The Influence of FWM to the Four-Channel DWDM System

Petr Ivaniga and Tomas Ivaniga

***Abstract*—** In 21st century it is not possible to create optical communication lines without software tools simulating a real network under the given conditions. This article is focused to the FWM (Four-Wave Mixing), which occurs in the DWDM (Dense Wavelength Division Multiplexing) systems. This phenomenon appears in thickening systems and results in crosstalk between channels. In order to influence expression of FWM was created a four-channel DWDM system according to the recommendation ITU-T G.694.1 with the speed of 10 Gbps. The resulting signal was evaluated based on BER (Bit Error Rate) and the connected Q-factor for the channel No.3. The created system shows the influence of the system by the non-linear effect FWM during the compression between the channels.

***Keywords*—**BER, DWDM, FWM, Q-factor, WDM

I. Introduction

Today's times could be characterized as an information age in which is continuous demand for the transmitted information or the transmission speed [1], [2]. The volume of data transmitted over data networks and telecommunication continues to grow and this leads the constructors to look for new solutions that could meet the growing demand for telecommunication services.

Mostly used transmission media have been the metallic lines such as coaxial cable or twisted pair cable. However, with the development of IP telephony, such as video applications - video telephony and video streaming - and other multimedia applications the use of metallic lines started to be insufficient and greatly limiting [3], [4]. It was therefore necessary to find a new kind of wiring that exceeds the abilities and possibilities of metallic lines. This new type of wiring becomes optical links [5]. The optical lines have compared to metallic lines a virtually unlimited bandwidth and also significantly higher transmission speeds.

The indisputable advantage of fiber lines is not subject to corrosion and because the light generated by a laser or LED is used for the transmission on the optical fiber, it is resistant to electromagnetic interference. The physical dimensions of optic cables are also smaller than those of copper cables. The most significant problem in the design of the route remains its own fiber attenuation and dispersion. When using multiplex in single mode fiber, we have to consider the polarization mode dispersion [6], [7]. All types of dispersion contribute to the undesired expansion of the transmitted optical pulses. The extension is in the time domain, it is reflected at the receiving end as a decrease in signal level to form various undesired interferences. The attenuation and dispersion depend also on production technologies, installation and final disposal of fiber optic cables. Attenuation and dispersion characteristics help to better understand this issue. Improvement of production processes, improvement of optoelectronic components, precision when installing networks, are the main factors for the development of optoelectronic speed telecommunications systems. Deployment of high-speed multiplexing techniques and systems, for example WDM for optoelectronic communication systems, creates new opportunities and ways of expansion of transmission capacity, which contributes to increased transmission rates of up to hundreds of Gbps while maintaining the quality of the transmission channel [8], [9]. It is ongoing extensive research of the WDM network. Significant advances in WDM technology enable its wide application in practice [10]. The use of WDM technology allows much better use of the bandwidth of the optical fiber. With the gradual densifying WDM is increasingly reflected also a non-linear phenomenon FWM.

II. Four-Wave Mixing

The mixing of two or more optical waves of different wavelengths in the optical fiber produces at the other wavelengths new optical waves. This is known as FWM, which results in the formation of the new frequency components [10], [15]. FWM is analogous phenomenon as IMP in electrical waves. FWM is very important in the design of multi-channel transmission systems, specifically designed for OFDM (Orthogonal Frequency Division Multiplexing) systems because FWM crosstalk caused those.

FWM is a type of optical Kerr effect, which arises in the light of two or more different wavelengths to enter the fiber. In general, the FWM occurs when light of three different wavelengths induced into the fiber. This leads to a new wave with a wavelength that does not match any of the others. FWM is a type of optical parametric oscillation. In the transfer of dense wavelength division signals it is necessary to avoid FWM, but for some applications, provides an effective technical base for the equipment with optical fibers [11].

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FWM also provides the core technology for the measurement of nonlinearities and chromatic dispersion optical fibers. In the mixing process, there are four photons [13]. The frequencies f_i, f_j, f_k, and propagation constants β_i, β_j, β_k. The photon energy is calculated as $h*f$ where h is Planck constant. For the phase photons adaptations is true that the energy conservation law and the law of conservation of momentum:

$$f_{ijk} = f_i + f_j + f_k.(i, j \neq k), \quad (1)$$

$$\beta_{ijk} = \beta_i + \beta_j + \beta_k.(i, j \neq k), \quad (2)$$

An example of FWM is shown on Fig.1.

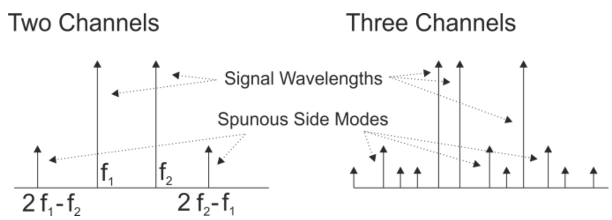

Fig. 1 Example of FWM

The output power, the power of the newly created signal can be expressed as:

$$P_F(L) = \frac{1024\pi^2}{\pi^4\lambda^2 c^2}(D_x) \cdot \frac{P_i(0)P_j(0)P_k(0)}{A_{ef}^2} e^{-\alpha L} \cdot \frac{(1-e^{\alpha L})^2}{\alpha^2}\eta \quad (3)$$

where P_i, P_j and P_k are the powers of the input components with the frequency f_i, f_j a f_k, P_F is the power of the signal created by FWM with the frequency f_{ijk}, λ is the wavelength, n is the refraction index, c is the speed of light in vacuum, α is the loss coefficient, L is the length of fibre, A_{eff} is the effective area of the optical fibre core, D is the degrading factor and X is the non-linear susceptibility. η represents the dependence between the effectivity of FWM and the phase discord:

$$\eta = \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2} \cdot \left[1 + \frac{4e^{-\alpha L}\sin^2(\Delta\beta \frac{L}{2})}{(1-(e^{-\alpha L}))^2} \right] \quad (4)$$

where $\Delta\beta$ represents the phase discord. Then $\Delta\beta$ is

$$\Delta\beta = \beta(f_i) + \beta(f_j) - \beta(f_k) - \beta(f_{fi}) \quad (5)$$

where the coefficient β is the propagation constant. Effectivity η is maximal, so its value is 1, when $\Delta\beta = 0$. Effectivity decreases with the increasing frequency [14]. FWM is a non-linear effect with degrading impact on multichannel optical transfer systems . Due to this, FWM is the effect to be avoided in DWDM transfer systems. But for some applications this effect is desired, offering technological base for the optical devices. FWM also represents the grounds for measuring non-linearity and chromatic dispersion in optical fibres [16].

III. Creating Topology for FWM Verification

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 [4], [8]. *OptSim* allows to simulate various types of multiplexes on professional level, for example WDM, DWDM, TDM (Time Division Multiplexing), as well as cable television (CATV) or all-optical LAN. With *OptSim* we can propose and experimentally verify optical networks before their real deployment. With the virtual measuring devices we measure various parameters of the network or display them as a graph. We know, for example, to measure the number of erroneous bits BER, eye diagram, eye openness, inter-symbol interference, power levels, optical spectrum, power spectrum, and others.

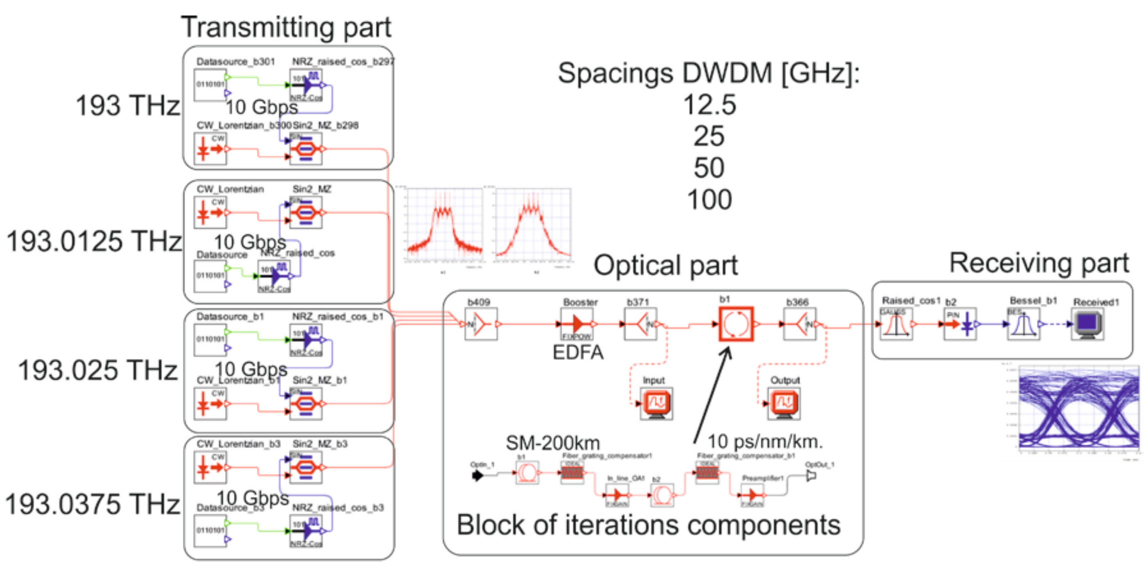

Fig. 2 Scheme of DWDM system created in software programme *OptSim*

In Fig. 2 is a four-channel DWDM system created in *OptSim*. This model of an optical communication system consists of three parts:

A. *Transmitting part*

It consists of four DWDM channels. All of these channels comprise a data source Datasource, which generates a pseudo-random bit sequence on a speed of 10 Gbps. This sequence of bits is encoded in the block NRZ_raised_cos. The block generates coded NRZ electrical signal. Further, the signal is modulated onto optical carriers whose source is a laser CW_Lorentzian, sinus modulator Sin2_MZ. The spacing between channels are specified according to ITU-T G.694.1. In Fig. 3 is transmitting part which contains four components.

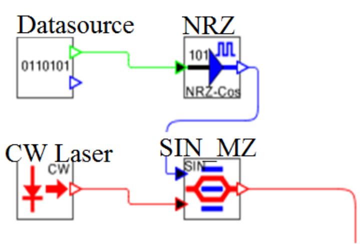

Fig. 3 Example of FWM

B. *Optical part*

These four channels are multiplexed by optical splitter. The resulted signal is amplified and further transmitted to the single mode fiber. With *OptSim* we induce a nonlinear phenomenon FWM. On exiting of the optical transmission part is the signal degraded due to FWM and sent towards the recipient. The Brillouin scattering and Raman crosstalk are not present in optical fiber [12]. In Fig.4 there is an optical part which consists of six components.

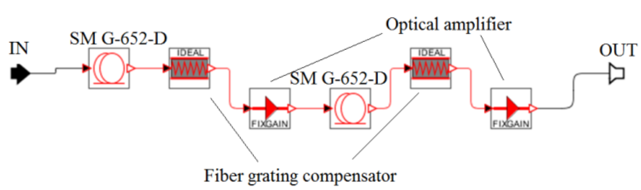

Fig. 4 Block of iterations components

C. *Receiving part*

The output optical signal is converted into electrical energy. By using probes can be seen the eye diagram and analyze BER, Q-factor, jitter and eye openness. In Fig. 5 is receiving part.

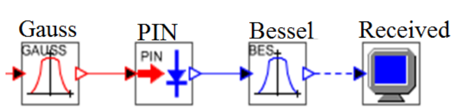

Fig. 5 Receiving part

IV. Results of Spacing Between Output Channels DWDM

The simulations were carried out in a DWDM system in four various spacings. The following simulation shows FWM effect on output channels.

A. *DWDM System with the Spacing of 12.5 GHz According to the ITU-T G.694.1*

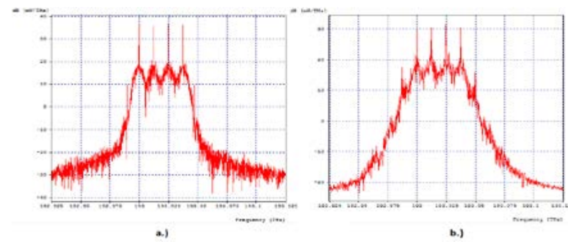

Fig. 6a, 6b Input and output optical spectrums in multiplexed input signals for the spacing of 12.5 GHz

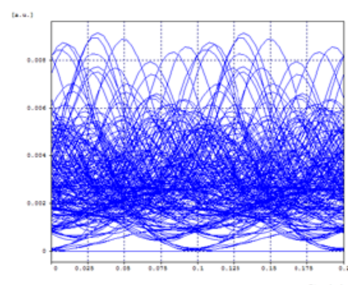

Fig. 7 Eye diagram for the spacing of 12.5 GHz.

B. *DWDM System with the Spacing of 25 GHz According to the ITU-T G.694.1*

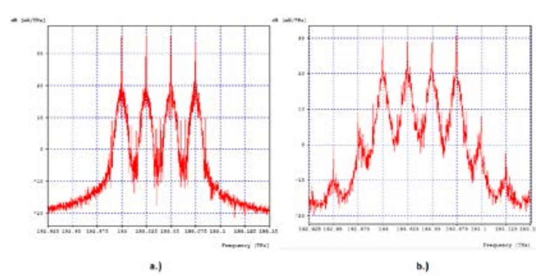

Fig. 8a, 8b Input and output optical spectrums in multiplexed input signals for the spacing of 25 GHz

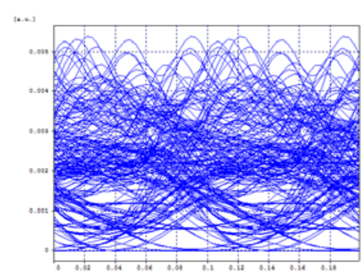

Fig. 9 Eye diagram for the spacing of 25 GHz.

C. *DWDM System with the Spacing of 50 GHz According to the ITU-T G.694.1*

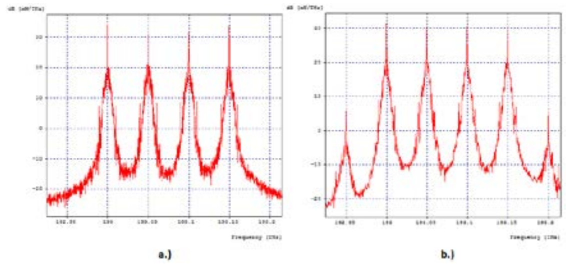

Fig. 10a, 10b Input and output optical spectrums in multiplexed input signals for the spacing of 50 GHz

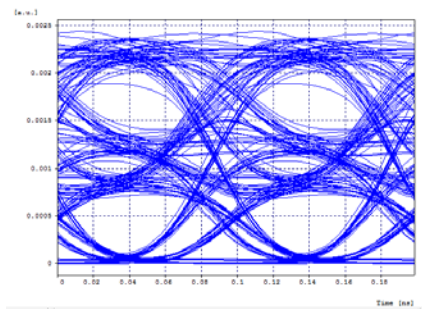

Fig. 11 Eye diagram for the spacing of 50 GHz

D. *DWDM System with the Spacing of 100 GHz According to the ITU-T G.694.1*

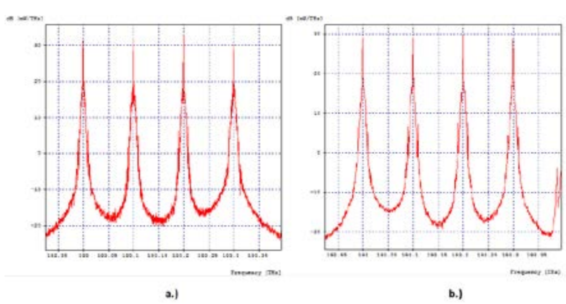

Fig. 12a, 12b Input and output optical spectrums in multiplexed input signals for the spacing of 100 GHz

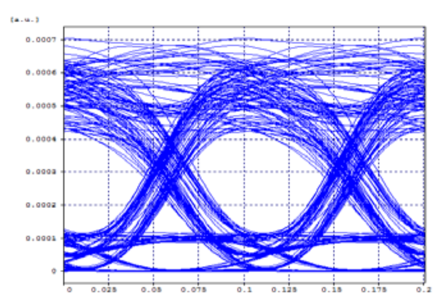

Fig. 13 Eye diagram for the spacing of 100 GHz

The simulation results (Jitter, BER, Q-factor) for the spacings are in Tab I.

TAB.1. THE RESULTS OF EACH SIMULATION

Spacings DWDM [GHz]	**Jitter [ns]**	**BER [-]**	**Q-factor [dB]**
12,5	0.0200656	0.0227501	6.020600
25	0.0237582	0.0227501	6.020600
50	0.0280411	0.0223817	6.045923
100	0.0208569	$6.8833\ 10^{-6}$	13.672364

V. CONCLUSION

The results of these simulations show how is the spacing size effect between channels in an optical communication system, and the output signal quality. The characteristics of each resource and inter-channel spacing is fully compliant to ITU-T G.694.1.For spacing between channels 12.5 GHz is Q-factor, which shows the quality of transmission as signal-to-distortion, the Q-factor value = 6.020600 dB and BER = 0.0227501.

After switching frequency (wavelength) resources to 25 GHz spacing, the values of Q-factor and BER are the same, Q factor = 6.020600 dB and BER = 0.0227501. For spacing of 50 GHz the transmission quality rose slightly to Q-factor = 6.045923 dB and BER = 0.0223817. Finally, the frequency (wavelength) resources set at the spacing between the channels100 GHz. In this case, the Q-factor = 13.672364 dB and BER = $6.88313.10^{-6}$.

Based on the simulations carried out and the results achieved can be said that the influence of FWM in DWDM systems can be suppressed to some extent appropriate choice between channel spacing. The simulation, in which the fiber length was constant, showed that in case of spacing values of 12.5 GHz and 25 GHz the impact of FWM is present. At intervals of 50 GHz is transmission quality better and the spacing of 100 GHz is FWM phenomenon already well suppressed.

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