TELKOMNIKA Telecommunication, Computing, Electronics and Control
Vol. 18, No. 6, December 2020, pp. 2878~2885
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v18i6.16136

Mitigation of non-linear four-wave mixing phenomenon in a fully optical communication system

Petr Ivaniga[1], Tomáš Ivaniga[2]
[1]Department of Information Networks, Faculty of Management Science and Informatics, University of Žilina, Slovakia
[2]Department of Electronics and Multimedia Communications, Faculty of Electrical Engineering and Informatics, University of Technology Košice, Slovakia

Article Info

Article history:

Received Mar 25, 2020
Revised May 23, 2020
Accepted Jun 25, 2020

Keywords:

Bit error rate
DWDM
Four-wave mixing
Q-factor

ABSTRACT

This paper aims to point out the nonlinear phenomenon occurring in coarse/dense wavelength division multiplex (C/D-WDM) systems. This phenomenon has to be taken into account during the design of the optical network itself, as wavelengths in the optical fiber are constantly densified. The paper points out the emergence of the non-linear four-wave mixing (FWM) phenomenon and how it relates to the dispersion in the optical fiber together with the transmit power. The output of the paper is a proposed design of the system that points to the improvement of the bit error rate (BER) with a suitable choice of dispersion and suitable transmission power.

Corresponding Author:

Petr Ivaniga,
Department of Information Networks, Faculty of Management Science and Informatics,
University of Žilina,
Univerzitná 8215/1, 010 26 Žilina, Slovakia.
Email: petr.ivaniga@fri.uniza.sk

1. INTRODUCTION

Optical system providers are forced continuously to increase the overall transmission capacity of the system by increasing the volume of data transferred. The increase in data transmission is mainly due to the increasing popularity of cloud and multimedia services [1-3]. It is a logical and economically manageable step for providers to make a gradual transition to higher data rates when increasing the capacity of systems, provided that the existing infrastructure, in which considerable money has been invested, is used as much as possible. In optical wavelength division multiplex (WDM) multiplexing systems, a suitable option is to replace several original lower bit rate channels with a higher bit rate channel system. Thus, several optical systems coexist and the newly deployed system is required to be backward compatible with the original system.

2. DENSE WAVELENGTH DIVISION MULTIPLEX

The idea of the realization of the wave division multiplex WDM was described and theoretically processed in the last century in the early sixties. At the end of the seventies, two signals with different optical wavelengths were practically transmitted through one optical fiber (OF). From now on, intensive development has been underway to improve WDM. In the twenty-first century, these systems are an integral part of the backbone optical transmission networks, as they can transmit thousands of optical signals with different optical wavelengths, one fiber by one. The whole system comprises n optical sources and n optical detectors, wherein an optical signal is modulated for each wavelength used in the transmitting unit. Figure 1 ilustrates WDM system.

Transmitters are made up of optical radiation sources, with distributed feedback (DFB) lasers being used most often because their spectral width is in units of MHz. The DFB uses a resonator that is made up of a Bragg lattice with a periodic refractive index change, generating narrow spectral radiation whose width does not exceed the width of a single dense wavelength division multiplex (DWDM) channel. Merging of all wavelengths into one OF takes place in the multiplexer block. The opposite function, that is, dividing the individual wavelengths, takes place in the demultiplexer block. There are diffraction multiplexers with Bragg lattices or interference multiplexers arrayed waveguide grating (AWG) [4, 5]. AWGs are made of two waveguides at the inlet and at the outlet of an ordered waveguide grid that is composed of long asymmetric parallel waveguides. AWG technology allows us to do 50 GHz multiplexing of multiple channels, while it can be integrated on the silicon layer and does not suffer from chromatic dispersion. However, its disadvantage is its dependence on temperature. Multiplexers with Bragg grids achieve high accuracy and less loss. It is also a disadvantage that they need additional components (circulators, couplers) to function, which mainly introduces a chromatic dispersion into the system. It is also possible to add and allocate individual wavelengths using optical add-drop multiplexer (OADM) or reconfigurable optical add-drop multiplexer (ROADM), depending on customer requirements.

When the optical path is transmitted, the optical signal is attenuated and for this reason, it is necessary to refresh the signal in individual sections. An optical amplifier can be inserted into the optical path in three ways: as a booster, which is placed directly behind the optical transmitter and serves to amplify the signal to the highest possible level that can be tied to the OF [6-8]. It can also be placed as an IN-Line, which is inserted continuously into the optical path (80-120 km) or as a preamplifier, which is placed in front of the receiver and amplifies the signal to a value acceptable to the receiver unit (bit error rate (BER) acceptable). In practice, optical amplifiers such as erbium-doped fiber amplifier (EDFA), semiconductor optical amplifier (SOA) and Raman optical amplifier (ROA) are used.

Upstream of the demultiplexer, the signal is converted from the optical domain to the electrical domain using a PIN (P-I-N photodiode) or avalanche photodiode (APD) photodiode. Although the photodetector converts only the intensity of the optical radiation into an electrical signal, in the case of more advanced modulation formats, the receiver is equipped with additional elements such as a Mach-Zhender interferometer or a 90° hybrid optical coupler. Currently, coarse wavelength division multiplex (CWDM) and dense wavelength division multiplex (DWDM) standards are used. When choosing which standard to use in practice, we decide on the end price, the number of users, the bit rate, and how the network will grow.

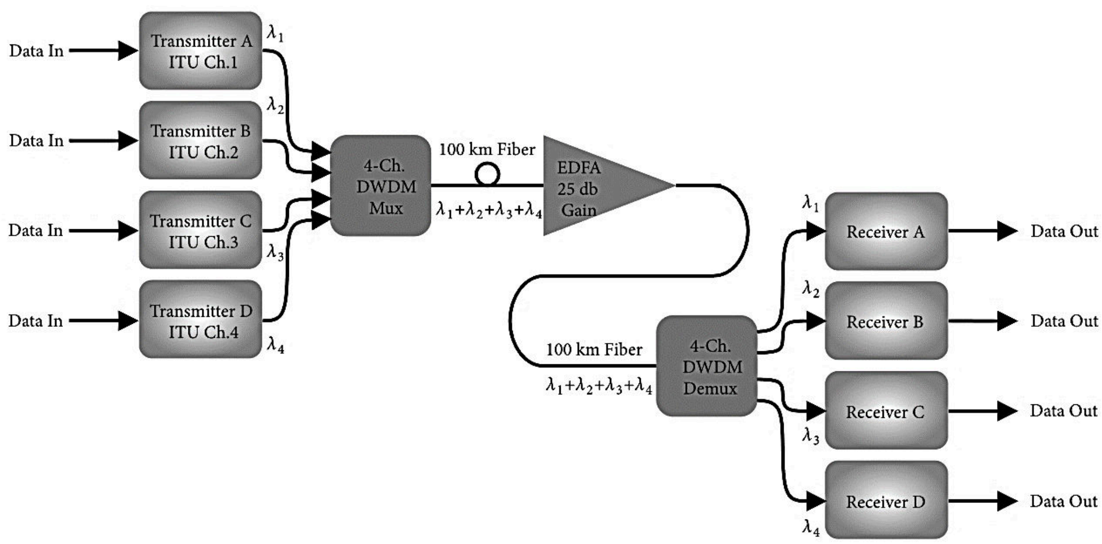

Figure 1. Design of DWDM system [4]

The primary parameter of WDM systems is their total transmission capacity, also identified as CWDM, which we calculate as follows:

$$C_{WDM} = \sum_{k=1}^{n} v_{pk}, \tag{1}$$

where v_{pk} is the transmission rate of the k-th channel and n is the total number of channels of the WDM system. Each channel is assigned a certain spectrum width, regardless of whether the channel uses it or not. If the channel spacing is unnecessarily large, the system achieves worse overall spectral efficiencies, which can be defined by the following relation:

$$\eta_{WDM} = \frac{c_{WDM}}{B_{WDM}} \tag{2}$$

where B_{WDM} is the total bandwidth taken by the WDM system [8]. Nowadays, WDM technology can be used directly in switches using small form-factor pluggable (SFP) or compact small form-factor pluggable (CSFP) slot in the form of MiniGBIC modules.

3. FOUR WAVE MIXING

Four-wave mixing is a process that has a physical nature in non-linear polarization. A minimum 3-channel demultiplexer with frequencies ω_i, ω_j and ω_k is required to create this phenomenon [9]. The condition is that the three frequency components are evenly distributed. Of all the signals that arise in this mixing process, the ω_{ijk} signal is the most disturbing signal is the signal of ω_{ijk}

$$\omega_{ijk} = \omega_i + \omega_j - \omega_k, \text{pre } i \neq k \wedge j \neq k. \tag{3}$$

Depending on the particular frequencies, this signal (frequency) may be close to one of the original frequencies and thus cause intense inter-channel interference [10-12]. In multi-channel WDM systems with N-channels, the individual channels mix, resulting in a large number of interfering frequency components N x $(N - 1)^2$. Figure 2 illustrates an example of mixing three initiation signals. According to the conversion, 1 to 12 undesirable frequency components may be created. FWM, unlike self phase modulation (SPM) and cross phase modulation (XPM), is a process independent on transmission speed in the channel but is strongly dependent on channel spacing periodicity and chromatic dispersion.

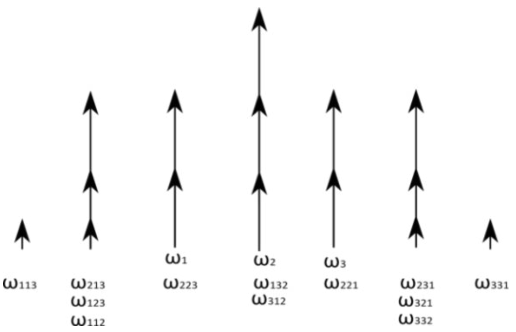

Figure 2. Principle of FWM

For dispersion shifted fiber (DSF) fibers, the phenomenon of four-wave mixing in WDM systems is a severe issue. On the contrary, it does not act as a severe obstacle to the standard FWM OF. This motivated the development of a non-zero dispersed shifted non-zero-dispersion shifted fiber (NZ-DSF) fiber. The effect of four-wave mixing depends on the relationship between the phases of the interacting signals. Assuming there was no chromatic dispersion phenomenon, all signals would be spread at the same group rated speed. In this case, the FWM itself would be amplified [13, 14]. In real WDM systems, however, the chromatic dispersion applies and therefore the individual signal components have different group rate speeds. The phases of these frequency components alternate (overlap) and mix. The speed difference is more significant in systems where channel spacing is more significant (in systems with chromatic dispersion). The following relationship expresses the optical power loss caused by the FWM; in other words, the power of newly formed frequency component P_{ijk}:

$$P_{ijk} = \left(\frac{\omega_{ijk}\bar{n}d_{ijk}}{3cA_e}\right)^2 P_i P_j P_k L^2, \tag{4}$$

where L is the length of the line without increasing losses and chromatic dispersion. P_i, P_j, P_k correspond to the power of the waves (frequency components) entering from the FWM process itself, $\bar{n}$ which is the non-linear component of the refractive index (3 x 10^{-8} μm^2/W) and d_{ijk} is the so-called degradation factor [15-18]. Since losses and chromatic dispersion cannot be avoided in real systems, the length of line L is replaced by the effective length L_e and with amplifiers distributed every n km

$$L_e = \frac{1-e^{-\alpha L}}{\alpha} \tag{5}$$

The chromatic dispersion compensates for the effect of four-wave mixing. The actual P_{ijk} value can be modeled using the n_{ijk} mixing efficiency coefficient

$$P_{ijk} = \eta_{ijk}\left(\frac{\omega_{ijk}\bar{n}d_{ijk}}{3cA_e}\right)^2 P_iP_jP_kL_e^2, \tag{6}$$

$$n_{ijk} = \frac{\alpha^2}{\alpha^2+(\Delta\beta)^2}\left[1+\frac{4e^{-\alpha l}sin^2(\Delta\beta l/2)}{\left(1-e^{-\alpha l}\right)^2}\right], \tag{7}$$

where $\Delta\beta$ is the difference between the transmitting constants of the signals ω_i, ω_j, ω_k a ω_{ijk}:

$$\Delta\beta = \beta_i + \beta_j - \beta_k - \beta_{ijk}. \tag{8}$$

In an optical network designed according to the DWDM standard, for which the channels are 100 GHz (0.8 nm) apart, there is a maximum of 1 dB of power loss per channel due to FWM. That is, if the power attributed to all channels has a P-value, then the power loss for each channel must be less than P. The FWM effect increases as the length of the transmission line increases and this limits the performance of the individual channels [19]. The dependence of the maximum transmitted power per channel (mW) versus distance (km) for standard SMF fiber and DSF fiber is shown in Figure 3 [20]. For the single SMF fiber, the dispersion reference value is 17 ps/nm/km. In the case of dispersed displaced DSF, the chromatic dispersion is zero.

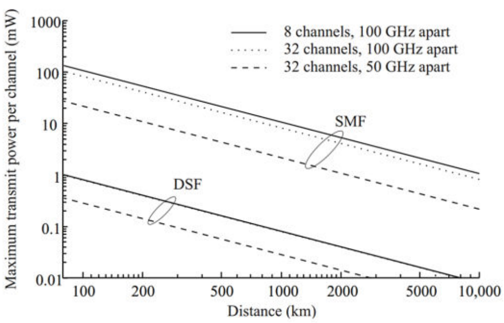

Figure 3. Dependence of maximum transmitted power per channel depending on the distance

A comparison of SMF and DSF shows that DSF comes with significantly worse peak power than the SMF fiber. This is due to the higher efficiency of DSF fiber mixing due to the low chromatic dispersion value [21-23]. The power balance per channel deteriorates as the number of channels increases. There are several ways to eliminate the adverse effect of FWM:

- Uneven channel placing. This solution is possible mainly in WDM systems with a small number of channels.
- Increase the frequency separation between channels, resulting in a more significant group speed difference. This solution has the disadvantage of amplifying a disproportionately large portion of the frequency spectrum and also amplifying the effect of the SRS.
- Utilization of larger wavelengths beyond 1560 nm using DSF [24, 25]. Despite the use of DSF, a significant amount of chromatic dispersion is employed in such a WDM system, and this reduces the FWM effect.
- Generally, in this type of non-linearity, FWM suppression is achieved by reducing the transmitted input power and reducing the distance between the amplifiers.

If from an application point of view, the channels can be multiplexed or re-multiplexed at approximately half the transmission path, or demultiplexing, in this case, it is possible to introduce different delays for each channel. This step ensures some randomness between the phases of the information channels.

4. DWDM IMPLEMENTATION FOR FWM EXAMINATION

DWDM technology is used for the FWM demonstration, its schematic model bases from Figure 1. DWDM proposed system with different input values has been published in [26]. For a simulation is designed model of an 8-channel DWDM system where input blocks of pseudo-random data are modulated by external NRZ modulation with transmission speed 10 Gbit/s. The channel spacing between the channels is 100 GHz and ranges from 192.8 THz to 193.5 THz. The data is multiplexed after modulation and the amplification occurs before entering the OF through an EDFA amplifier. This is followed by 100 km of OF with an optical grid to compensate for chromatic dispersion and an optical amplifier. After demultiplexing of the optical signal, the signal is filtered according to the required channel by a PIN photodiode and the evaluation takes place in the spectral and electrical analyzer from which we detect the signal spectrum, eye diagram, BER and Q-factor. Two simulations are performed. In the first simulation, the dispersion in OF is changed and in the second one, the optical signal with the dispersion is changed.

4.1. Changing dispersion in OF to alleviate FWM

The whole system will be evaluated based on BER and related Q-factor. Mathematical derivation of BER and Q-factor has been published in [15, 22]. We varied the dispersion from 0 to 1 ps/nm/km with an increment of 0.2 and from 1 to 9 ps/nm/km with an increment of 2. The resulting values are shown in Table 1. In Figure 4, Figure 5 and Figure 6 are the resulting spectra with an eye diagram for dispersion values of 0, 1 and 9 ps/nm/km.

From Table 1, we can conclude that the non-linear FWM phenomenon decreases with increasing dispersion in OF, but at the same time, the signal is scattered at high dispersion in OF. For this reason, it is necessary to choose the correct dispersion value at the design of the optical system itself in order to avoid the generation of a side signal and thus not to decrease the BER at the output. In our system, the dispersion value is only acceptable up to 5 ps/nm/km to maintain BER ($1.92 \cdot 10^{-14}$).

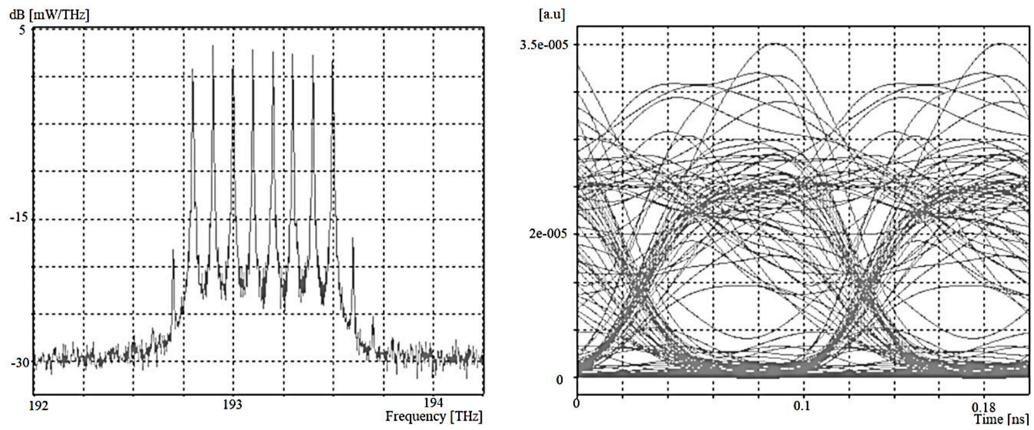

Figure 4. Output spectrum and eye diagram for D = 0 ps/nm/km

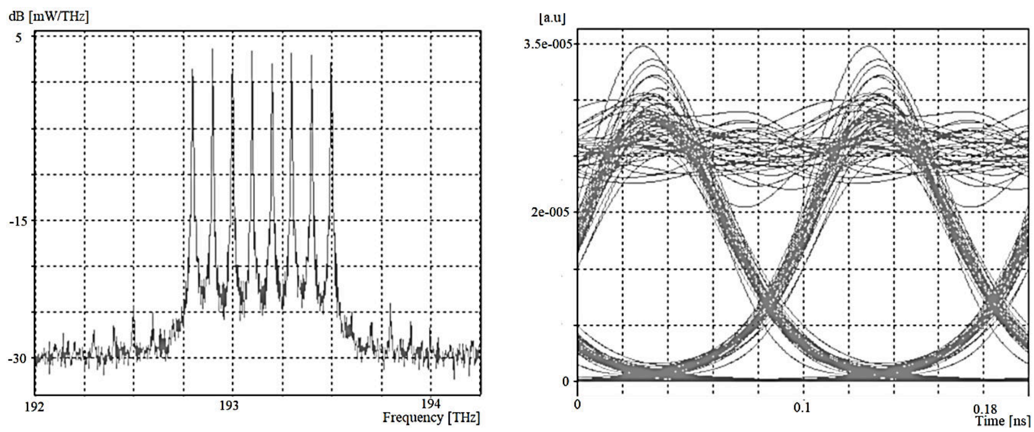

Figure 5. Output spectrum and eye diagram for D = 1 ps/nm/km

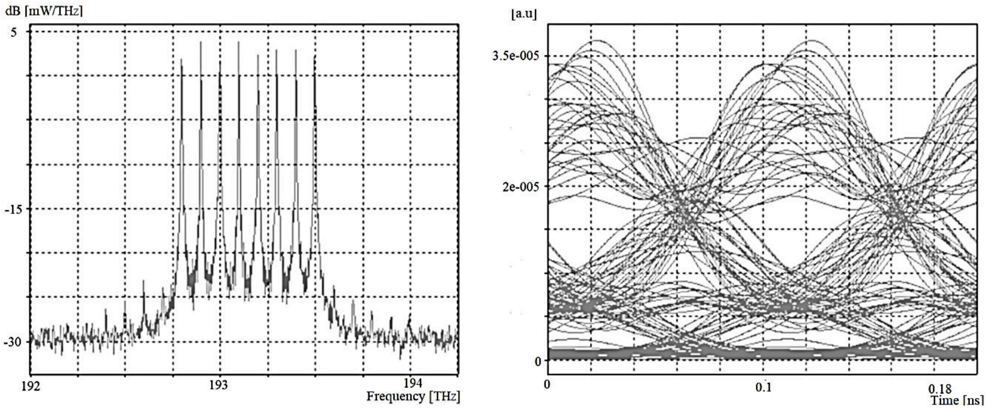

Figure 6. Output spectrum and eye diagram for D = 9 ps/nm/km

Table 1. The resulting BER values with changed dispersion in the OF

Dispersion [ps/nm/km]	BER [-]	Q[-]	Q[dB]
0	$1.87\cdot10^{-04}$	3.574	11.065
0.2	$3.53\cdot10^{-11}$	6.675	16.489
0.4	$6.25\cdot10^{-40}$	13.826	22.814
0.6	$2.67\cdot10^{-38}$	13.036	22.303
0.8	$1.00\cdot10^{-40}$	15.702	23.919
1	$5.22\cdot10^{-36}$	12.569	21.986
3	$6.87\cdot10^{-13}$	7.229	17.182
5	$1.92\cdot10^{-14}$	7.673	17.699
7	$1.87\cdot10^{-08}$	5.641	15.027
9	$2.99\cdot10^{-04}$	3.308	10.392

4.2. Changing the input signal to mitigate the FWM

In this simulation, we point out the relation of the input signal to the FWM (the need for a suitable transmit power at the input). In this system, D = 5 ps/nm/km from the previous simulation was set. The laser power is varied from -5 to 9 dBm with an increment of 2 (The resulting BER and Q-factor for a particular power are shown in Table 2). When the transmit power is set from -6 dBm to -9 dBm, the BER increases from $2.91\cdot10^{-12}$ to $4.99\cdot10^{-7}$. For this reason, it makes no sense to use a low input power value because using optical amplifiers would distort the signal. In Figure 7, Figure 8 and Figure 9, we can see the resulting spectrums with an eye diagram for a particular optical power.

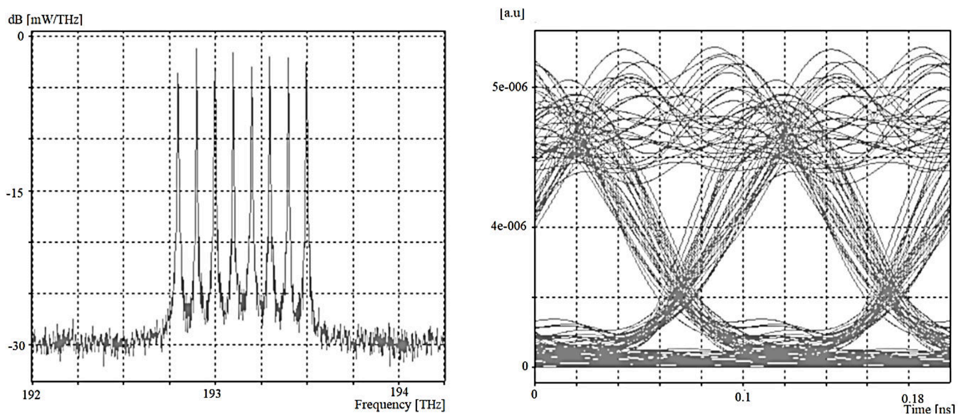

Figure 7. Output spectrum and eye diagram for *Tx* = -5 dBm

As can be seen from Table 2, BER can be influenced by a suitable choice of *Tx* at the input. We can conclude that the higher the signal level is above the noise, the better the BER. From the simulation, we can further say that the lower value of the input signal causes less influence of FWM. The lowest power *Tx* = -5 dBm produces the lowest FWM value as shown in Figure 7. Of the individual simulations, the best signal value is when *Tx* is in the range of -5 to 3 dBm, which corresponds to BER values ($<-10^{-12}$).

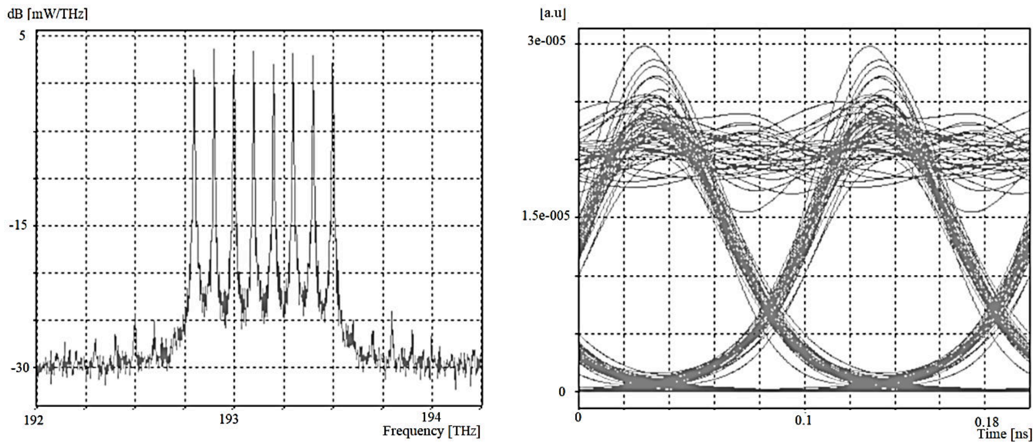

Figure 8. Output spectrum and eye diagram for *Tx* = 3 dBm

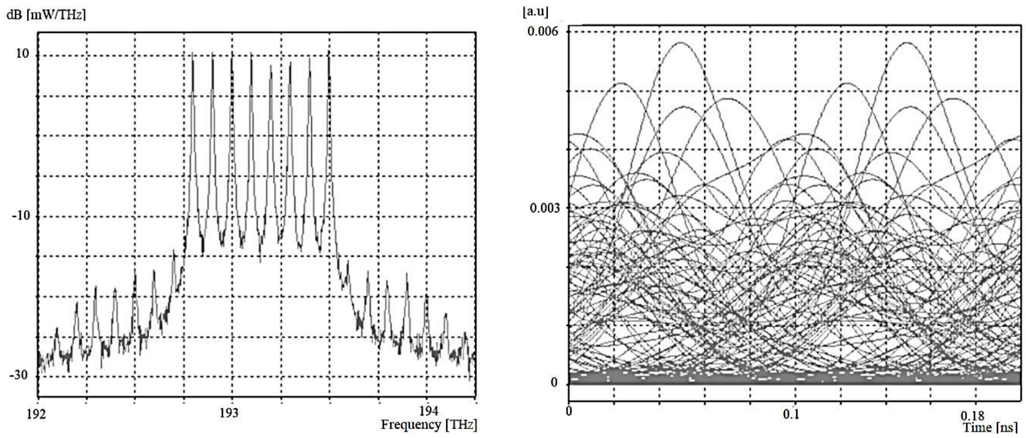

Figure 9. Output spectrum and eye diagram for *Tx* = 9 dBm

Table 2. The resulting BER values when the Tx is changed in the transmitting portion

Tx [dBm]	BER [-]	Q[-]	Q[dB]
-5	$3.87 \cdot 10^{-12}$	7.009	16.914
-3	$5.06 \cdot 10^{-11}$	7.075	16.989
-1	$2.90 \cdot 10^{-15}$	7.820	17.865
1	$2.04 \cdot 10^{-12}$	7.047	16.960
3	$3.40 \cdot 10^{-11}$	6.627	16.426
5	$6.50 \cdot 10^{-08}$	5.386	14.626
7	$2.29 \cdot 10^{-05}$	3.697	11.358
9	$7.02 \cdot 10^{-03}$	2.613	8.343

5. CONCLUSION

The paper aimed to describe the non-linear phenomenon of FWM since it is nowadays necessary to consider it in the design itself. The paper described the basic mathematical principle of the phenomenon in the DWDM system and its possible elimination at the output. In experimental simulations, we pointed out its origin and how it relates to dispersion in optical fiber. We also pointed out that a suitable choice of dispersion can minimize FWM. In the next simulation, with the appropriate dispersion choice D = 5 ps/nm/km, we changed the transmit power at the input. From Table 1 and Table 2, we can create an optical system with acceptable values at the output, unless the bit error rate rises above the value 10^{-9} when it is no longer possible to distinguish the individual optical pulses of the output.

REFERENCES

[1] F. Khair, I. W. Mustika, Fahmi, D. Zulherman and F. Hario, "Comparative Analysis of Dispersion Compensating Fiber in DWDM System Using 10 Gbps and 40 Gbps Bit Rate," *10th International Conference on Information Technology and Electrical Engineering (ICITEE)*, Kuta, pp. 412-417, 2018.

[2] V. Kachhatiya and S. Prince, "Wavelength division multiplexing-dense wavelength division multiplexed passive optical network (WDM-DWDM-PON) for long reach terrain connectivity," *2016 International Conference on Communication and Signal Processing (ICCSP)*, Melmaruvathur, pp. 0104-0108, 2016.
[3] R. Z. Ibragimov and V. G. Fokin, "Design of Long-Haul Coherent DWDM Optical Systems," *2018 XIV International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE)*, pp. 1-3, 2018.
[4] T. Ivaniga and P. Ivaniga, "Suppression of nonlinear XPM phenomenon by selection of appropriate transmit power levels in the DWDM systém, "*International Journal of Optics*, vol. 2019, pp. 1-8, 2019.
[5] N. Thakral and L. Kumar, "Performance evaluation of different hybrid optical amplifiers for DWDM system," *2016 IEEE Annual India Conference (INDICON)*, Bangalore, pp. 1-4, 2016.
[6] S. Sujith and K. G. Gopchandran, "A simulation study on DCF compensated SMF using OptSim," *International Congress on Ultra Modern Telecommunications and Control Systems*, Moscow, pp. 851-854, 2010.
[7] H. Nain, U. Jadon and V. Mishra, "Evaluation and analysis of non-linear effect in WDM optical network," *2016 IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*, Bangalore, pp. 36-39, 2016.
[8] T. Ivaniga and P. Ivaniga, "The In-Line placement of EDFA in CWDM/DWDM system for BER comparison at 1540 nm, "*Journal of Engineering Science and Technology Review*, vol. 12, no. 5, 1-7, 2019.
[9] J. N. Dike and D. A. Ogbe, "Optimizing the efficiency of Fiber-Optics Technology in Telecommunications systems," *2013 IEEE International Conference on Emerging & Sustainable Technologies for Power & ICT in a Developing Society (NIGERCON)*, Owerri, pp. 135-142, 2013.
[10] S. Thirumaran, S. K. Nithila Devi, P. Deepika and A. Vasanthi, "Optical phase conjugation in long haul optical transmission," *2012 International Conference on Devices, Circuits and Systems (ICDCS)*, Coimbatore, pp. 34-37, 2012.
[11] T. Huszaník, J. Turán and E. Ovseník, "Comparative analysis of optical IQ modulation in four-channel DWDM system in the presence of fiber nonlinearities," *2018 19th International Carpathian Control Conference (ICCC)*, Szilvasvarad, pp. 468-473, 2018.
[12] S. Sharma and S. Mohan, "Countering the gain behavior of Erbium Doped Fiber Amplifiers: A cross layer approach," *2013 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*, Kattankulathur, pp. 1-6, 2013.
[13] N. Choudhary and S. Pawar, "Time domain OCDMA PON architecture for 2048 optical network units," *2015 IEEE Bombay Section Symposium (IBSS)*, Mumbai, pp. 1-6, 2015.
[14] S. Fatimah Tuanku Abdullah and S. A. Jabar, "FWM effect in FTTH over DWDM for 320 Gbps link distance 80 km," *2012 International Conference on Computer and Communication Engineering (ICCCE)*, Kuala Lumpur, pp. 633-637, 2012.
[15] P. Ivaniga and T. Ivaniga, "10 Gbps optical line using EDFA for long distance lines, "*Przeglad Elektrotechniczny*, vol. 93, no. 3, 193-196, 2017.
[16] W. W. M. M. Han, Y. Win, N. W. Zaw and M. M. Htwe, "Minimization of Four Wave Mixing Effect in Long-Haul DWDM Optical Fiber Communication System," *2019 International Conference on Advanced Information Technologies (ICAIT)*, Yangon, Myanmar, pp. 19-24, 2019.
[17] V. Vardanyan, "Single-fiber optical transmission system with DWDM channels effect of four-wave mixing products," *2016 13th International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE)*, Novosibirsk, pp. 23-25, 2016.
[18] R. Bhatia, A. K. Sharma and J. Saxena, "Optimized alternate polarization and Four Wave Mixing in 60-Gb/s DWDM transmission system," *2014 Recent Advances in Engineering and Computational Sciences (RAECS)*, Chandigarh, pp. 1-4, 2014.
[19] T. Sabapathi, S. Sundaravadivelu and A. Vairamuthu, "Analysis of optical modulation formats for DWDM system," *2011 Third International Conference on Advanced Computing*, Chennai, pp. 68-73, 2011.
[20] B. Pamukti and D. Perdana, "Non-linear effects of high rate soliton transmission on DWDM optical fiber communication system," *2016 1st International Conference on Information Technology, Information Systems and Electrical Engineering (ICITISEE)*, Yogyakarta, pp. 26-30, 2016.
[21] S. P. Majumder and S. M. R. Ali, "Crosstalk analysis of a DWDM system with FBG-based optical multi/De-multiplexer," *2014 International Conference on Electrical Engineering and Information & Communication Technology*, Dhaka, pp. 1-5, 2014.
[22] P. Ivaniga and T. Ivaniga, "The design of EDFA with forward pumpimgat the distance line in DWDM, "*Journal of Engineering Science and Technology*, vol. 14, no. 2, 531-540, 2019.
[23] Ľ. Mikuš, "Evaluations of the error rate in backbone networks," *Elektrorevue*, vol. 12, no. 2, pp. 1–10, 2010.
[24] D. Zraková, M. Kubina, and G. Koman, "Influence of information-communication system to reputation management of a company," *Procedia Engineering*, vol. 192, pp. 1000–1005, 2017.
[25] J. Smiesko, " IP Network Management of Source for IP Traffics," *Scientific Papers of the University of Pardubice. Series D, Faculty of Economics & Administration*, vol. 21, no. 32, 109-117, 2014.
[26] T. Ivaniga, L. Ovsenik and J. Turan, "Influence of Self-Phase Modulation on 8 and 16-Channel DWDM System with NRZ and Miller Coding," *Carpathian Journal of Electronic and Computer Engineering*, vol. 8, no. 1. pp. 17-22, 2015.