium are already in a saturated status, and a higher level of energy transfer to the amplified signal is no longer possible. The saturation power is defined as the output power, at which 3 dB decrease in amplification is observed, in respect to the maximum possible level of amplification [23].

The dominating source of noise in optical signal amplifiers is the amplified spontaneous emission (ASE), which originates in the gain medium [25]. The amount of noise generated by amplifiers depends on various factors. The most important of these are the gain medium material parameters (e.g., the spontaneous lifetime of the energy level), gain spectrum, noise bandwidth, amplifier saturation, and population inversion parameters. The problem of noise generated by an amplifier is most explicit in systems, where it is required to use multiple amplification stages, therefore placing the amplifiers in a cascade, such as backbone optical networks. Each amplifier in such cascades not only amplifies the transmitted signal but also the noise generated by the amplifier from the previous amplification stage and additionally adds ASE noise of its own [23]. To assess the amount of ASE noise generated by the amplifier, the noise figure (NF) parameter is normally used. This value describes the optical signal-to-noise ratio (OSNR) changes, as the signal passes through the amplifier [23, 26].

In the studies conducted by the authors, using simulation software OptSim, the performance of SOA, EDFA, lumped Raman amplifier (LRA), and the distributed Raman amplifiers (DRA) under equal operating conditions has been compared. The simulation scheme introduced for this purpose is displayed in **Figure 2**. Such a structure of the WDM transmission system simulation model will also be used further in the research, when the operations of an amplifier are analyzed.

The performance of different types of amplifiers has been compared in a 16-channel dense wavelength division multiplexing (DWDM) transmission system with 10 Gbps transmission speed per channel, 50 GHz channel spacing, and non-return-to-zero on-off keying (NRZ-OOK) (on-off keying) modulation format. In each case, also the length of the dispersion-compensating fiber (DCF) has been determined. Optical amplifiers have been used as in-line amplifiers. The comparison of SOA, EDFA, LRA, and DRA performance is available in **Table 1**.

The largest transmission distance has been achieved in a system with the DRA. Here, just like in the case of LRA, the attainable amplification is limited by the impact of fiber nonlinearity on the quality of the amplified signal. A 1150 mW co-propagating pumping radiation is used for DRA pumping. The amplification process occurs in the transmission line section between the DRA pumping source and the receiver block. Thus, the single-mode fiber (SMF) attenuation reduces the signal amplification rate in the direction from the amplifier to the receiver block, which allows achieving much larger amplification than in the case of LRA, and accordingly increases the attainable transmission distance. Irrespective of the

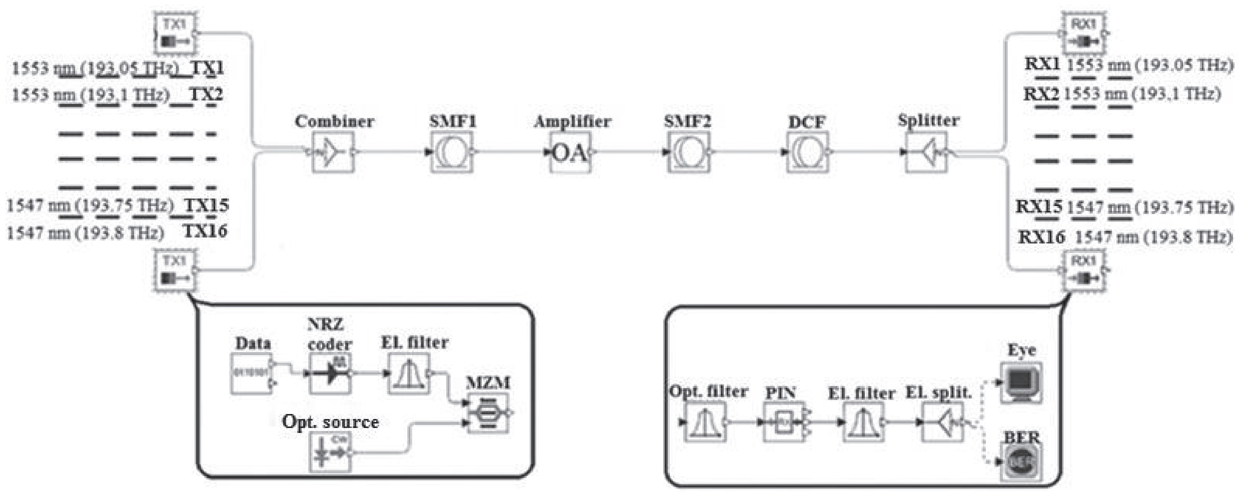


**Figure 2.** Simulation model of the 16-channel 10 Gbps DWDM transmission system used for comparison of optical amplifier performance.

| Amplifier type | - | SOA | EDFA | LRA | DRA |
|---|---|---|---|---|---|
| Transmission distance (km) | 69 | 112 | 135 | 119 | 146 |
| DCF length (km) | 5 | 15 | 20 | 17 | 20 |
| Gain in wavelength range from 1546 to 1553 nm (dB) | - | 17.4 | 23.4–25.1 | 19.9–20 | 24.9–25 |
| NF in wavelength range from 1546 to 1553 nm (dB) | - | - | 4.5–4.6 | 3–3.1 | −8.6 |
| Level of interchannel cross talk in the channel with the highest bit error rate (BER) (dBm) | −55.5 | −50 | −47.9 | −48.3 | −49.3 |

**Table 1.** Summary of the results obtained in the 16 channel 10 Gbps DWDM transmission system depending on the type of amplifier used (Column 2—without using an amplifier).

fact that the average amplification in the case of DRA is larger just only by 0.7 dB than in the case of the EDFA amplifier, the achieved transmission distance is larger by 11 km than in the system with EDFA. This can be explained by the low amplification efficiency of the Raman amplifiers at low powers of the amplified optical radiation. Thus, the signal, the power of which is much larger than the noise power, will be amplified more effectively than the noise generated by the amplifier. Nevertheless, such characteristic of the amplifier should also be interpreted as a serious drawback of the distributed Raman amplifiers, as the need arises to use powerful pumping lasers (1150 mW strong pumping radiation is necessary to achieve amplification of 25 dB). EDFA pumping source power is equal to 316 mW. EDFA is able to ensure a high level of signal amplification; however, this could be achieved only in a 35 nm wavelength region in the "C" optical band. The typical noise figure of EDFAs is higher than in the case of LRA and DRA. The main deficiency of SOAs is a very high number of produced signal impairments; therefore, this type of amplifiers is rarely used in WDM systems, even though their gain spectrum is much broader in comparison with EDFAs.

Taking into account the excessive number of SOA produced signal impairments, the strong wavelength and unevenness of the EDFA produced gain, and the low amplification effectivity of Raman amplifiers, it is clear that, if Cisco and Bell Labs forecasts are correct, then it will be necessary to find another optical signal amplification solution that could ensure a higher level of amplification over a broader wavelength band and at the same time that would amplify signal impairments as little as possible.

The first possible solution is to combine the aforementioned optical amplifiers into a hybrid optical amplifier, which would allow compensating for the negative properties of various amplifier types, for instance, to expand and equalize the EDFA gain spectrum, or would reduce the SOA-generated noise proportion in the amplifier output.

Another possible solution is the use of fiber optical parametric amplifiers (FOPAs). This type of amplifiers can ensure a high level of amplification over a broad wavelength band, and, if compared to other lumped amplifier types, given an optimized configuration, they produce very small number of signal impairments. Moreover, parametric amplifiers can also be used for all-optical signal processing purposes, for example, for wavelength conversion [27, 28],

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dispersion compensation [29], time-division-multiplexed signal demultiplexing [20], and 2R and 3R all-optical signal regeneration (2R—signal power and form regeneration; 3R—signal power, form, and phase regeneration) [30, 31].

## 3. Hybrid optical signal amplification

This chapter is dedicated to studies of hybrid optical amplifiers, which were obtained by applying the combinations of currently commercially used optical amplifiers (SOA, EDFA, and Raman amplifiers). The possibilities of applying hybrid Raman-EDFA and Raman-SOA solutions in WDM transmission systems for improving the operations of existing lumped in-line amplifiers have been studied and demonstrated. Due to the excessive number of SOA produced signal distortions and the strong wavelength dependency of EDFA produced gain, the implementation of EDFA-SOA hybrid solution has not been considered.

The unevenness of the EDFA gain spectrum and signal distortions caused by ASE noise significantly affect the performance of the whole transmission system, especially in systems with several amplification spans. To demonstrate the impact of the unevenness of EDFA gain spectrum and of the generated signal distortions, a 16-channel 10 Gbps DWDM transmission system simulation model has been introduced with four amplification spans. Equal power of the optical flow has been ensured at each amplifier input.

The obtained results are shown in **Figure 3**. After each amplification span, BER value of the detected signal increases by 2–3 orders (given the same input signal power). Upon comparing the EDFA gain spectra after the first and fourth amplification span, it is found that amplification decreases on average by 11.6 dB, whereas the amplification difference between the channels increases from 1.3 to 4.3 dB. The following conclusions are drawn:

- Every additional EDFA not only generates the amplified spontaneous emission noise but also amplifies the noise produced by the previous amplification spans. This significantly degrades the quality of amplifiable signal.
- The ASE power level after each amplifier is gradually increasing. Accordingly, part of the erbium ion population inversion is used to amplify the noise generated in the previous amplification spans. As a result, the part of the obtained population inversion, which was used for signal amplification, has decreased.

The slope of the gain spectrum increases after each amplification span. Uneven amplification is undesirable in multichannel WDM systems, especially in systems with several cascaded EDFA in-line amplifiers, as it leads to difference between power levels of various channels, which, accordingly, will lead to a signal quality degradation in channels with a lower amplification level.

Summing up all the aforementioned results, it has been concluded that it is necessary to configure the EDFA amplifier in a way to obtain the overall amplification spectrum that is as even as possible in the frequency range used for transmission, as well as to reduce the number of EDFA produced signal distortions.

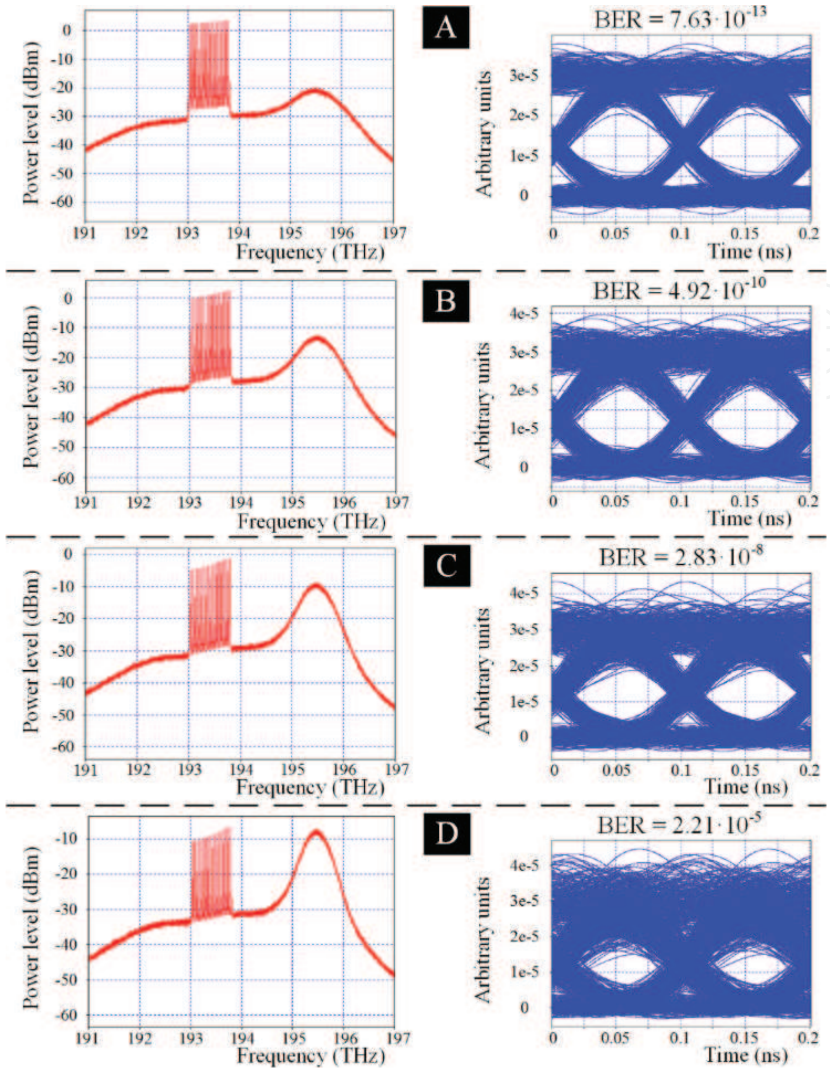


**Figure 3.** Optical spectra (the power level depending on frequency) at the output of the EDFAs (to the left) and eye diagrams of the signal detected in the ninth channel (to the right) after first (A), second (B), third (C), and fourth (D) stages of amplification.

### 3.1. Raman-EDFA hybrid amplifier

In the Raman-EDFA optical amplifier combination, most noise is generated by the EDFA amplifier. Therefore, in most cases, the Raman amplifier is used as a preamplifier in such cascades. EDFA amplifiers provide lower noise figures when functioning closer to the saturation point. Therefore, in hybrid amplifiers, EDFA with a relatively short doped fiber should be used (the longer the doped fiber, the higher level of amplification is obtained by the photons generated by spontaneous emissions). For further analysis of the hybrid Raman-EDFA solution, a simulation model is used, which is shown in **Figure 4**.

In the simulation model, the optical flows that are produced by the 16 transmitters are combined and transferred through a 150 km long standard single-mode fiber (SMF1). The signal power level at the SMF1 fiber output in all 16 cannels has reached −37.1 ± 0.1 dBm. The overall optical flow has been amplified by the EDFA in-line amplifier or by the hybrid Raman-EDFA

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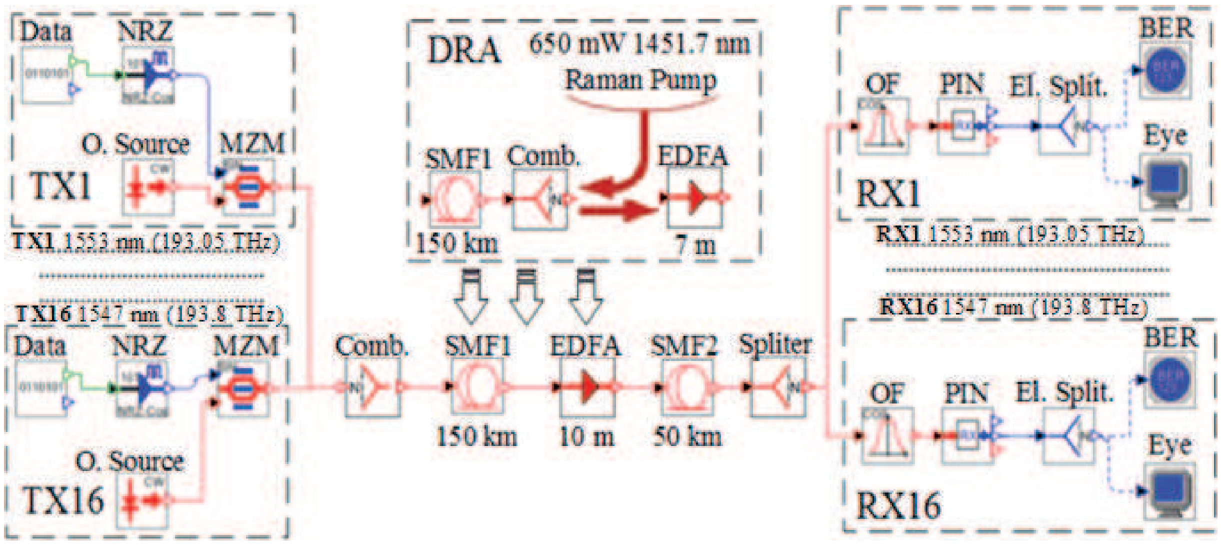


**Figure 4.** Simulation model of the 16-channel 10 Gbps DWDM transmission system with an EDFA in-line amplifier or with a hybrid Raman-EDFA amplifier.

amplifier (arrows in **Figure 4** show the layout of the hybrid amplifier) and afterward transferred through a 50 km long SMF (SMF2). Dispersion compensation has been performed using a fiber Bragg grating (FBG), and then the optical flow has been divided among 16 receivers, using an optical power splitter.

After comparing the gain spectra produced by the EDFA in-line amplifier and the hybrid Raman-EDFA amplifier (see **Figure 5**), it has been found that implementation of the hybrid solution allows reducing the gain difference among all 16 channels from 1.5 dB (in the case of the EDFA) to 0.1 dB (in the case of the hybrid amplifier).

As can be seen in **Figure 6**, implementation of the hybrid solution has ensured OSNR improvement in all 16 channels from 1.7 up to 2.6 dB, that is, an average increase of ~2 dB. Such OSNR improvement can be explained by the following facts:

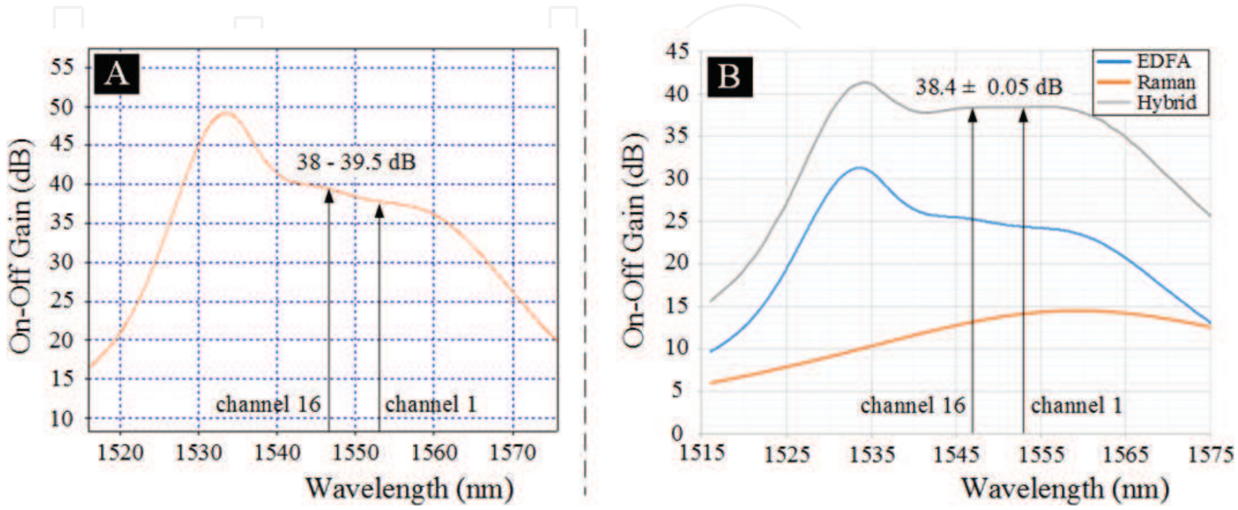


**Figure 5.** Gain spectra of the EDFA in-line amplifier (A) and of the hybrid Raman-EDFA amplifier (B).

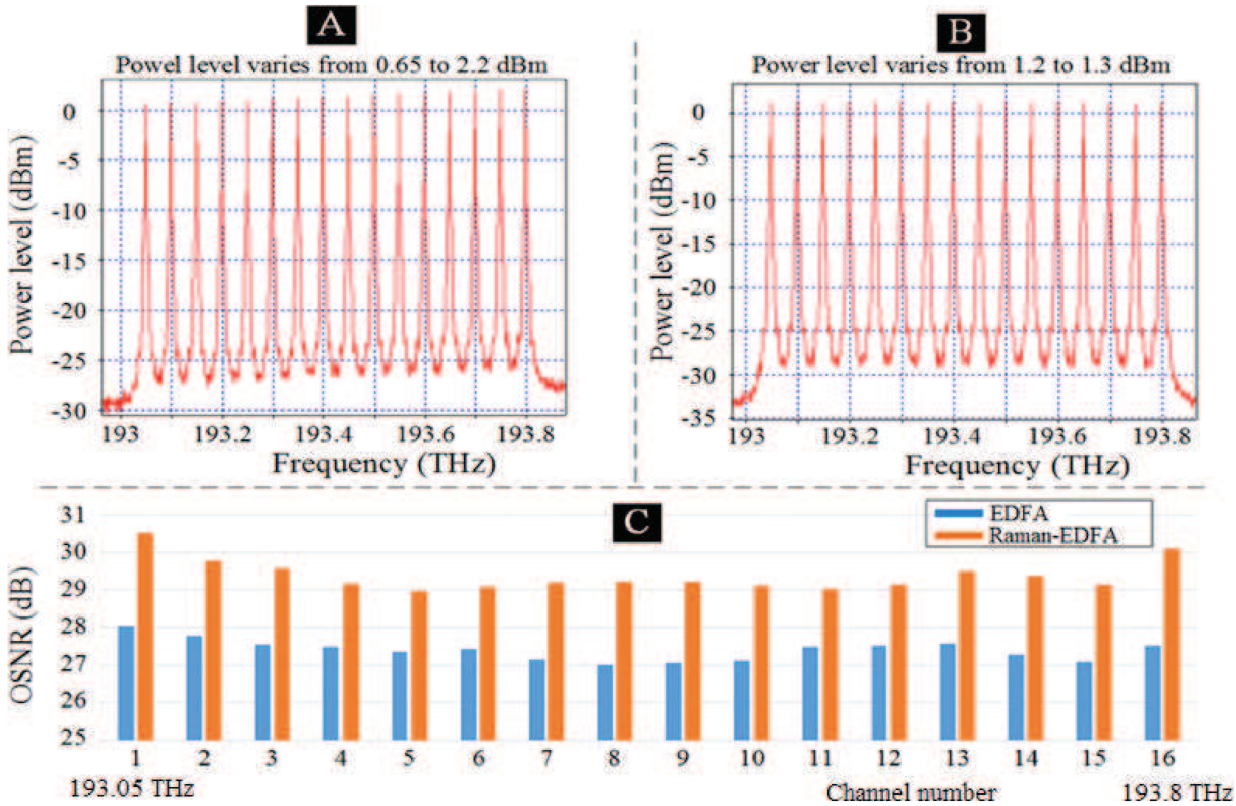


**Figure 6.** Signal spectra at the output of the EDFA (A) and at the output of the hybrid Raman-EDFA amplifier (B) and OSNR comparison among all 16 channels in the system with the EDFA in-line amplifier and the hybrid Raman-EDFA amplifier (C).

- The usage of the distributed Raman amplifier has raised signal power at the input of the EDFA by 13.1–14.1 dB; therefore, the EDFA functions closer to the saturation point.
- The EDFA fiber length has decreased by 3 meters, which allows reducing the required input signal power for saturation of the EDFA.
- The coherent nature of stimulated Raman scattering (SRS) ensures that in SMF1 optical fiber, the signal is amplified more effectively than the low power optical noise, which allows obtaining negative noise figure values (from −0.4 to −0.6 dB in the wavelength region used for transmission), and accordingly improved OSNR.

In the case of the hybrid amplifier, it has been found that raising the signal power at the input of the EDFA and reducing the length of the erbium-doped fiber (EDF) allow obtaining lower noise figure values by 0.3–0.4 dB for the EDFA.

Upon performing a comparison of operations of the aforementioned EDFA and Raman-EDFA solutions, it can be concluded that the hybrid amplifier can ensure more even amplification over a broader wavelength region and higher OSNR values. However, more powerful lasers are necessary for implementing such solutions, which increases the costs of developing this solution. For the EDFA in-line amplifier, 316 mW of pumping power is required to amplify

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the −37.1 dBm input signal by more than 38 dB. In the case of the hybrid solution, the Raman amplifier required 650 mW of pumping power to ensure that gain is high enough and that its slope can compensate the slope of the EDFA with 200 mW pump gain spectrum, but the total pumping power of the hybrid amplifier has reached 850 mW. However, the hybrid solution ensured gain difference below 1 dB over a 23 nm wavelength range (from 1538 to 1561 nm, by 17 nm more than that used for transmission of all 16 channels), which allows significantly increasing the number of channels in WDM transmission systems.

### 3.2. Raman-SOA hybrid amplifier

The Raman-SOA hybrid solution is configured in a way to reduce the number of signal distortions produced by the semiconductor optical amplifier and also to increase the attainable transmission distance. The introduced simulation model of the transmission system used for studying this amplifier combination is similar to the one used previously (see **Figure 7**). Wavelength grid is chosen based on ITU-T G.694.1 recommendation where the central frequency is 193.1 THz.

The transmission line span length between the transmitter block and SOA is specifically selected to ensure optimum signal power at the input of the semiconductor amplifier. Inserting the distributed Raman amplifier in a cascade before the semiconductor amplifier would increase the signal power in SOA input, which would lead to a more explicit manifestation of nonlinear optical effects in the semiconductor material and would, accordingly, deteriorate the quality of the amplifiable signal. Therefore, it is the semiconductor amplifier that is used as the first in the cascade.

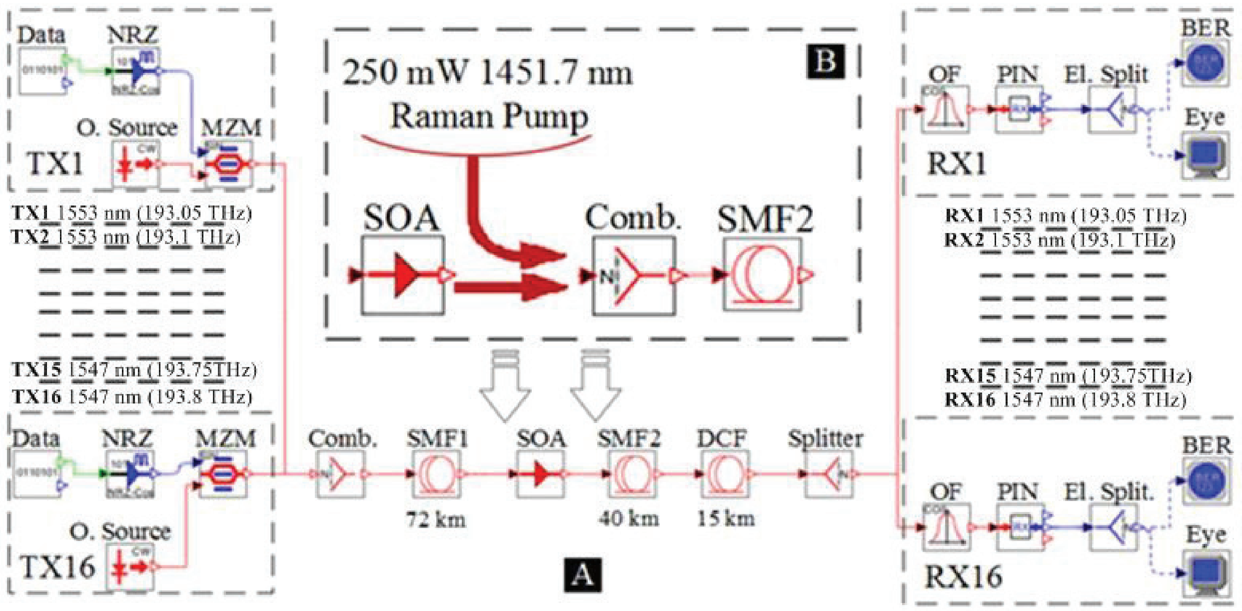


**Figure 7.** Simulation model of the 16-channel 10 Gbps DWDM transmission system with the SOA in-line amplifier (A) or with a hybrid Raman-SOA amplifier (B).

The implementation of the hybrid Raman-SOA solution allows using such mode of the semiconductor amplifier, in which it produces minimum distortions of the amplified signal, whereas the amplification deficit, which occurs after reducing the pumping current value by 43 mA, is compensated by the DRA with a 250 mW 1451.7 nm co-propagating pump. The implementation of the Raman-SOA hybrid solution allows increasing the attainable transmission distance by 12 km. The gain spectrum of the DRA is shown in **Figure 8a**. Eye diagrams for channels with the highest BER value in a system with the SOA amplifier (ninth channel $f$ = 193.45 THz) and in a system with the Raman-SOA hybrid amplifier (tenth channel$f$ = 193.5 THz) are shown accordingly in **Figure 8b** and **c**. From **Figure 8a**, it can be seen that the DRA produced amplification is large enough to compensate the amplification deficit of 5.3 dB that occurs after reducing the SOA pumping current by 43 mA. SOA amplifier (9th channel) and Raman-SOA hybrid amplifier (10th channel) be selected, because they are the worst channels.

After comparing **Figure 8b** and **c**, it has been found that implementation of the Raman-SOA hybrid solution allows obtaining approximately the same BER level as in the case of SOA in-line amplifier, but at signal power lower by 1.5 times. This shows that, by using SOA together with the distributed Raman amplifier and introducing relevant SOA pumping current adjustments, it is possible to substantially lower the amount of SOA produced noise and, therefore, to improve the quality of the amplified signal.

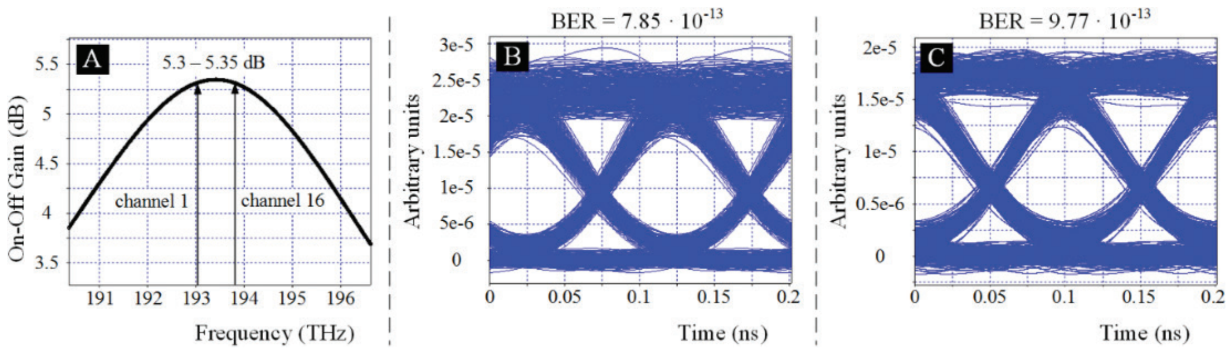


**Figure 8.** DRA produced gain spectrum (A) and eye diagrams of the ninth channel in the system with the SOA in-line amplifier (B) and the tenth channel in the system with the Raman-SOA hybrid amplifier (c).

## 4. Evaluation of parametric amplifiers and its application

Parametric amplifiers can be based on degenerate FWM (in the single-pump case) and on nondegenerate FWM (in the dual-pump case). FOPA produced gain will reach its maximum, if the phase-matching condition is met or if the phase-mismatch parameter k is equal to zero. In the case of a single-pump FOPA, irrespective of the broad amplification range, the amplification spectrum is not even. In the experimental transmission system, described before, the gain −3dB bandwidth has reached 2.2 THz (see **Figure 9**). It has been found that for ensuring an optimum operation mode of a single-pump FOPA, it is necessary to maintain a small negative linear phase deviation in respect to the zero-dispersion frequency, which would compensate the nonlinear phase mismatch. That is why the pumping radiation wavelength must be slightly larger than the fiber zero-dispersion wavelength (ZDWL).

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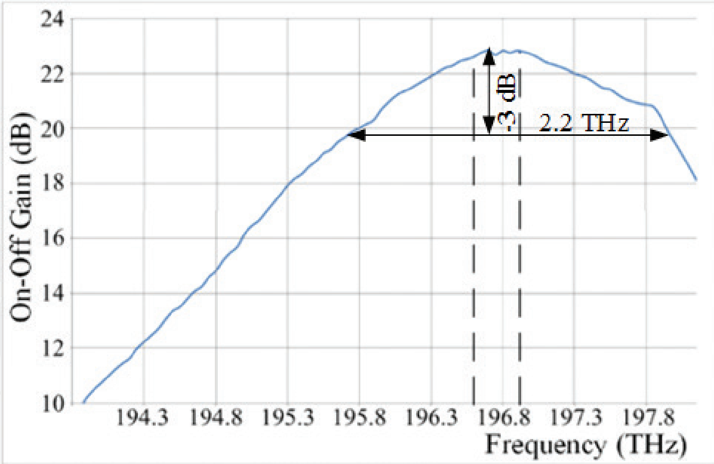


**Figure 9.** Gain spectrum of the single-pump FOPA with 660 mW 1553.9 nm pumping radiation.

The gain spectrum bandwidth is very dependent on the nonlinearity parameter of the medium and on the pumping radiation power and the length of the gain medium highly non-linear fibers (HNLFs). Thus, by increasing the fiber length, it is possible to achieve a higher level of amplification, but in this case, the gain spectrum width will be reduced accordingly (the longer the fiber, the larger the accumulated phase mismatch is). Due to this reason, when constructing FOPA amplifiers, it is not recommended to use HNLFs that are longer than 1 km. If they are configured in a way to achieve as wide gain spectrum as possible, it is required to use as short HNLF as possible, but to maintain the achievable amplification level, the pump power must be increased, or a fiber with a higher nonlinearity coefficient must be used. When selecting the pumping radiation parameters, one must keep in mind that, by changing the pumping radiation power, also the nonlinear phase mismatch is changed. Therefore, along with adjusting the pump power, its wavelength also needs to be reconfigured.

The performance of single-pump parametric amplifiers is affected by various factors, which must be taken into account when designing a specific FOPA. It is necessary to selectively choose the pumping radiation parameters to ensure as high amplification efficiency as possible and to avoid occurrence of excessive channel-channel four-wave mixing (CC-FWM) and pump-channel four-wave mixing (PC-FWM) produced interchannel cross talk, which in its turn is produced due to excessive pumping. The SBS threshold increase is also very important; otherwise, the amplification effectiveness will decrease, and the amplified signal will be distorted.

One of the most effective solutions of increasing the SBS threshold is phase modulation of the pumping radiation. However, as can be seen from the results shown in **Figure 10**, if the choice of frequencies modulating the pumping radiation phase is not thoroughly considered, a substantial expansion of spectrum of the idler spectral components will occur. Therefore, in systems, in which idlers are used for all-optical signal processing, it must be ensured that the chosen pumping radiation phase-modulation does not produce excessive spectral broadening of idlers (in the results shown in **Figure 10**, idler spectral broadening has reached 54% at the level of −15 dB from the maximum power spectrum). For initiating the FWM process, it is also necessary to preserve the angular momentum among the four photons involved in the parametric interactions, as the parametric gain has explicit polarization dependence.

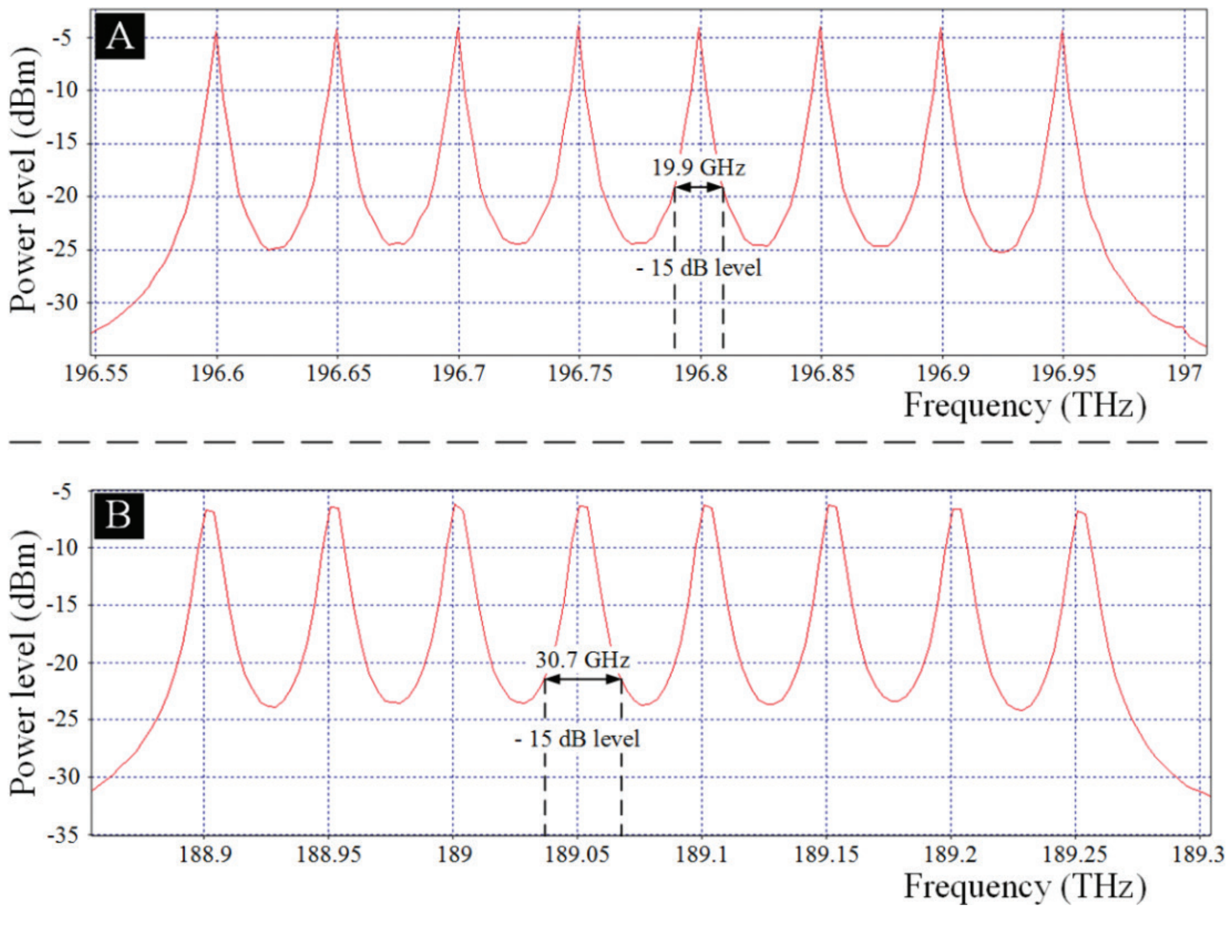


**Figure 10.** Spectra of the amplified signal (A) and the generated idlers (B) at the output of the single-pump FOPA.

Unlike single-pump FOPAs, dual-pump FOPAs can ensure even amplification over a very broad wavelength band. To achieve even amplification in a broad wavelength band, it is necessary to ensure that the wavelengths of the pumps are placed symmetrically in respect to the gain medium ZDWL, whereas the frequency distance between ZDWL and pumping radiations must be large enough (depending on the specific FOPA configuration), to avoid the impact of PC-FWM-generated components on the quality of the amplified signal.

Since dual-pump FOPAs both degenerate and nondegenerate FWM, for one input signal, it is possible to obtain at least five idlers (see **Figure 11**, where $\omega_1$ and $\omega_2$ are the pumping source frequencies, but $\omega_3$ is the signal), which are directly related to the amplifiable signal frequency. This leads to amplification spectrum depressions at frequencies near the frequencies of the pumps. It has been concluded from the results obtained in this study that at 0.5 mW pump power it is recommended that the amplified signal frequency is at a distance of at least 1.2 THz from pump frequencies.

Just like in the case of single-pump FOPAs, dual-pump FOPAs also require the usage of one of the methods for mitigation of the negative impact of SBS. However, in the dual-pump case, it is important to note that by manipulating with the phase of both pumping radiations it can

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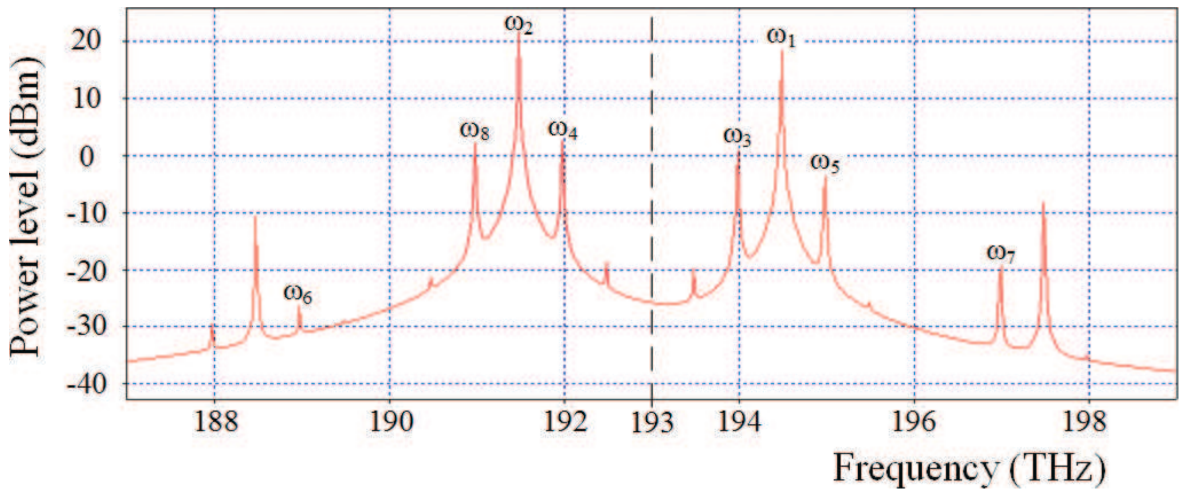


**Figure 11.** Optical spectrum at the output of a dual-pump FOPA with 200 mW 191.5 THz pumps and 500 meter long HNLF.

be achieved that the relevant idler will not experience spectral broadening. The amplification efficiency in the case of dual-pump FOPAs is highly dependent on the SRS triggered energy transfer between the pumps. It is not possible to fully avoid this effect. To reduce its impact, normally higher power is used for the pump with the higher frequency than for the other pumping radiation, thus achieving that the average power difference between the pumps is minimum over the entire gain medium.

In traditional WDM transmission system architecture, one optical source is required to produce a single-channel carrier. It is not the most cost-effective solution, as, by increasing the number of transmission channels, the number of required light sources increases accordingly. Due to this reason, an increasing number of studies are conducted to find such transmission system architecture, which would be able to ensure a higher number of signal carriers using fewer optical sources [32–34]. FOPAs during the process of parametric amplification generate idler spectral components, which, in essence, are phase-conjugated copies of the amplified signal. These idlers could be used not only for wavelength conversion or 2R and 3R signal regeneration but also for increasing the number of carriers on the transmitter side of a WDM transmission system.

Therefore, a model of a dual-pump FOPA has been introduced for doubling the number of existing carriers in a WDM transmission system. For this reason, a simulation model of a 32-channel DWDM transmission system has been created with 10 Gbps transmission speed per channel, 100 GHz channel spacing, and NRZ-OOK modulation format. This system simulation model is displayed in **Figure 12**. The authors chose SMF length of 20 km, because it is the typical line length of optical access networks. EDFA preamplifier is used here for insertion loss compensation of transmission line and other transmission elements.

The main feature in the simulation model, which is presented in **Figure 12**, is that the FOPA is placed before the transmitter block or at the 32-channel modulator inputs. The optical

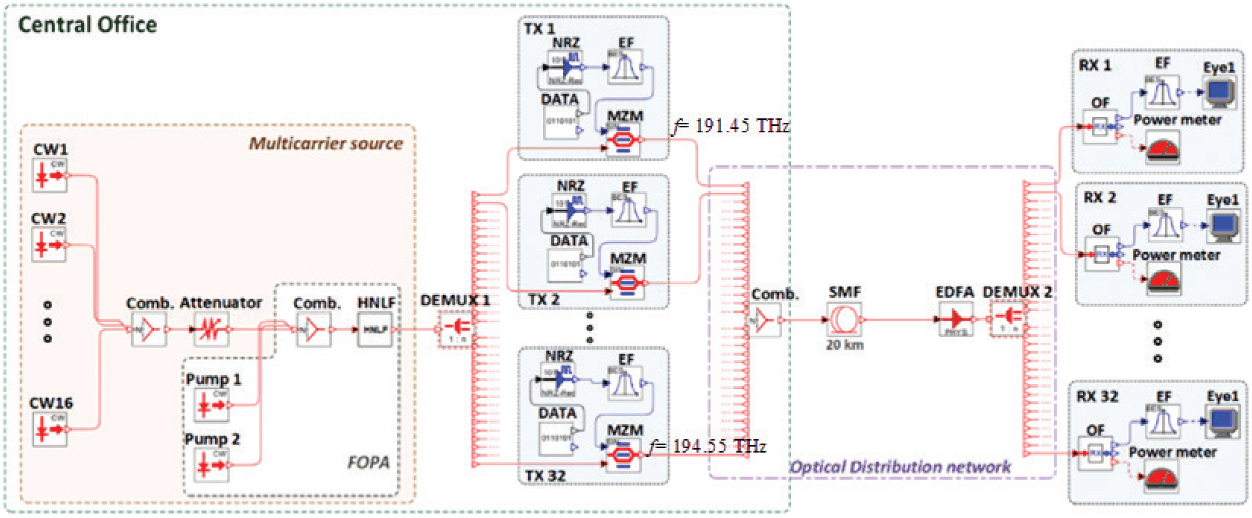


**Figure 12.** Simulation model of the 32 channel 10 Gbps WDM transmission system with the provided multicarrier source solution, which is based on wavelength conversion using a dual-pump FOPA.

multicarrier source consists of continuous radiation lasers (CW1–CW16), an optical attenuator, two powerful pumping sources, two optical splitters, and a 500 m long HNLF. One of the main goals of this experiment is to obtain 32 carriers with even frequency distribution (equal channel spacing), which can be achieved by using idlers $\omega_4$. Taking into account that the distribution of idlers $\omega_4$ and the initial light source frequencies are symmetrical in respect to the gain medium ZDWL, it has been decided to place the carrier with the lowest frequency higher by 50 GHz than the HNLF ZDWL (193 THz). Therefore, the frequencies of the 16 initial carriers are distributed in a range from 193.05 to 194.55 THz with 100 GHz channel spacing (see **Figure 13a**). The optical flow sent through the parametric amplifier is not modulated and basically represents a continuous radiation set. At the output of the HNLF, a combination is obtained consisting of 16 initial carriers, 16 idlers $\omega_4$ (generated as a result of parametric processes), 2 pumps, and other third-order spectral components (see **Figure 13b** and **c**). The pump power for both pumps is set to 400 mW each (26 dBm), and 190 and 196 THz frequencies are temporarily chosen.

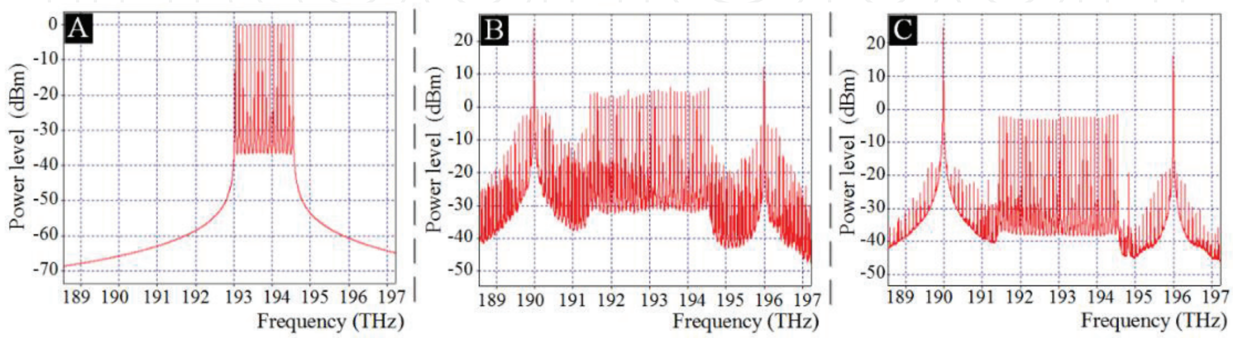


**Figure 13.** Optical spectrum at the input of the FOPA when initial carrier power is set to 0 dBm (A) and optical spectra at the output of the HNLF when the power of the initial carriers is set to 0 dBm (B) and to −10 dBm (C).

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It has been found that when given an excessively high level of input signal power, CC-FWM processes will trigger explicit interchannel cross talk (see **Figure 13b**). Due to this reason, when the idlers obtained as a result of parametric processes are used for increasing the number of carriers, it is necessary to limit the power of the carriers at the amplifier input. Based on the obtained results, the power level of the initial carriers at the input of the amplifier is reduced to −10 dBm. The alignment of idlers in respect to the central frequencies of the throughput band of demultiplexer filters is achieved by changing the frequency of the first pumping radiation (frequency obtained in simulations −196.01 THz). With the aforementioned amplifier configuration, the maximum power level difference among all the 32 channels has been reduced to 1.9 dB.

To assess the performance of the proposed system architecture solution, BER value dependence on the received signal power in the channel with the poorest signal quality (the highest BER) is obtained. These results are compared to the corresponding results obtained in a system with traditional architecture (with 32 laser sources, which function in a continuous radiation mode). The obtained results are shown in **Figure 14**. It has been found that power penalty of 1.8 dB exists between the system with the proposed multicarrier source and the conventional 32-channel solution. It is important to note that part of the obtained power penalty is directly related to the large amount of ASE produced by the EDFA used as a preamplifier for ensuring the necessary signal power at the input of the received block.

There are at least two alternatives to the proposed system architecture, which can produce more than one carrier per optical source: spectrum-sliced systems [33, 35] and systems, which are based on FWM use for producing third-order spectral components (without the initial carriers) [34, 36]. Nevertheless, the use of idlers $\omega_4$ produced by FOPA for doubling the number of carriers in WDM systems ensures the best carrier signal stability and, therefore, the highest quality of the transmittable signal.

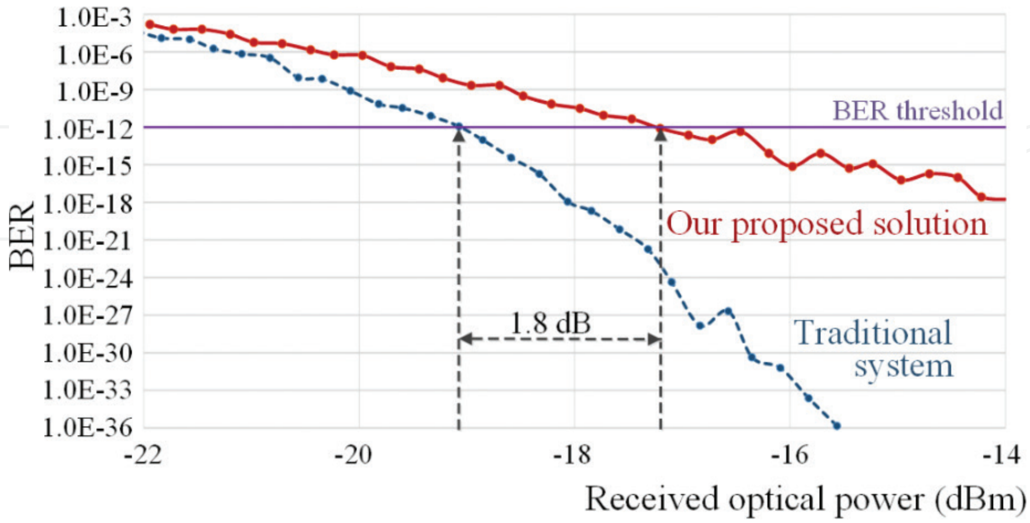


**Figure 14.** BER value dependence on the power of the detected signal for the 12th channel ($f$ =192.55 THz; $\lambda$ = 1557 nm) in the system with the proposed multicarrier source solution (solid line) and in the system with traditional architecture (dashed line).

It has been found that for dual-pump FOPAs the maximum amplification efficiency is achieved when both pumps are linearly polarized with the same state of polarization (SOP) and their SOP corresponds to the SOP of the amplified signal. However, when the SOP of both linearly polarized pumps is orthogonal to the SOP of the amplified signal, amplification decreases to its minimum value, and in a broad frequency region, it is equal to zero. The results obtained in this paper have shown that the same situation is observed also in the case of single-pump FOPAs.

This property of parametric amplifiers can be used for emphasizing one state of polarization from a combination of two orthogonally polarized optical components. The key problem, which is observed when the FOPA is used for emphasizing a specific state of polarization, is ensuring the conservation of the relative positioning of signal and pump SOP throughout the entire length of HNLF. This problem occurs due to the following reasons:

- Due to the effect of fiber birefringence, SOP of optical radiation changes along the fiber, and, as result, random SOP rotation is observed. It is very difficult to compensate such a random SOP change, as the rotation rate is affected by various factors, such as temperature, the frequency of the transmitted radiation, internal and external mechanical loads, etc. It is possible to avoid rotation of SOP of the pumps and the amplified signal by using polarization-maintaining HNLF as the gain medium.
- When the amplified signal and the pumps are propagating in the gain medium, additionally to fiber birefringence, their states of polarization are also affected by self-phase modulation (SPM) and cross-phase modulation (XPM) nonlinear effects. Therefore, when configuring the parametric amplifier, it is first necessary to avoid excessing pumping; otherwise, it can lead to a more explicit occurrence of SPM and XPM, which decreases the efficiency of the FWM process in the gain medium.

It is not possible to completely avoid changes in relative positioning of the SOP of the signal and the SOP of the pump. To demonstrate this, a simulation model is introduced, where a single-pump FOPA (500 mW, 1533.9 nm) amplifies a signal with −31 dBm total optical power at the input of the HNLF. At first, both the signal and the pump are linearly co-polarized. During the simulation, the SOP of the pump is rotated in respect to the SOP of the amplified signal, and the power of the signal is observed at the output of the FOPA. It has been found that by using polarization-maintaining fibers, under the influence of SPM and XPM, a change in the relative positioning of the signal SOP and the pump SOP is observed. As a result of this change, even when the signal is orthogonally polarized in respect to the SOP of the pump at the input of the HNLF, the signal obtains 1.5–1.6 dB gain. When the SOP of the amplified signal is co-polarized with the SOP of the pump, the obtained amplification reaches 18.3 dB, which is by 16.7 dB higher than in case of orthogonal relative positioning of the SOP at the input of the HNLF.

As it has already been previously mentioned, the polarization dependence of the parametric gain can be used for emphasizing radiation with a specific SOP from the flow of orthogonally polarized optical components, which in its turn can be used for emphasizing polarization-multiplexed signals and 2PolSK to NRZ-OOK modulation format conversion.

For conversion of 2PolSK signal to NRZ-OOK modulation format, cases of single-channel and multichannel systems are considered. To avoid changes in relative positioning of the states of polarization between pumping radiations, single-pump parametric amplifiers are used in both cases. In both cases, the FOPA is placed at the receiver (or receiver block) input.

At first, a single-channel transmission system simulation model is introduced with 2PolSK modulation format, 150 km long optical fiber, a FOPA preamplifier (which simultaneously performs modulation format and wavelength conversion functionality), and two receivers for detecting the converted NRZ-OOK signal at signal and idler frequencies. The introduced simulation model is displayed in **Figure 15**.

In case of a single-channel system, the primary task is to assess the new modulation format conversion solution created within the scope of this paper, by obtaining a power penalty introduced specifically by the process conversion of the modulation format. Based on the obtained results, 535 mW, 1554.1 nm pumping radiation is chosen, the phase of which is modulated with the following frequency tones: 180 MHz, 420 MHz, 1.087 GHz, and 2.133 GHz. Such configuration ensures 14.8 dB gain for the logical "1" component of 2PolSK signal, which is sufficient for ensuring BER value below the $10^{-12}$ mark for the obtained NRZ-OOK signal.

Based on the obtained results, it has been concluded that the idler requires lower pump power to ensure BER values below the $10^{-12}$ mark, even though the gain for idler is lower by 0.8 dB than the signal (see **Figure 16**). Therefore, in the case of a single-channel system, it is recommended to process the idler spectral component as the informative signal. These results can be explained by the fact that the signal at its initial frequency contains the orthogonally polarized logical "0" component, which for the obtained NRZ-OOK signal is interpreted as noise.

It has been found that the power of the obtained NRZ-OOK signal that is necessary to ensure BER value below $10^{-12}$ is −23.65 dBm, whereas the necessary idler power is −23.8 dBm (see **Figure 17**). In a standard single-channel system with NRZ-OOK modulation format, the signal power required to ensure BER value below the $10^{-12}$ threshold has reached −24 dBm. Thus, there is a power penalty of 0.4 dB between the NRZ-OOK signal from the standard

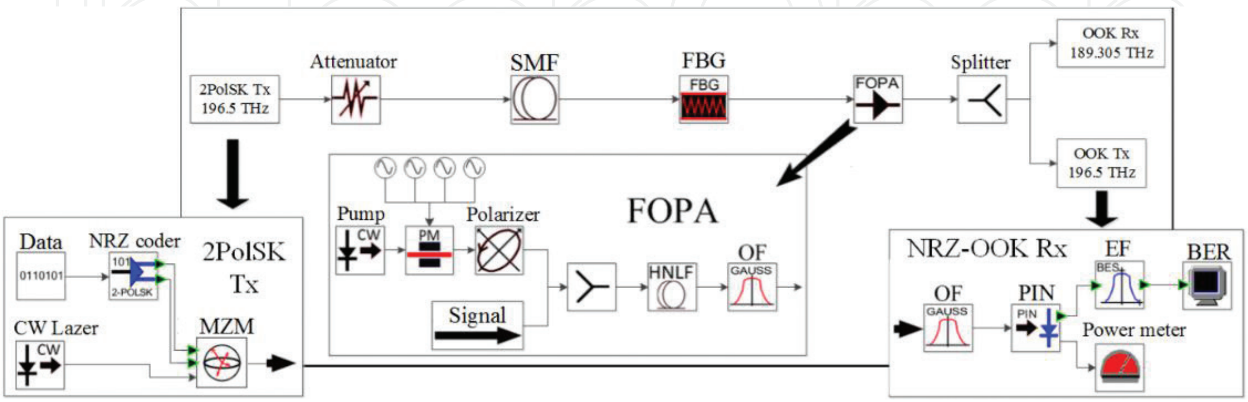


**Figure 15.** Simulation model of the single-channel transmission system, where a single-pump FOPA with linearly polarized pumping radiation is used for 2PolSK to NRZ-OOK modulation format conversion.

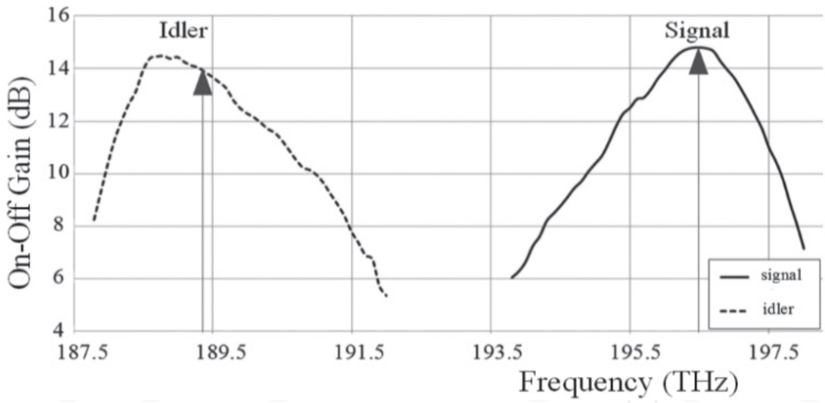


**Figure 16.** Gain spectrum produced by the single-pump FOPA with linearly polarized pumping radiation at signal frequencies (solid line) and at idler frequencies (dotted line).

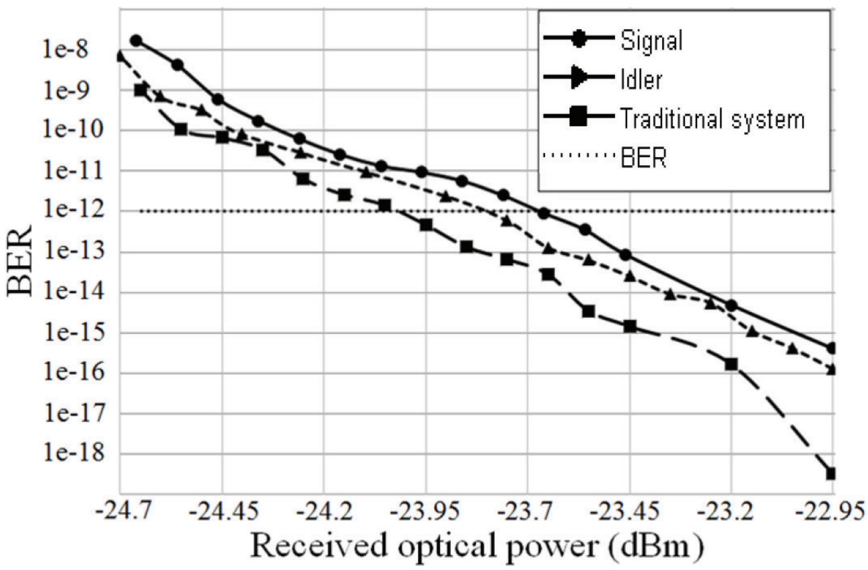


**Figure 17.** BER value dependence on the detected signal power in the standard single-channel transmission system (dashed line) and in the system with modulation format conversion at the initial signal frequency (solid line) and at idler frequency (dotted line).

single-channel system and the converted signal. It is important to note that the power penalty between the NRZ-OOK signal from the standard single-channel system and the generated idler is lower by 0.1 dB (only 0.2 dB). These results are explained by the fact that the idler produced during the FWM process does not contain the logical “0” component of the initial 2PolSK signal, which in this case is interpreted as noise for the converted NRZ signal. The obtained power penalty values are also attributable to the relative intensity noise, which is transferred from the pumping radiation to the amplifiable signal, as well as to the phase SOP mismatch between the pump and the amplified signal that occurs due to SPM and XPM.

In the case of the multichannel system, the goal is to assess the performance of the developed modulation format conversion solution in the presence of interchannel cross talk. When converting 2PolSK signal to NRZ-OOK modulation format, using FOPA with linearly polarized pumping radiation, one must pay special attention to the control of the level of interchannel cross talk produced by the CC-FWM interactions because if the SOP pumping radiation and SOP signal coincidence, the FWM process takes place with its maximum efficiency, including also production of the CC-FWM interchannel cross talk.

To assess the performance of the proposed solution in the presence of interchannel cross talk, a 16-channel 10 Gbps DWDM transmission system is introduced with 2PolSK initial modulation format and 100 GHz channel spacing (see **Figure 18**). In this system, the access network is divided into two branches, eight channels in each. The first branch consists of eight channels, occupying frequency range from 194.5 THz (1541 nm in wavelength) to 195.2 THz (1536 nm), whereas the second branch is occupying frequency range from 196.2 THz (1528 nm) to 196.9 THz (1523 nm). Only those results are included in this paper, which are obtained in the second access network branch, where the signal is divided among eight receivers using an optical splitter with 10.5 dB attenuation.

Based on the obtained results, in the second access network branch, 790 mW 1554.15 nm pumping radiation is used, the phase of which is modulated with the same frequency tones as in the case of a single-channel system: 180 MHz, 420 MHz, 1.087 GHz, and 2.133 GHz. It has been found that to ensure BER values below the $10^{-12}$ threshold, all eight idlers require pump power that is by 35 mW higher than in the case of the signals at their initial frequency. The obtained gain for the idler spectral components is lower by at least 2.2 dB, whereas the gain spectrum slope near its maximum is higher than in the initial signal frequency band (see **Figure 19**). The obtained level of amplification in the initial signal frequency band changes in the range from 30.3 to 30.9 dB among all eight channels; thus, the amplification difference between the channels reaches 0.6 dB. Between the idler spectral components, such difference has reached 2.6 dB (from 26.1 to 28.7 dB), but the biggest amplification difference between the signal at its initial frequency and the corresponding idler has reached 4.2 dB. This explains the need for pump power exceeding 35 mW to ensure BER values below the $10^{-12}$ mark in the idler frequency band.

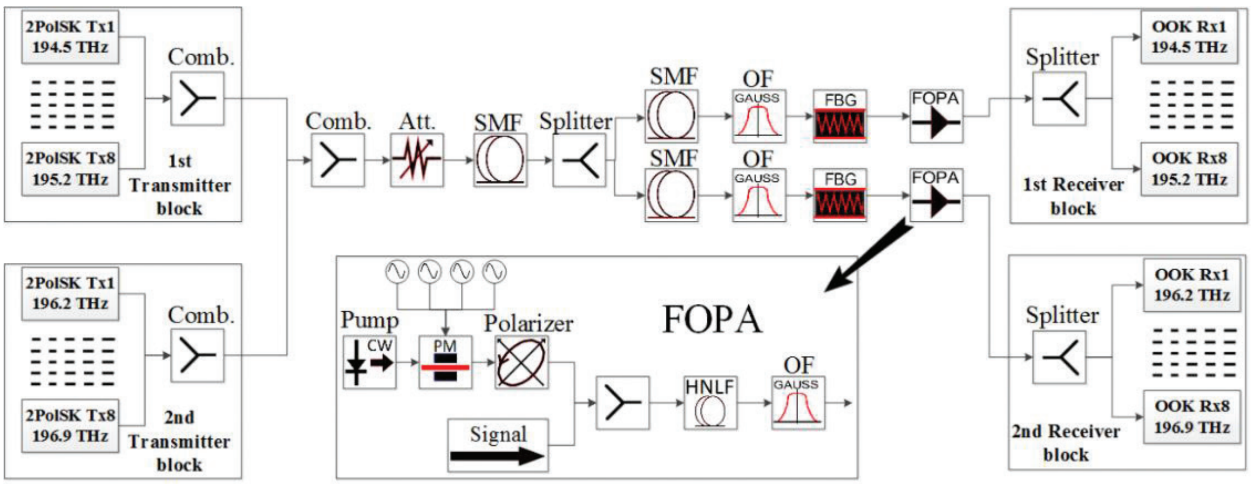


**Figure 18.** Simulation model of the 16-channel WDM transmission system with two access network branches, where in each branch the FOPA preamplifier is used for 2PolSK to NRZ-OOK (on-off keying) modulation format conversion.

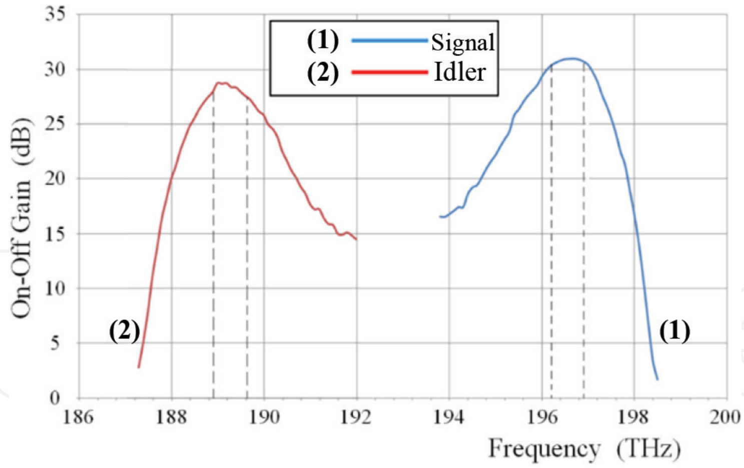


**Figure 19.** Gain spectrum ensured by the FOPA with 790 mW 1554.15 nm linearly polarized pumping radiation at initial signal frequencies (1) and idler frequencies (2).

To assess the performance of the proposed solution, the results obtained in the second branch of the access network are compared to the standard eight-channel DWDM system without signal amplification. The detected signal power required to ensure a certain BER value in the fifth channel of the second access network branch both at the initial signal and idler frequencies is compared with the same results obtained in the standard eight-channel DWDM system. As seen in **Figure 20**, in a system with modulation format conversion, to ensure BER values below the $10^{-12}$ mark, the required signal power is at least −23.5 dBm. In the standard eight-channel system, the corresponding required power level is −23.9 dBm; therefore, in this case, the power penalty between the signal with the converted modulation format and the signal from the standard eight-channel solution is 0.4 dB. It must be particularly emphasized that, contrary to the single-channel system, in the multichannel system, the idler BER values are higher than those of signals at their initial frequencies—when receiving the idler corresponding to the fifth channel, at least −23.15 dBm is required to ensure a BER value below the $10^{-12}$ threshold, which is more by 0.3 dB than receiving the signal of the fifth channel at its initial frequency.

It has been found that in case of the idler, larger amplitude fluctuations are observed, which densify the logical “0” and “1” component levels of the eye diagrams. The cause behind generating noise of such range is CC-FWM produced interchannel cross talk, which is produced as a result of parametric amplification and creates third-order spectral components, the frequencies of which correspond to the frequencies of the amplified signals. As mentioned previously, the gain difference between the idlers is much larger (by 2 dB) than between the signals at their initial frequencies. Therefore, more explicit manifestation of CC-FWM processes is observed, which also produces additional interchannel cross talk. Moreover, the cross talk caused by CC-FWM is not only transferred from signals at their initial frequencies to the idlers but is also generated between the idlers.

It has also been found that the pumping radiation-phase modulation leads to spectral expansion of the idlers by approximately 40%, which, accordingly, results in additional interchannel

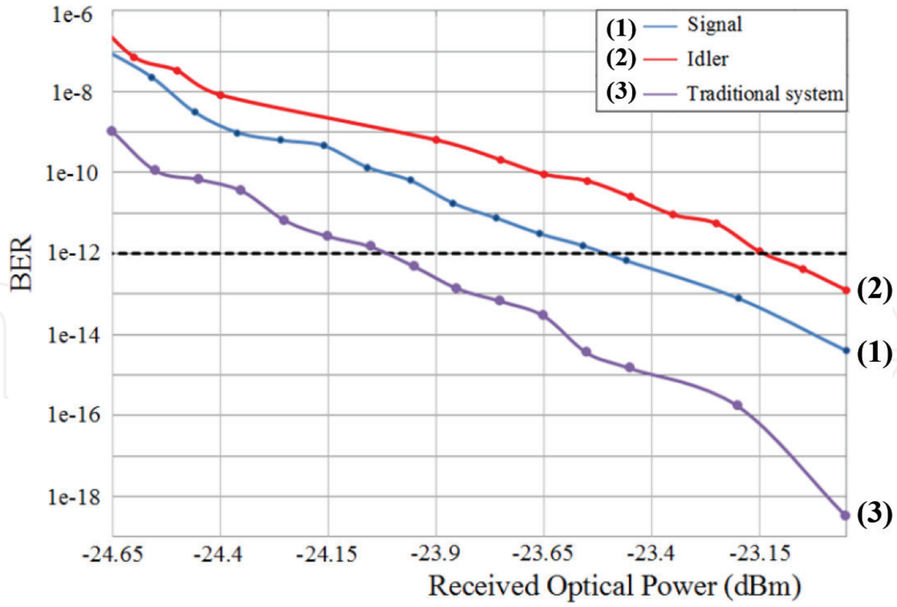


**Figure 20.** BER value dependence on the detected signal power in the standard eight-channel transmission system (3) and in the fifth channel on the second branch of the multichannel system with modulation format conversion at the initial signal frequency (1) and idler frequency (2).

cross talk. Interchannel cross talk caused by the CC-FWM interactions and idler spectral broadening is the main reason why, in the case of idlers, the power penalty in relation to the standard system is larger by 0.4 dB than for signals at their initial frequencies.

The second studied application of parametric gain polarization dependence is the emphasizing of a signal with a specific SOP from a combination of two polarization-multiplexed NRZ-OOK signals. For this purpose, a two-channel 10 Gbps transmission system with NRZ-OOK modulation format and polarization multiplexing is introduced (see **Figure 21**). Both signals, the SOP of which are mutually orthogonally allocated, are transmitted using the same frequency −196.5 THz.

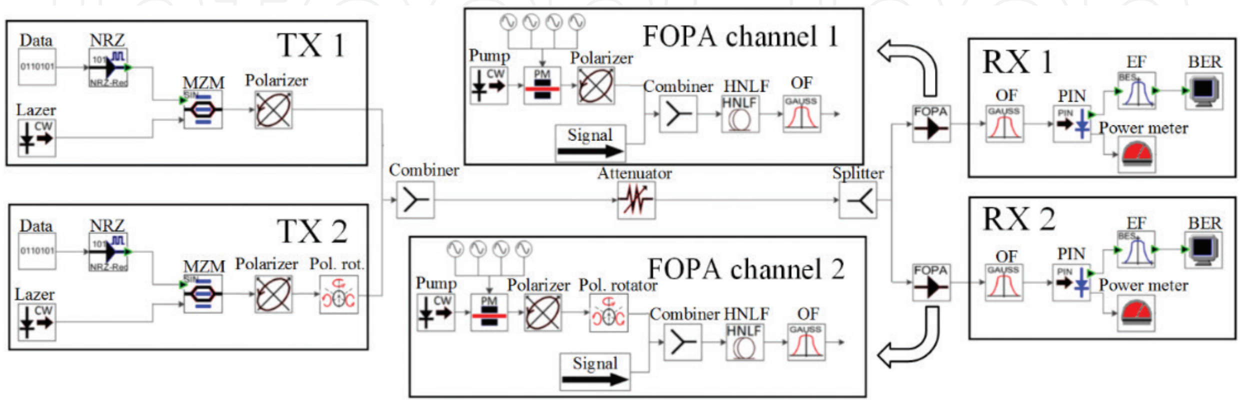


**Figure 21.** Simulation model of the two-channel optical transmission system with FOPA for division and amplification of polarization-multiplexed signals.

Based on the obtained results, a decision has been made to use 530 mW 1553.9 nm pumping radiation in the case of both FOPA, because this is the lowest pump power that can ensure BER values below the $10^{-12}$ threshold in both the first and the second channel. Previously described results have shown that phase modulation of the pump can cause spectral broadening of idlers. In a situation, when the probability that both orthogonally polarized optical radiations are observed simultaneously in the logical "1" level is high, the mutual deviations of the SOP of optical components have a bigger impact on the quality of the amplified signal than in the case when such simultaneous transmission of logical "1" is not performed (e.g., in the case of 2PolSK signal). Therefore, it is important to minimize the phase mismatch between the pumping radiation and the amplified signals, which can also cause a change of the relative positioning of SOP between the signal and the pump. Bearing in mind this fact and having observed the FOPA produced gain spectrum and in the OSNR at the output of the amplifier, the following frequency tones have been selected for pumping-radiation phase modulation: 0.13 GHz, 0.42 GHz, 1.087 GHz, and 1.94 GHz. The obtained signal gain in the first channel has reached 20 dB, whereas in the second channel, it has reached 20.1 dB. Idler component gain maximum is lower by 0.7 dB (see **Figure 22**).

To assess the performance of the proposed solution, BER value dependence on the received signal power is obtained, and these results are compared with the same results obtained in a standard single-channel transmission system with NRZ-OOK modulation format without optical signal amplification. It can be concluded from the results shown in **Figure 23** that there is a power penalty of 0.8 dB between the signal detected in the first channel and the signal from the standard single-channel NRZ-OOK system. The power penalty for the idler spectral component has reached 0.5 dB.

Unlike the system with modulation format conversion, in this case, a situation has been observed, when, given the same frequency, it is possible that the logical "1" of orthogonally polarized components is observed simultaneously in both channels. Thus, the effect of orthogonally polarized radiation on the divided signal quality is higher than in a system with modulation format conversion. This is the fact, which mainly explains a larger power penalty value than

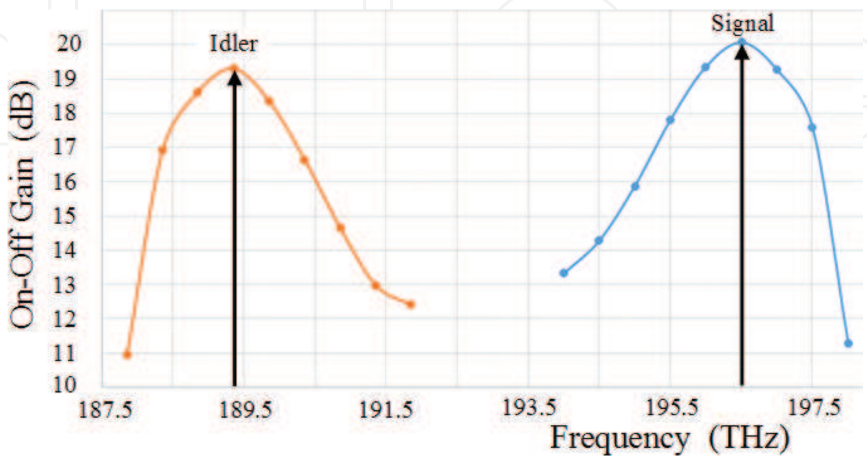


**Figure 22.** FOPA produced on-off gain for the first channel at idler frequencies (left side) and at the initial signal frequencies (right side).

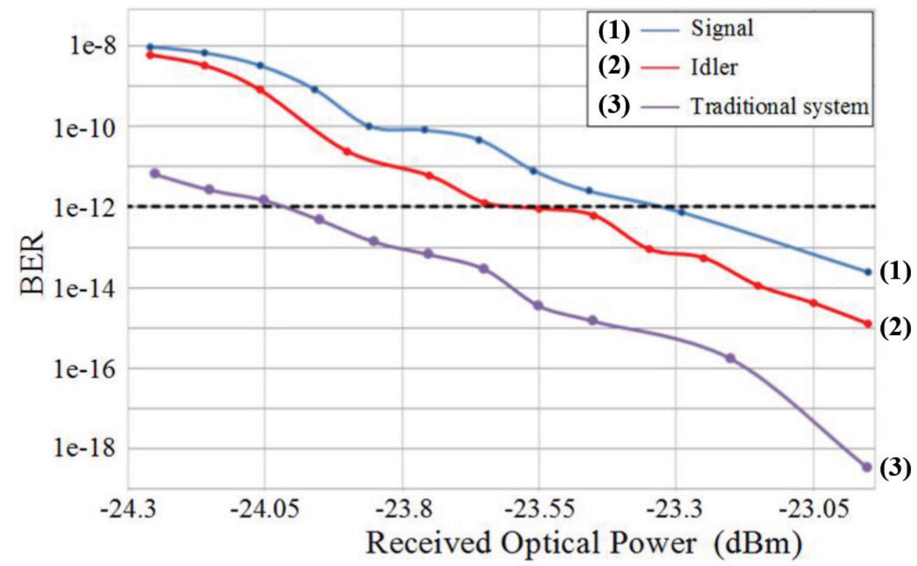


**Figure 23.** BER value dependence on the power of the detected signal in the standard single-channel system (3) and in the first channel of the system with the chosen FOPA configuration of the signal at its initial frequency (1) and of the idler (2).

in a single-channel system with modulation format conversion. A lower power penalty value in the case of idler component is explained by the fact that the orthogonally polarized radiation of the second channel is not included in the parametric amplification and idler generation process, and, therefore, it is not reflected in the idler itself. Irrespective of the fact that the amplification of orthogonally polarized (second channel) radiation is much lower (1–2 dB), its power level is still sufficiently high to affect the BER value of the divided signal, which in our case produces an additional power penalty of 0.3 dB. The idler use has allowed achieving a lower power penalty in respect to the standard single-channel system with the NRZ-OOK modulation format, whereas to achieve a BER value below the $10^{-12}$ threshold, it is necessary to use pump power that is larger by 10 mW than that when receiving the initial signal with 196.5 THz frequency.

Upon comparing the amplification spectra in a single-channel system with modulation format conversion and in a system with polarization-multiplexed signal division, it has been concluded that the amplification obtained in the latter case is larger by 5.2 dB (14.8 and 20 dB, respectively), irrespective of the fact that the pumping radiation power differs only by 5 mW. This is explained by the following two factors:

- In a system with signal division from orthogonally polarized signal combination, the signal power level at the input of the HNLF fiber is lower by 3.4 dB (−44.1 dBm). Therefore, the amplifier requires a lower pumping radiation power for ensuring a specific amplification level.
- Secondly, to minimize the idler spectral broadening in a system with polarization-multiplexed signal division, the frequency tones used for pumping radiation-phase modulation are reconfigured, and the achieved amplification difference clearly shows that with the given configuration SBS mitigation is more effective than in a system with modulation format conversion.

Upon summing up all the information presented in this chapter, it can be concluded that polarization dependence of the parametric amplification can be used for emphasizing optical radiation with a specific state of polarization from a flow of two orthogonally polarized optical radiations. FOPA with linearly polarized pumping radiation can be used both for 2PolSK signal conversion into NRZ-OOK modulation format and for signal emphasizing from a flow of two polarization-multiplexed optical signals. In both cases, such FOPA configurations have been found, which ensure that the BER values of the processed signal are below the $10^{-12}$ mark, and at the same time, none of the proposed solutions cause power penalty that exceeds 1.8 dB in comparison with the relevant standard solutions.

## 5. Conclusions

The implementation of the hybrid Raman-EDFA amplifier has allowed not only equalizing the gain spectrum but also increasing OSNR in all channels by 1.7–2.6 dB. The usage of the distributed Raman amplifier in cascade as a preamplifier has allowed the EDFA to operate closer to the saturation point, and, therefore, the EDFA noise figure decreased by 0.3–0.4 dB. The OSNR increase is also related to the fact that due to the coherent nature of Raman scattering, DRA amplifies the signal more effectively than the noise, which allows obtaining negative noise figure values (from −0.4 to −0.6 dB).

The implementation of the hybrid Raman-SOA amplifier has enabled the use of such SOA configuration, at which SOA produced the lowest amount of amplified signal distortions. As a result, by using the Raman-SOA hybrid amplifier, it is possible to obtain approximately the same BER level as in the case when the SOA is used as a single in-line amplifier for a signal, which is weaker by 1.5 times. This has allowed increasing the attainable transmission distance by 12 km or by 11%.

While changing the power of FOPA pumping radiation, the nonlinear phase mismatch of the parametric process also changes. Therefore, while configuring the pump power, the wavelength must also be changed accordingly.

Modulation of the FOPA pumping radiation phase, which has been used for increasing the SBS threshold, has caused spectral expansion of idlers by 54%. Therefore, the frequency tones used in systems with wavelength conversion for pumping radiation-phase modulation must be selected in a way that ensures that the spectral expansion of idlers remains as low as possible.

By manipulating with the parameters of dual-pump FOPA, it is possible to achieve an increase in the number of carrier signals from 16 to 32, simultaneously ensuring equal channel spacing of 100 GHz and maximum difference in power levels of 1.9 dB among all channels. It has been found that, in case when each carrier signal power at the input of the FOPA is equal to 0 dBm, the CC-FWM interactions produce considerable interchannel cross talk. Due to this reason, when using the idlers to double the number of carriers, it is necessary to control the power of carrier signals in the amplifier input.

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It has been found that even when using polarization-maintaining HNLF fibers, due to the influence of self-phase modulation and cross-phase modulation, a change in interposition of SOP of the signal and FOPA pumping radiation has been observed, as they are transmitted through HNLF. As a result, the signal, the SOP of which is orthogonal in respect to the SOP of the pumping radiation at HNLF input, has been amplified by 1.5–1.6 dB.

In a single-channel system with 2PolSK signal conversion to NRZ-OOK modulation format, power penalty of 0.4 dB has been observed between the NRZ-OOK signal from the standard single-channel system and the converted signal, whereas in the case of the idler spectral component, the power penalty is lower by 0.2 dB. These results can be explained by the fact that the idler produced by the parametric FWM process does not contain the logical “0” component radiation from initial 2PolSK signal, which for the converted NRZ signal is interpreted as noise.

In the multichannel system with modulation format conversion, a more explicit manifestation of CC-FWM processes has been observed among the idlers rather than among channels at initial frequencies. This can be explained by the fact that pump power exceeding 35 mW is required to obtain BER values below the $10^{-12}$ threshold in all eight channels in the idler frequency band than for signals at their initial frequencies. As a result of such amplification difference, more explicit CC-FWM manifestation has been observed, which accordingly has led to additional interchannel cross talk. Additionally, cross talk generated by CC-FWM has not only been transferred to the idlers from the signals at their initial frequencies but also generated among the idlers.

Unlike the system with modulation format conversion, in the system with signal emphasizing from the flow of two orthogonally polarized signals, a situation is observed, when at the same frequency it is possible that the logical “1” components are observed in both channels simultaneously. Therefore, the influence of orthogonally polarized radiation on the quality of the emphasized signal is larger by 0.4 dB (in the case of idlers, by 0.3 dB) than in a system with modulation format conversion.

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