Effect of the FWM Influence on the CWDM Signal Transmission in the Optical Transmission Media

Rastislav Róka, Martin Mokráň

***Abstract*—** This paper deals with analysis of negative influences on the optical signal transmitted in the environment of optical transmission media and is focused especially on the Four Wave Mixing (FWM) effect. The FWM is one of nonlinear effects in the optical transmission media with the strongest impact on transmitted signals utilizing a wavelength division multiplexing. Consequently, a simulation model for the appropriate CWDM optical transmission path is introduced with short descriptions of functional blocks representing technologies utilized in this specific environment. The created Simulink modeling scheme of real environmental conditions at the signal transmission using the Coarse Wavelength Division Multiplexing (CWDM) allows executing different requested analyses for advanced optical signal processing techniques. Finally, some results from the CWDM simulation are introduced for the signal transmission influenced by different negative effects in the optical transmission medium. Using the presented simulation model, it is possible analyzing transmitted optical signals with eye diagrams and determined the impact of negative influences on the optical frequency spectrum.

***Keywords*—**the FWM influence, the CWDM optical transmission path, the wavelength division multiplexing, the optical single-mode fiber

I. Introduction

The optical fiber represents an environment, which is suitable for long distance information transmission using optical signals. Since a need for higher transmission speed is growing [1]-[5], it is necessary looking for methods with more effective utilization of the bandwidth, which is available in the optical fiber. One of these methods is the Wavelength Division Multiplexing (WDM) that allows transmission of multiple data channels through the one optical transmission path.

For successful understanding of the WDM signal transmission in optical networks, it is necessary exactly to recognize essential negative influences in the real environment of optical fibers [6]-[8]. For the expansion of communication systems on the optical transmission medium, it is necessary to have a detailed knowledge of their transmission environments and related influences in the real developing of customer and business installations.

This lecture discusses features and characteristics of environmental influences on optical signals transmitted by means of WDM networks. A main attention of the optical transmission environment is focused on substantial linear and nonlinear effects, especially on the Four Wave Mixing (FWM) effect. The FWM is a nonlinear effect with one of the strongest impacts on transmitted WDM signals, which arises when at least three signals (WDM channels) on different wavelengths forming a new false wave are present in the optical fiber. Therefore, this paper is devoted to this theme. Moreover, the description of the proposed CWDM optical communication path's simulation model is introduced. The created WDM simulation model represents a reach enough knowledgebase that can be helpful for various tests and performance comparisons of various novel multiplexing, modulation and encoding techniques suggested and intended to be used at signal transmissions in the optical communication path's environment.

II. Principles of WDM Systems

Negative environmental effects play an important role in a transmission of optical pulses through the optical fiber. Knowing which fundamental linear and nonlinear interactions dominate is helpful to conceive techniques that improve a transmission of optical signals, including multiplexing, advanced modulation formats, optical signal processing and a distributed optical nonlinearity management. Basic transmission parameters of the standard optical Single-Mode Fiber (SMF) utilized in telecommunications are determined by linear and nonlinear effects [13], [14].

Linear effects represent a majority of losses at the optical signal transmission signal through the optical fiber. These linear effects are mainly caused by the attenuation and the dispersion. The attenuation limits a distance of the optical signal transmission and the dispersion influences transmission rates of optical signals. Nonlinear effects in the optical fiber may potentially have a significant impact on the performance of WDM optical communication systems. In the WDM system, these effects place constraints on the spacing between adjacent wavelength channels and they limit the maximum power per channel, the maximum bit rate and the system reach.

This work is a part of research activities conducted at Slovak University of Technology Bratislava, Institute of MICT, within the KEGA agency project - 007STU-4/2016 "Progressive educational methods in the field of telecommunications multiservice networks" and VEGA agency project - 1/0462/17 "Modeling of qualitative parameters in IMS networks".

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As was mentioned before, the FWM is the nonlinear effect with one of the strongest impacts on WDM signals. Basically, FWM arises when optical signal of three different wavelengths enters the fiber and form a new false wave on another wavelength. A schematic spectrum of FWM in WDM system is shown on Fig. 1, where λ_1, λ_2 and λ_3 are the transmitted waves and λ_{FWM} is the new generated false wave. The presence of this false wave (λ_{FWM}) can lead to interferences between channels, generating of additional noise that decreases a system performance and a power of required signals lost to false signals.

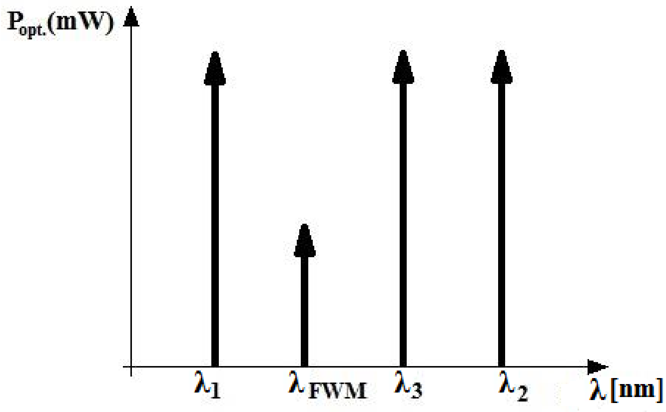

Fig.1 The example of the Four way mixing (FWM)

The count of mixing components increases with the count of WDM channels. The number of mixing components M is defined as:

$$M = \left(\frac{1}{2}\right) N^2 (N - 1) \tag{1}$$

where N is the number of transmitted WDM channels [9]-[11].

Each channel in the WDM system, which is transmitted through the shared optical fiber, is represented by a different wavelength of the light radiation [6], [7]. To the WDM multiplexer enters a number of channels, which are coupled into one resulting optical signal at the fiber input using the optical coupler. On the other fiber end, the WDM demultiplexer splits one coupled signal to corresponding individual optical channels using the optical splitter and a set of optical filters. Wavelengths, which pass through particular optical filters, should correspond to wavelengths, which are used for individual channel transmissions. A scheme with basic system principles of the WDM transmission is shown on Fig. 2.

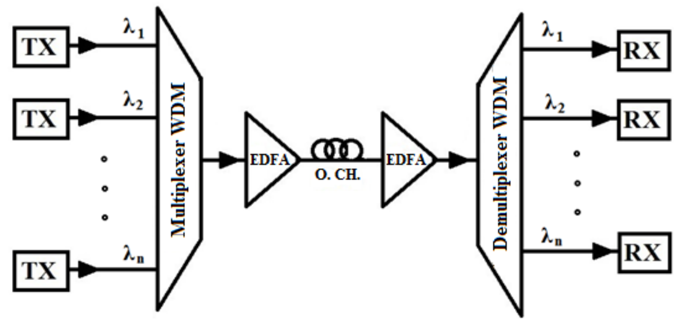

Fig. 2 The principle scheme of the WDM system

The transmission capacity of WDM systems is dependent on the number of transmitted channels and on the channel spacing. If the wavelength distance between optical channels is smaller, then more channels can be transmitted in optical transmission windows. The wavelength band is strongly dependent on the operation band of utilized optical amplifiers, concretely the EDFA.

A. The Coarse Wavelength Division Multiplexing

The Coarse Wavelength Division Multiplexing (CWDM) is a simpler version of the WDM multiplexing technique, where no optical amplifiers are considered [8], [14], [15]. Therefore, its simulation and analyzing is much easier than the Dense Wavelength Division Multiplexing (DWDM).

For the CWDM system, there is used a larger channel spacing that allows utilizing simpler and therefore cheaper system components, e.g. non-cooled lasers with a larger wavelength tolerance and optical filters with a wider passband. The CWDM technology uses II. and III. optical transmission windows (concretely, wavelengths from 1270 nm to 1610 nm) with the 20 nm channel spacing and 18 transmitted channels. The CWDM technology is used for short and medium distance network applications [8].

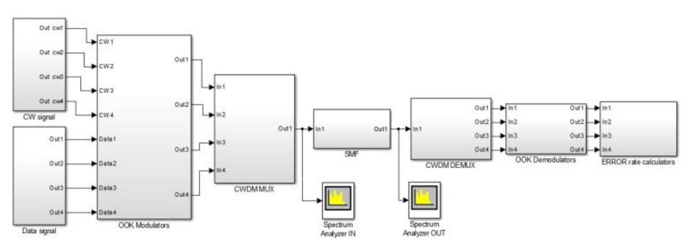

Fig. 3 The Simulink model of the 4-channel CWDM optical transmission path

III. The Simulation Model for the CWDM System

For modeling of the optical transmission path, we used the software program *Matlab 2014 Simulink* together with additional libraries like *Communications System Toolbox* and *DSP System Toolbox*. The realized model (Fig. 3) represents the CWDM signal transmission in the environment utilizing optical single-mode fibers for very high-speed data signals transmitted by four different wavelengths. For more accurate simulation of negative effects on each channel, this model of optical transmission path is divided into four paths (each channel has its own path) that are interconnected with each other. This interconnection interacts the transmitted channel using adjacent channels (i.e. the 1. channel is affected by 2., 3. and 4. channels, the 2. channel is affected by 1., 3. and 4. channels, etc.). Since effects on the channels are simulated individually, the CWDM Multiplexer block is connected after the SMF block of the optical transmission path.

Optical communication technologies will always be facing the limits of high-speed optical signal processing and advanced optical modulation formats, which are important factors to take into account when discussing more effective utilization of possible transmission capacities in the optical fiber. Therefore, a main task of the CWDM simulation model is an analysis of various multiplexing, modulation and encoding techniques.

For the CWDM optical transmission path, the channel wavelengths are selected as follows corresponding to the 20 nm CWDM channel spacing:

1. channel: λ_1=1571 nm => f_1= 190,83 THz
2. channel: λ_2=1551 nm => f_2= 193,29 THz
3. channel: λ_3=1531 nm => f_3= 195,81 THz
4. channel: λ_4=1511 nm => f_4= 198,41 THz

This Simulink model of the CWDM optical transmission path consists of next fundamental parts:

- Sources of data signals
- Sources of CW optical signals
- OOK Modulators
- CWDM Multiplexer
- Model of the SMF optical transmission path
- CWDM Demultiplexer
- OOK Demodulators
- Block for BER calculating

The Data signal block consists of four (Bernoulli) binary generators, which represent informative flows modulated and multiplexed into four outgoing signals. One of the data signal sources is shown on Fig. 4.

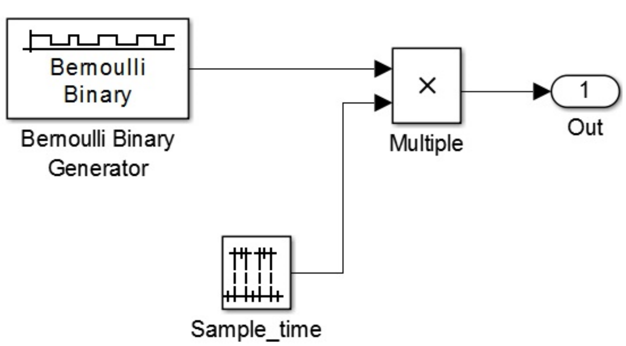

Fig. 4 The functional scheme of the Data signal source

The CW signal block represents a set of carrier signal sources, which enters the OOK Modulators block. It is the basic block for advanced optical modulation techniques and its output simulates optical signals needed to information transmission. One carrier signal source consists of several sine generators, which are set to generate many continuous wave (CW) signals at the same time, since a real source of the optical radiation is not monochromatic (i.e. it has not only one carrier wavelength (λ), but there are more wavelengths ($\Delta\lambda$)). The internal connection of the CW signal source is shown on Fig. 5.

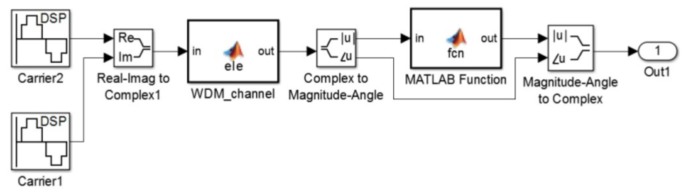

Fig. 5 The functional scheme of the CW signal source

Outputs of the Data signal and CW signal blocks are connected to the OOK Modulators block. This block consists of four MZM OOK modulators whereby internal connections of the OOK modulator are described in [16], [17]. The detailed scheme of the OOK Modulators block is shown on Fig. 6.

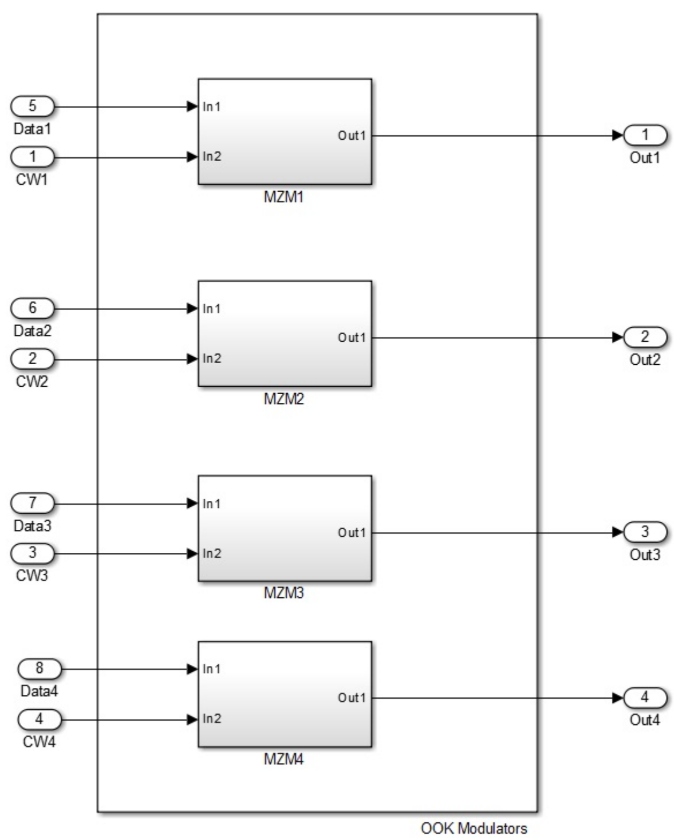

Fig. 6 The detailed scheme with internal connections of the OOK Modulators block

Optical modulated signals are going into the CWDM MUX block where are coupled into one originating signal before transmission in the optical SMF medium. Internal connections of the CWDM multiplexer is shown on Fig. 7.

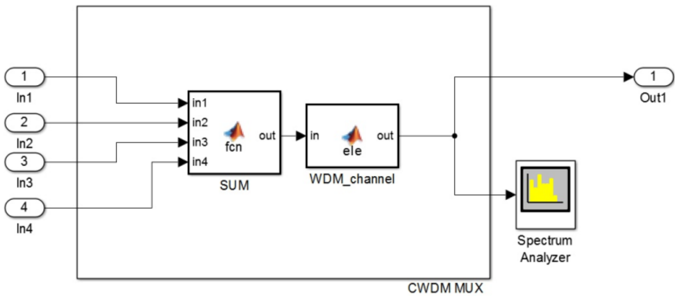

Fig. 7 The principle scheme of the CWDM MUX block

The outgoing signal from the CWDM Multiplexer block goes into the SMF block that simulates the optical transmission path with negative environmental effects on transmitted optical signals like dispersions, an attenuation and non-linear negative effects. Details of the SMF block are available in [13], [18], [19].

After passing through the SMF block, the one transmitted signal enters the CWDM DEMUX block. The task of this demultiplexer is splitting the incoming signal into individual outgoing signals, whereby each of them contains only one data channel. The CWDM DEMUX block consists of a set of filters (for each outgoing channel one), which are represented with band-pass filters. Filters are designed using *the Digital Filter Design* block that is contained in the *Matlab Simulink DSP System Toolbox*. Internal connections of the CWDM demultiplexer is shown on Fig. 8.

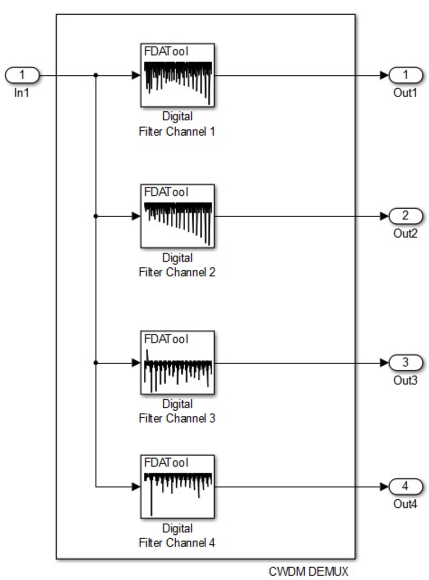

Fig. 8 The detailed scheme with internal connections of the CWDM DEMUX block

Using this simulation model the 4-channel CWDM optical transmission path, it is possible to analyze a distance between logical levels with an eye diagram. The eye diagram for second simulated channel (λ_2=1551 nm) transmitted through the SMF block is shown on Fig. 9.

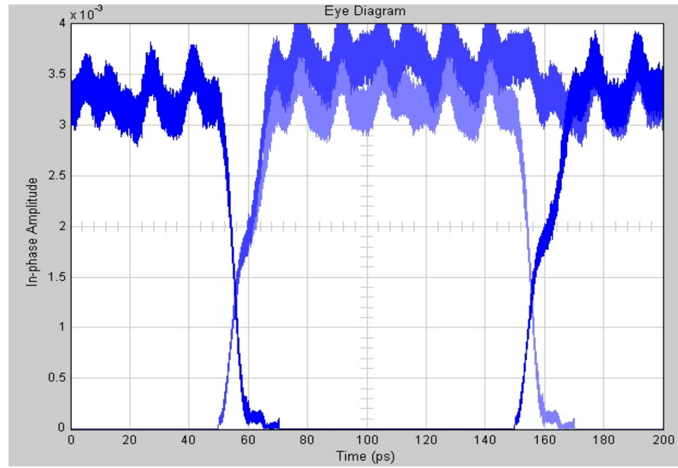

Fig. 9 The eye diagram for OOK optical signals after transmitting in the 80 km optical transmission path using the 4-channel CWDM system

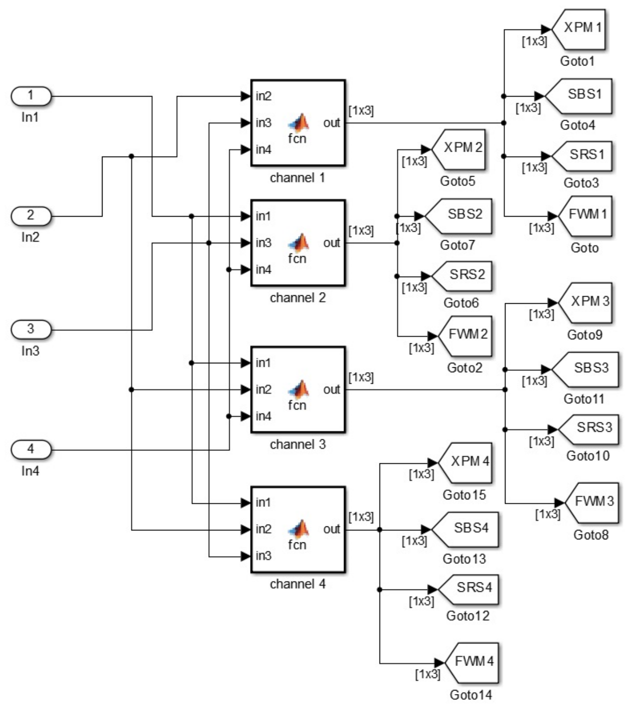

Fig. 10 The detailed scheme with internal connection of the Nonlinear effects block for the 4-channel CWDM system

On Fig. 10, the internal connection of nonlinear effect channels is shown. The task of this auxiliary block is preparing WDM channels outgoing from OOK modulators for using in the Nonlinear effects block of SMF optical transmission paths for the 4-channel CWDM system. For each transmitted channel, three other channels are multiplexed and used as input for the Nonlinear effects block. E.g., 2., 3. and 4. channels are sent to the Nonlinear effects block for specifying their influence on the 1. channel.

IV. Results from the CWDM Simulation

The CWDM signal transmission's simulation is performed in MATLAB Simulink 2014 and consists from implementation of four wavelength channels using the CWDM technique to the simulation model of negative environmental influences at the signal transmission in the optical transmission path [12], [13], [18], [19]. In our simulation, it is assumed the fiber length of L = 80 km and 4 different wavelengths λ_1 - λ_4. Parameters of the optical single-mode fiber are set up particularly for each wavelength. For example, the total attenuation a_{total}= 16,8 dB (i.e. $\alpha_{specific}$ = 0,21 dB/km) and other specific values CD = 10 ps/km, PMD = 10 ps/(nm.√km) are valid for the wavelength λ_2 = 1551 nm. For a simulation, the OOK technique is used with the same 10 Gbit/s transmission speed for each channel.

The simulation model of the 4-channel CWDM optical transmission path also allows analyzing an impact of the optical transmission path on utilized signal spectrum. The spectrum for all four CWDM simulated channels is shown on Fig. 11. On Fig. 11, the spectrum of signals entering the SMF block is marked as "IN" and the spectrum of outgoing signals is marked as "OUT".

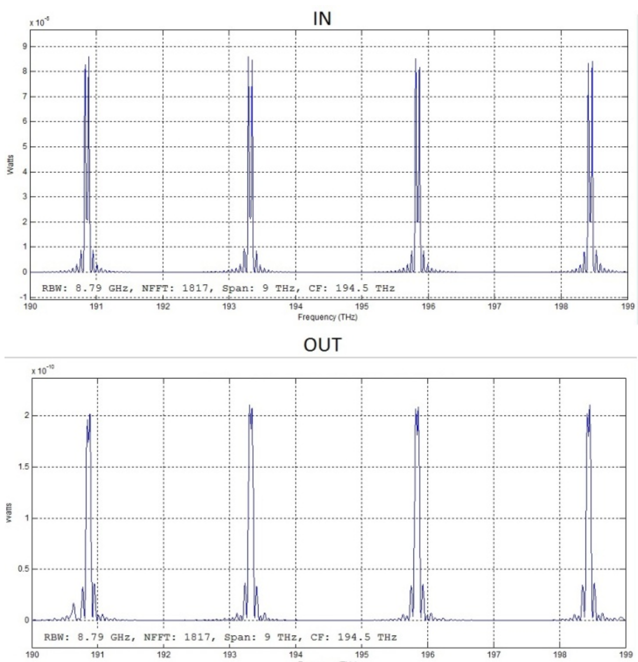

Fig. 11 The frequency spectrum of four CWDM channels (a) entering IN and (b) outgoing OUT the SMF block

As can be seen on Fig. 11, the strongest impact of nonlinear effects is visible on the 1. channel (see the left sideband) where a new false element in the spectrum is present. On the Fig. 12, a particular spectrum of the second simulated channel (λ_2 = 1551 nm) entering and outgoing the SMF block is presented. This signal spectrum after transmission is changed due to negative influences of the optical medium. Shapes of signal sidebands are deformed and unsymmetrical. Environmental effects with the strongest impact are dispersions (CD and PMD) and the FWM effect.

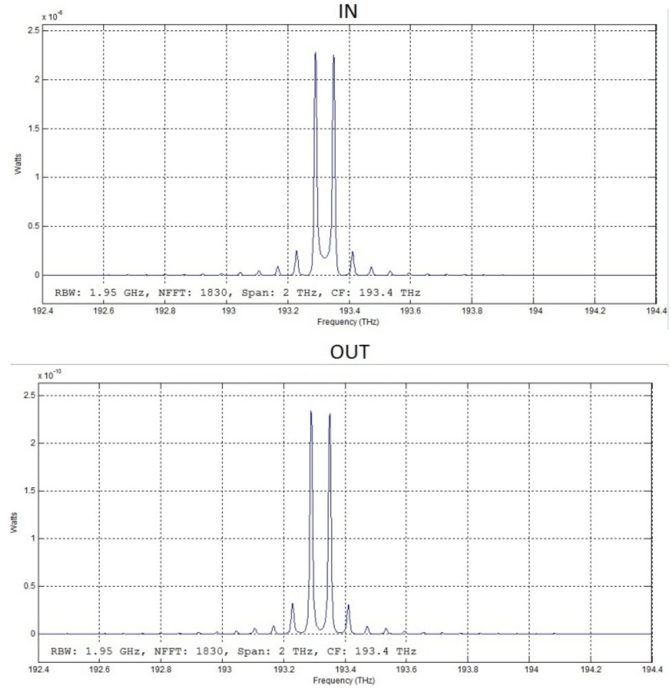

Fig. 12 The detailed frequency spectrum of the 2. CWDM channel (a) entering IN and (b) outgoing OUT the SMF block

On the Fig. 13, particular spectra of the second simulated channel (λ_2 = 1551 nm) for individual negative environmental influences are presented. In the simulation model of the CWDM optical transmission path, following negative influences considered for the optical transmission medium included [12], [13], [18], [19] are included:

- Chromatic dispersion (CHD)
- Polarization mode dispersion (PMD)
- Four way mixing (FWM)
- Self-phase modulation (SPM)&Cross phase modulation (XPM)
- Stimulated Raman scattering (SRS)&Stimulated Brillouin scattering (SBS)&Attenuation

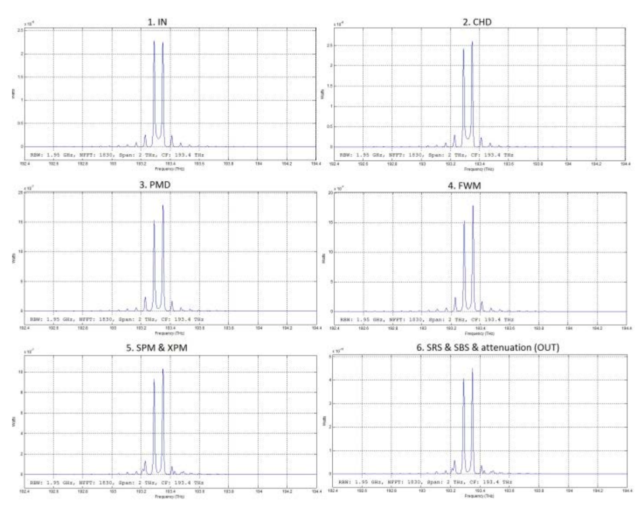

Fig. 13 The detailed frequency spectrum of the 2. CWDM channel for individual negative environmental influences

V. Conclusion

This paper deals with main features, characteristics and the simulation of negative environmental influences in the optical transmission medium at the CWDM signal transmission and is focused especially on the FWM (Four Wave Mixing) effect. Also, basic principles of optical communication systems utilizing the Coarse WDM technique are introduced.

Modeling of the CWDM multiplexing technique with four wavelength channels in the optical transmission medium using MATBAL Simulink 2014 environment is presented. The Simulink model of the 4-channel CWDM optical transmission path allows executing different requested analyses for advanced optical signal processing techniques. The impact of this optical transmission path on transmitted optical signals is presented using eye diagram and frequency spectrum. The original model used in [1] is modified to achieve more accurate simulation of negative influences (especially the FWM) in the optical transmission environment. In this case, negative effects are simulated individually for each channel with interconnections between each other. These interconnections simulate interferences between wavelength channels.

In the eye diagram, the larger distance between logical levels can be caused by a simpler implementation of CW source (with low noise level) for logical 0. In the frequency spectrum, it can be seen the strongest impact of negative environmental influences, which affects the symmetry and shapes of optical signal sidebands. The strongest impact on spectrum is observable for the 1. channel (Fig. 11) where a new false part of sideband is generated.

In a future, the model of the 4-channel CWDM optical transmission path will be enhanced by increasing the number of CWDM channels to maximum (18 channels) and by improving the CW signal source. Moreover, the extension of this model for the DWDM signal transmission will be prepared in the next step.

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