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*Research Article*

# Suppression of Nonlinear XPM Phenomenon by Selection of Appropriate Transmit Power Levels in the DWDM System

**Tomáš Ivaniga**[1] **and Petr Ivaniga**[2]

[1]*Department of Electronics and Multimedia Communications, University of Technology Košice, Košice, Slovakia*
[2]*Department of Information Networks, Faculty of Management Science and Informatics, University of Žilina, Žilina, Slovakia*

Correspondence should be addressed to Tomáš Ivaniga; tomas.ivaniga@tuke.sk

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In the 21st century, it is not possible to implement fully optical communication systems without software tools to test the system for all unwanted phenomena occurring during real-time operation. With ever-increasing transmission rate and low latency, nonlinear phenomena are associated with higher power levels and smaller spacing between channels began to appear in OFs (optical fibers). This paper aims to implement a four-channel DWDM (Dense Wavelength Division Multiplex) system on which the nonlinear XPM (cross-phase modulation) phenomenon will be investigated. At the output of the system, we will eliminate the phenomenon (partially suppressed) by the appropriate choice of transmitting power levels (power levels operating at 193,025 THz to 193,175 THz) when the OF is dispersed. In optical transfer data systems a system is functioning if the measured BER parameter is not bigger than $10^{-12}$.

## 1. Introduction

One of the parameters for assessing the quality of life in our modern age is also access to information and information resources in general, their veracity, timeliness, and punctuality. Current development trends in the area of communication technologies, in addition to the nonlinear increasing requirements for transmission speed and the increase in the volume of transmitted data, also highlight the quality requirements of high-speed infrastructure [1–3]. This steady increase in requirements moves from the development of telecommunication services and is due to the rapidly evolving use of information technology of various broadband multimedia services. The optimal use of telecommunications services by users is conditional on the maximum possible utilization of the OF transmission bandwidth. More efficient use of fiber optic transmission bandwidth is currently enabled by WDM (Wavelength Division Multiplexing) technology, with ongoing upgrades to achieve higher speed and transmission quality.

One of the systems working on the WDM platform is the DWDM transport transmission system, which will be discussed in more detail in the next subchapter. Thanks to DWDM systems it is possible to attain the transfer speed of 1T. Considering the ever-increasing amount of transmitted data, the demand for data transmission speeds increases, approximately 1.5 times a year, along with the increasing demand for transmission quality [4]. The second chapter is devoted to WDM and their standards CWDM and DWDM. Next chapter is focused on nonlinear phenomenon XPM and its possible applications. In the last chapter is created a 4-channel DWDM system in programme OptSim, where XPM is shown.

## 2. WDM Technology

The continually increasing bandwidth requirements have prompted telecom operators to look for new technologies that would allow them to work at high bandwidths [4]. The solution provides a WDM wavelength division multiplex which employs multiple optical waves transmitting with one OF for data transmission, each of which is at a different wavelength.

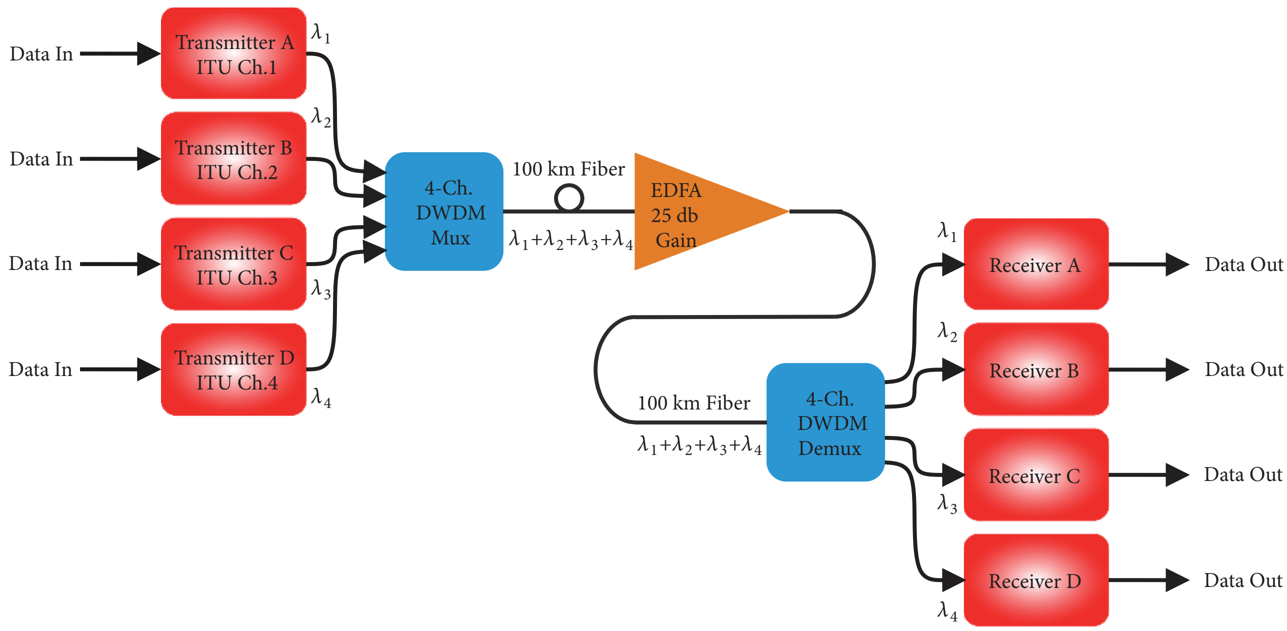


Figure 1: Suggestion for 4-channel DWDM system.

The implementation of WDM devices into existing optical networks is very simple and easy, as it is only necessary for the technology to innovate or complete the transmission systems, while the OFs remain physically unchangeable [5–8]. For this reason, WDM transmission systems are currently the most used and come with the best advantages. WDM networks have several significant advantages compared to conventional optical networks:

(i) Make better use of the transmission capacity of optical networks

(ii) One OF can transmit signals with different transmission rates and different modulation and signal types

(iii) Simultaneous transmission of analog and digital signals at different wavelengths

(iv) If we need to increase the transfer capacity, there is no need to increase the transfer rate on one channel but add another wavelength

(v) The demand for the speed of electronic support circuits (optoelectronic transducers, modulation circuits, etc.) decreases

As WDM disadvantages we can mention

(i) Additional attenuation of WDM multiplexers and demultiplexers

(ii) Use of quality and stable light sources for different wavelengths

(iii) The need for top quality filters

(iv) The technological difficulty and hence a higher price level for each component

*2.1. DWDM Technology.* By implementing DWDM technology in optical transport networks, we will be able to transmit data at a speed of even several Tbit.s$^{-1}$, which are transmitted over a thousand-kilometer distance. These features make this technology highly competitive for international telecommunications transmission providers, despite its financial cost. DWDM systems utilize bandwidth mainly around the basic width of 1550 nm, and the channels used range from 1525 to 1610 nm, with a pitch of 0.2 nm to even 0.1 nm by default [6]. Currently, 16-, 24-, 40-, 80-, 128-, and 256-channel systems are commercially used. The 40-channel system uses a 100 GHz channel range and 50 GHz for an 80-channel system. This separation determines the width of the spectral wavelength of each channel, i.e., as the channels are close to each other [8]. The number of channels used also depends on the OF used on the optical path, but for standard SM (single mode) OF we can transport data over a distance of more than 80 km without using an amplifier. If we have to transmit data over long distances, signal amplifiers placed in cascade style are used every approximately 80-100 km [7–9]. By competing among the companies that are trying to break the record in achieving the highest speed, bridging distance, and using multiple channels on a single OF, the DWDM technology is moving fast. This trend is likely to continue until the physical limits for this technology reached its boundaries. Figure 1 shows the basic DWDM system topology. More than 1000-channel systems can theoretically be used. Most recently, 1024 wavelength single-strand transmission devices have been demonstrated where the transmission capacity is 100 Gbit.s$^{-1}$ per length. This value goes over beyond today's needs, but it may not be soon enough when data is transmitted, and the progress keeps up as the forecast shows.

Initially, only the point-to-point network topology was used in DWDM technology, but nowadays, different types such as a circle, star, or polygonal topology are being combined. This is important for service providers who need to cover a vast territory with optical networks and flexibly respond to the possibility of extending the network to a new territory. Depending on the topology and OF length, signal amplifiers are placed. The need for an amplifier can be estimated from a distance between the transmitter and the receiver and the parameters of the transmission system such as the number of wavelengths, channel width, channel spacing, modulation technique, transmission rate, and OF type.

DWDM systems apply to many types of networks on all network layers, such as those used from intercontinental systems that connect entire continents to intercity networks where technology is only deployed on several network nodes. They apply to various types of operations such as SONET/SDH, ATM, IP, TDM, and the like, where each wavelength can transmit another type of service. The result is practical systems designed to transfer different types of services. In DWDM networks, the ITU G.709 protocol is used, which encapsulates the transmitted data and provides functions for operating, managing, maintaining, and deploying services to the system [10]. It also provides control, protection, and repair of data in various forms. Correction mechanisms significantly reduce transmission error rates and allow multiple distances without signal regeneration.

*Key advantages of DWDM are*

(i) High data transfer efficiency by a single OF
(ii) Theoretical range up to 100 km, without the need for a signal amplifier
(iii) Compatibility with other technologies
(iv) Easy extensibility with additional data channels
(v) Optical-level backup to minimize downtime
(vi) Easy expansion for additional DWDM/CWDM sites
(vii) The possibility of creating different logical topologies
(viii) Management using a Simple Network Management Protocol supervisory channel
(ix) Multiple uses of existing OFs

*2.2. CWDM/DWDM.* The fusion of wave multiplexes WDM is implemented mostly to increase the total capacity of the transfer system. This increase of WDM capacity can be reached in several ways, not necessarily exclusive of one another. The first option is to add more channels to the system, though that would result in the increase of the whole work spectrum which can already be exhausted because the majority of the components operate only within a limited spectrum. The second method is the decrease of gaping between channels, e.g., 100 GHz, 50 GHz, 25 GHz, to 12.5 GHz [11, 12]. The last solution would be to increase the data speed of individual channels. The coexistence of systems is understood as the incorporation of systems with higher data transfer speeds of its channels (e.g., 40 Gbit.s$^{-1}$) into the existing systems with lower data transfer speeds of their channels (e.g., 10 Gbit.s$^{-1}$).

In the technical terminology such systems could be found under *"The hybrid transfer systems 10G/40G"* or "*mix 10G/40G.*" According to the recommendation ITU-T G.696.1 the majority of fully optical communication systems work with a transfer speed of 10 Gbit.s$^{-1}$ using NRZ (Nonreturn to Zero) with gaping of 50 GHz or 100 GHz [11]. Because considerable finances have been devoted to the construction of systems with a transfer speed of 10 Gbit.s$^{-1}$, uprooting the entire system for something newer would be very costly. Therefore, it is logical that the next step for operators regarding how to increase transfer speeds would be to use the already existing infrastructure. It goes without saying that the new system would also be expected to be retroactively compatible. Due to the stated reasons, the 40 Gbit.s$^{-1}$ and 100 Gbit.s$^{-1}$ systems have a number of limitations requiring some attention. They are able to exist within the old infrastructure (OFs of type SMF) without changes to the dispersion map, resistance to nonlinear effects and PMD (Polarization Mode Dispersion), the signal's transition through OADM (Optical Add-Drop Multiplexor), their mutual influencing between 10 Gbit.s$^{-1}$ and 40 Gbit.s$^{-1}$/100 Gbit.s$^{-1}$, and the option of maintaining the 50 GHz gaping. Increasing the transfer speed from 10 Gbit.s$^{-1}$ to 40 Gbit.s$^{-1}$ and more brings several problems, making the typical solution of the classic amplitude modulation OOK-NRZ (On-Off Keying Nonreturn to Zero) unusable for this level. This is why the systems with greater transfer speed utilize the duobinary modulations (DPSK and DQPSK) and phase modulation PSK (Phase Shift Keying). At the mentioned transit the BER is increased 16 times, caused by the chromatic dispersion, squaring the speed multiple. The value of chromatic dispersion at the speed of 10 Gbit.s$^{-1}$ is tolerated by NRZ to 1000 ps/nm/km, whereas for the speed of 40 Gbit.s$^{-1}$ it is only 60 ps/nm/km [11, 13]. That implies that, with the increase of transfer speed, dispersion compensation is necessary if not indispensable. The other restriction is the requirement for OSNR which has to be larger by 6 dB (10 dB) for the 40 Gbit.s$^{-1}$ (100 Gbit.s$^{-1}$) receiver, if the original BER is to be maintained. Also the resistance against PMD decreases with the multiplication of speed to the limiting points of 3 ps for 40 Gbit.s$^{-1}$ and 1 ps for 100 Gbit.s$^{-1}$ [11]. It is created due to the production imperfections of OF and it causes a delay between polarisation components. Its compensation is not a stochastic process, compared to the chromatic dispersion. OF from before 1994 are unusable for high-speed and high-capacity transfers because of their high values of PMD. It has been proven that the restriction due to PMD and chromatic dispersion is negligible if using a coherent reception with digital signal processing [14–16]. Also the influence of 10 Gbit.s$^{-1}$ or 40 Gbit.s$^{-1}$/100 Gbit.s$^{-1}$ needs to be mentioned.

If the system with a transfer speed of 10 Gbit.s$^{-1}$ OOK-NRZ is merged into a system with a speed of 40 Gbit.s$^{-1}$ using PSK, the 40 Gbit.s$^{-1}$ the system will interfere with XPM, which originates from amplitude modulation. The interaction between transfer systems with 10 Gbit.s$^{-1}$ and 40 Gbit.s$^{-1}$ can be influenced by a simple change of transfer power or by a correct placing of channels. With appropriate planning for dispersion compensation and by the introduction of

RDPS (Residual Dispersion Per Span) these reductions are possible: XPM and FWM (Four-Wave Mixing). This is closely connected with choosing the correct type of OF. ITU-T G.652 shows a greater chromatic dispersion than ITU-T G.655 or ITU-T G.653, so it is better to suppress the occurrence of nonlinear effects at the output. It has been experimentally discovered that the phase-modulated signals with a higher symbolic speed (e.g., DPSK) have the tendency to be less influenced by XPM than the signals with a lower symbolic speed (e.g., DQPSK) [17]. The other alternative to coexistence is the fusion of CWDM and DWDM systems (in technical terminology marked as "*CWDM/DWDM*").

## 3. Nonlinear Phenomena Focusing on XPM

Nonlinear phenomena in OFs are generated by changing the refractive index of the medium with optical intensity and inelastic scattering. The dependence of the output from the refractive index is responsible for the Kerr effect. Depending on the type of input signal, Kerr's effect is manifested in three different phenomena, such as the SPM (Self-Phase modulation), FWM (Four- Wave Mixing), and XPM. The basic description of SPM and its applications has been explained in [7]. The origin, elimination, and description and mathematical description of FWM have been described [15]. At high power levels, inelastic scattering can cause stimulated phenomena such as SBS (Stimulated Brillouin Scattering) and SRS (Stimulated Raman Scattering) [18, 19]. The diffusion intensity of light increases exponentially if the incident power exceeds a certain threshold. The difference between Brillouin and Raman scattering is that SBS generates (acoustic) phonons that are coherent and cause macroscopic acoustic waves in the OF, while SRS generates phonons that are incoherent and do not generate macroscopic waves. Apart from SPM and XPM, all nonlinear phenomena generate profits in specific channels at the expense of performance depletion from other channels. SPM and XPM only affect the signal phase and can cause spectral expansion, leading to increased dispersion. The following topic will be explained in the basic description of the XPM phenomenon.

Refractive index intensity leads to a nonlinear phenomenon called XPM. If two or more optical pulses propagate simultaneously, a cross-phase modulation is created, accompanied by the actual phase modulation of the SPM. It is caused because the nonlinear refractive index of the optical pulse depends on not only the intensity of this beam, but also the intensity of other propagating pulses. XPM converts power fluctuations at a particular wavelength into phase fluctuations in other propagating channels [13, 20–22]. XPM can result in a disproportionate extension of the spectral line and distortion of the pulse shape. The effective refractive index $n_{eff}$ of the nonlinear medium can be expressed by the input power $P$ and the effective base region $A_{eff}$ as

$$n_{eff} = n_l + n_{nl}\frac{P}{A_{eff}}, \tag{1}$$

where $n_l$ is linear refractive index and $n_{nl}$ is nonlinear refractive index. For fused silica OF $n_l$ is approximately 1.46 and $n_{nl}$ is approximately $3.2\text{x}10^{-20}\ \text{m}^2/\text{W}$ [23].

Nonlinear phenomena are dependent on the ratio of light output to a cross-sectional area of the OF

$$k_{eff} = k_l + k_{nl}P, \tag{2}$$

where $k_l$ is the linear portion of the spread constant and $k_{nl}$ is the nonlinear propagation constant [11, 23, 24]. The phase shift caused by the nonlinear constant is after passing the distance $L$ inside the OF stated as

$$\phi_{nl} = \int_0^L \left(k_{eff} - k_l\right) dz. \tag{3}$$

Consequently, the nonlinear phase shift is expressed by the relation

$$\phi_{nl} = k_{nl}P_{in}L_{eff}. \tag{4}$$

If several optical pulses coincide, the nonlinear phase shift of the first channel depends on not only the strength of this channel but also the signal strength of the other channels [23, 24]. For two channels, the nonlinear phase shift is stated as

$$\phi_{nl}^1 = k_{eff}L_{eff}\left(P_1 + 2P_2\right) \tag{5}$$

For the N-channel system, the shift for the *ith* channel is expressed by the relation

$$\phi_{nl}^i = k_{nl}L_{eff}\left(P_i + 2\sum_{n\neq i}^{N} P_n\right). \tag{6}$$

The second term in the above equation is a nonlinear sensitivity form and suggests that XPM is twice as efficient as SPM at the same energy [23]. The first part of the equation is the SPM contribution and the second part is the XPM contribution [18, 24, 25]. XPM is only valid if the influencing signals overlap in time. XPM limits system performance in the same way as SPM, i.e., frequency "*chirping*" and chromatic dispersion.

However, XPM can interfere with system performance more than SPM. XPM has a significant impact on the system, especially with a large number of channels.

*3.1. Threshold Values, Control, and XPM Application.* A phase shift can only occur if two pulses overlap in time. Due to this overlap, the phase shift is heavily dependent, and subsequent "chirping" is increased. Hence, the extension of the pulse is also increased, limiting the performance of the light wave propagating systems. The effect of XPM can be reduced by increasing the separation between channels. For increased wavelength spacing, the pulses overlap for such a short time that the XPM effect is virtually negligible. In DWDM systems, XPM converts power fluctuations in individual wavelength channels to phase fluctuations in other simultaneously propagating channels [18, 26, 27]. This causes a widening of the pulse, which can be significantly suppressed in WDM systems using standard nondispersive single mode OFs. One of the advantages of this kind of OF is its effective core area, which usually has a value of 80 $\mu$m$^2$. This large effective area is useful in reducing nonlinear effects because $k_{nl}$ is inversely proportional to $A_{eff.}$

XPM, as well as SPM, are dependent on OF interactions. The great length of interaction causes to some extent the creation of this effect. By maintaining a small interaction time, it can reduce this kind of nonlinearity.

*3.2. Threshold Values, Control, and XPM Application.* The phase shift in the optical pulse caused by the XPM effect can be used for optical switching. Many interferometric methods have been used to take advantage of phase shifting for ultrafast optical switching. An interferometer designed in such a way that a weak signal pulse is distributed evenly over two portions recording an identical phase shift in each portion is transmitted through constructive interference [26]. A built-in pulse of any wavelength, led into one of the parts, changes the signal phase through XPM in this section.

If the induced phase shift is too large (close to $\pi$), it creates destructive interference, and thus the signal pulse is not transmitted. The intense excitation pulse can, therefore, switch the signal pulse.

*3.3. XPM Application with Impulses Pressing.* Like SPM causing frequency *"chirp,"* as well as XPM frequency *"chirp,"* can be used to press (compress) pulse. For SPM techniques, the input pulse needs to be intense and energetic, but the XPM can compress even weak input pulses because the propagating intense excitation pulse produces a frequency *"chirp."* The pulsating impulse influences the XPM *"chirp"* and critically depends on the initial relative delay of the excitation signal [17, 19, 28, 29]. Given the use of the XPM pulse compression, it is necessary to strictly control the excitation pulse parameters, namely, its width, peak power, wavelength, and initial relative signal pulse delay.

*3.4. Influence of XPM to Complete an Optical Communication System.* A set of $M$ differential equations can describe mutual connection or the interaction between $M$ WDM channels. If only the effects of SPM and XPM are considered, these equations are given

$$\frac{\partial U_j}{\partial z} = -iy_j \left( \left| U_j \right|^2 + 2 \sum_{m \neq j}^{M} \left| U_m \right|^2 \right) U_j, \quad (7)$$

where $j = 1$ to $M$, $U$ is a slowly varying amplitude, $\gamma_j$ is a nonlinear parameter, and $z$ denotes the propagation distance traveled [23, 25]. In the case of a continuous wave, the nonlinear phase shift of j is due to the combination of SPM and XPM given by the relation

$$\phi_j = \gamma_j L_{eff} = \left[ P_j + 2 \sum_{m \neq j}^{M} P_m \right], \quad (8)$$

in which $P_j$ is the input power of the wave. Equation (8) shows that the impact of XPM is much more important than the impact of SPM in multichannel communication systems. However, OF dispersion generally decreases this effect. The effect of cross-phase modulation varies in amplitude and phase-modulated systems. If the power in each channel is the same for all bits, the main limitation results from independent phase fluctuations, which directly leads to a deterioration of the signal-to-noise ratio [13, 23]. Such phase fluctuations can be caused by the XPM phenomenon, by changes in intensity, which occur when semiconductor lasers are directly phase modulated [30, 31]. Within amplitude modulated direct detection systems, XPM does not affect the performance of the dispersion neglect system. Since the changes in the phase caused by the XPM phenomenon are related to frequency changes, the dispersion determines the additional time extension or compression of the spectrally extended pulses, affecting system performance.

## 4. Realization of a 4-Channel System to Eliminate XPM

*OptSim* is a programme that facilitates the modeling and simulation of optical communication systems. It contains more than 400 algorithms representing a wide variety of optical and optoelectronic components used in practice. The typical end-users of *OptSim* are companies engaged in the development and implementation of network infrastructures to access a remote network. *OptSim* allows simulating various types of multiplexes on professional level, for example, WDM, DWDM, TDM, and CATV or all-optical LAN. With *OptSim* we can propose and experimentally verify optical networks before their real deployment [5, 18].

A four-channel DWDM system was created to eliminate the XPM phenomenon. The simulations aimed to suppress the XPM phenomenon by varying the dispersion in the OV and uneven distribution of optical power in adjacent channels. The optical mesh with an OF, EDFA amplifier, and dispersion compensator was implemented in the following configuration: the output power of the EDFA booster is set at 9 dBm (7.943 mW) and the OF behind the amplifier at 100 km with losses of 0.33 dB.km$^{-1}$. Neither SBS nor PMD are taken into account in this topology.

An EDFA IN-Line amplifier is located behind the OF, which has a gain of 20 dB with NF = 4.5 (Figure 1). The length of the Erbium-doped OF was 14 m and it was chosen according to Figure 2 showing the best amplification was attained by precisely this length of OF.

An OF follows this with a length of 100 km with a specific attenuation of 0.33 dB.km$^{-1}$, and in the final stage, there is a compensator and an amplifier [28]. For our simulation 4 loops were created with a different increment. The individual receiving units are designed to filter only the desired signal. The first simulation was done with the intention of changing the transmission power of the spectrum from 193.025 THz to 193.175 THz with an increment of 0.05 THz (nonuniform transmission power -10 dBm, -30 dBm, -10 dBm, -30 dBm). In this simulation, we created an optical loop where we changed

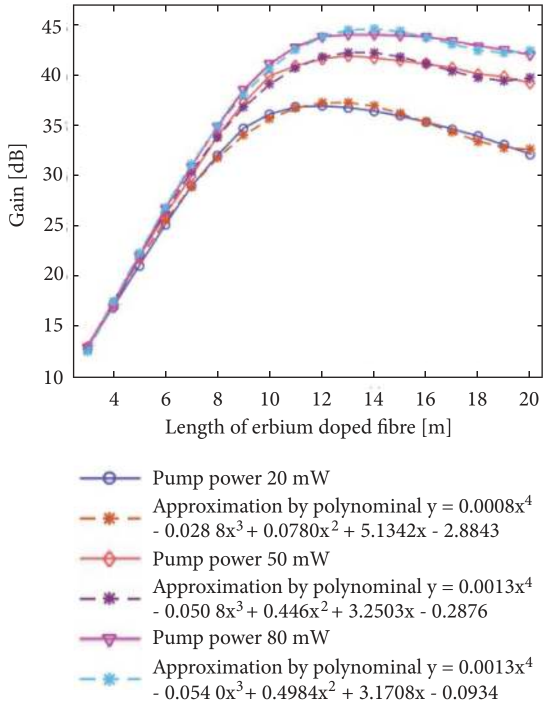


Figure 2: Length of Erbium-doped OF to EDFA gain.

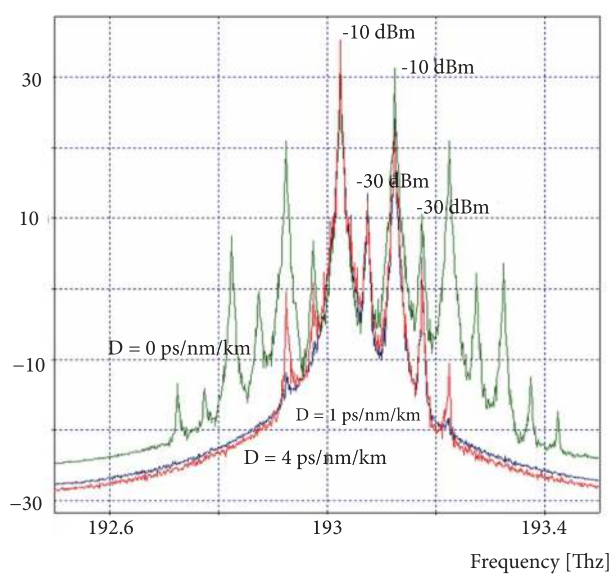


Figure 3: Final signal spectrum for simulation no. 1.

the dispersion with an increment of 1 from 0 ps/nm/ km to 4 ps/nm/ km at different power transmissions (Figure 3). The resulting BER and Q factor values at 193.075 THz are in Table 1.

Figure 3 presents a green curve showing a dispersion value of 0 ps/nm/ km, a blue curve showing a spectrum at a dispersion of 1 ps/nm/ km, and a red curve showing a 4 ps/nm/ km spectrum. From the resulting values in Table 1,

Table 1: Final results of BER simulations no.1 at 193,075 THz.

| Iteration | Variance [ps/nm/km] | BER | Q-factor |
|---|---|---|---|
| 1 | 4 | $2.78 \cdot 10^{-27}$ | 10.8897 |
| 2 | 3 | $1.81 \cdot 10^{-20}$ | 9.45166 |
| 3 | 2 | $2.49 \cdot 10^{-11}$ | 6.77286 |
| 4 | 1 | 0.000541 | 3.36911 |
| 5 | 0 | 0.022251 | 2 |

Table 2: Final BER results with simulation no. 2 193,075 THz.

| Iteration | Variance [ps/nm/km] | BER | Q-factor |
|---|---|---|---|
| 1 | 4 | $1.10 \cdot 10^{-40}$ | 13.6235 |
| 2 | 3 | $2.01 \cdot 10^{-28}$ | 11.2943 |
| 3 | 2 | $5.75 \cdot 10^{-16}$ | 8.01867 |
| 4 | 1 | $1.15 \cdot 10^{-17}$ | 5.12306 |
| 5 | 0 | 0.022501 | 2 |

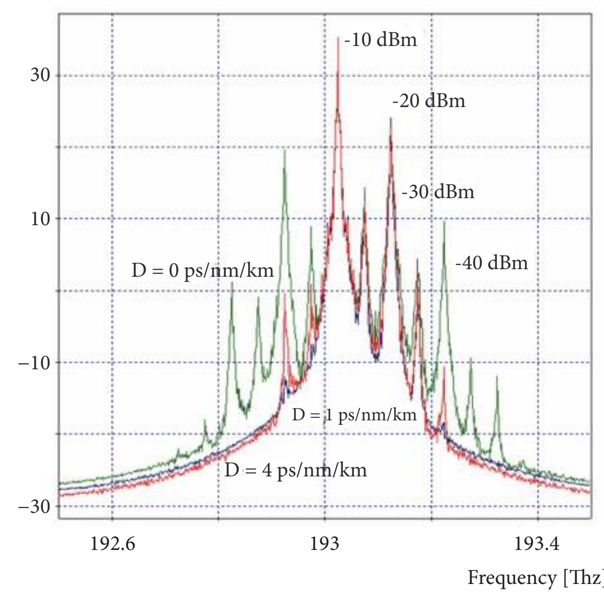


Figure 4: Final signal spectrum for simulation no. 2.

we can confirm that with the decrease in dispersion the value of BER increases. An optical channel at 193.075 THz will be accepted for dispersion values 4, 3, and 2. Due to the different input power values, we can partially suppress the XPM phenomenon at its output. The second simulation was applied to the same scheme, but we changed the transmitting power of all four channels (nonuniform transmit power -10 dBm, -20 dBm, -30 dBm, and -40 dBm). In Figure 4 we can see how the change in broadcasting power affects XPM.

The resulting BER and Q factor values at 193.075 THz at -10 dBm, -20 dBm, -30 dBm, and -40 dBm are given in Table 2. From the simulation results (Tables 1 and 2), we can conclude that the nonlinear phenomenon XPM could be partially suppressed by appropriate choice of transmitting power and dispersions. The line is accepted for dispersion values 4, 3, 2, and 1.

## 5. Conclusion

The aim of this paper was a basic description of the nonlinear XPM phenomenon occurring in xWDM systems. Two simulation topologies of a 4-channel DWDM system with 50 GHz output were designed to eliminate (suppress) XPM. The paper pointed to the improvement of BER at a particular wavelength with the appropriate choice of broadcasting power in neighboring channels (uneven distribution of power levels). By comparing Tables 1 and 2, we can state that the improvement of BER is achieved by a suitable choice of transmitting powers in neighboring channels. Simulation also pointed out that the presence of the OF dispersion affects line error and how it is related to the nonlinear XPM phenomenon.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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