

Realization of DWDM system according to the ITU-T.G.694.1 for investigation SPM

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Abstract: - In the article, a nonlinear phenomenon SPM (Self Phase Modulation), which occurs in the all-optical communications systems, is described. In the 21st century, the WDM (Wavelength Division Multiplex) system cannot be created without the software that simulates the system under real conditions. The most important WDM components include the EDFA (Erbium Doped Fiber Amplifier), in which amplification occurs at all wavelengths. 10 Gbps optical line of the DWDM (Dense Wavelength Division Multiplex) system in accordance with ITU-T.G.694.1 was created and the SPM phenomenon is observed at it.

Key-Words: DWDM, EDFA, SPM

1 Introduction

Wavelength division multiplexing networks are optical networks where a principle of wavelength division multiplexing is used. These networks allow a single fiber to transmit several optical carrier waves, each being at a different wavelength. It is a frequency multiplex in the optical transmission band of the transmission medium as the wavelength corresponds to the frequency of the optical signal carrier. This transfer technology allows deploying optical carrier waves carrying the data to the whole band of the medium permeability, taking into account the available transmission technologies, meaning one fiber is binding more optical wavelength ranges transmitting the data [1], [2]. The transmission at each wavelength can be achieved with a different transmission (bit) rate, another type of modulation and other forms of signal. The idea of WDM networks allows better use of built optical networks by transporting a single fiber with a number of carrier wavelengths, yet the structure of optical networks has not changed.

The disadvantage of WDM systems is the increased damping of the network due to the multiplexer and demultiplexer inserted into the transmission chain. In the mid-nineties the term Dense WDM started to be used after managing to transfer more and more channels with significantly smaller spacing in one fiber.

2 DWDM according ITU-T.G.694.1

Dense Wavelength Division Multiplexing is one of the most perfect and most widely used systems in today's optical communications. Spacing between channels is 0.8 nm, theoretically up to 0.1 nm in UDWDM (Ultra Dense Wavelength Division Multiplexing), means the ability to transmit a single fiber to several dozen channels. These channels are transmitted by optical fibers in parallel and without being dependent on each other, the transmission capacity of optical connection increases many times. Modern DWDM systems can operate 96 channels on a single physical link, in each such channel transmit enable a signal rate of 2.5 to 10 Gbps. In Fig. 1 a 4-channel DWDM system is displayed. Following components are used for a proper implementation of this technology laser DFB (Distributed FeedBack laser) with an extremely narrow spectral line, amplifier EDFA (Erbium Doped Fibre Amplifier) and spectral filters with high selectivity [3-5]. These devices are very sensitive to temperature and frequency stability. This is one of the main reasons of its high price. Regulation ITU-T G.694.1 "Spectral grids for WDM applications: DWDM frequency grid" defines the various transmission channels for DWDM wavelengths in the range of 1490 nm (200.95 THz) to 1620 nm (186.00 THz), S, C and L band. Channel spacing DWDM is based on the normalized initial frequency of 193.1 THz. The raster with the spacing

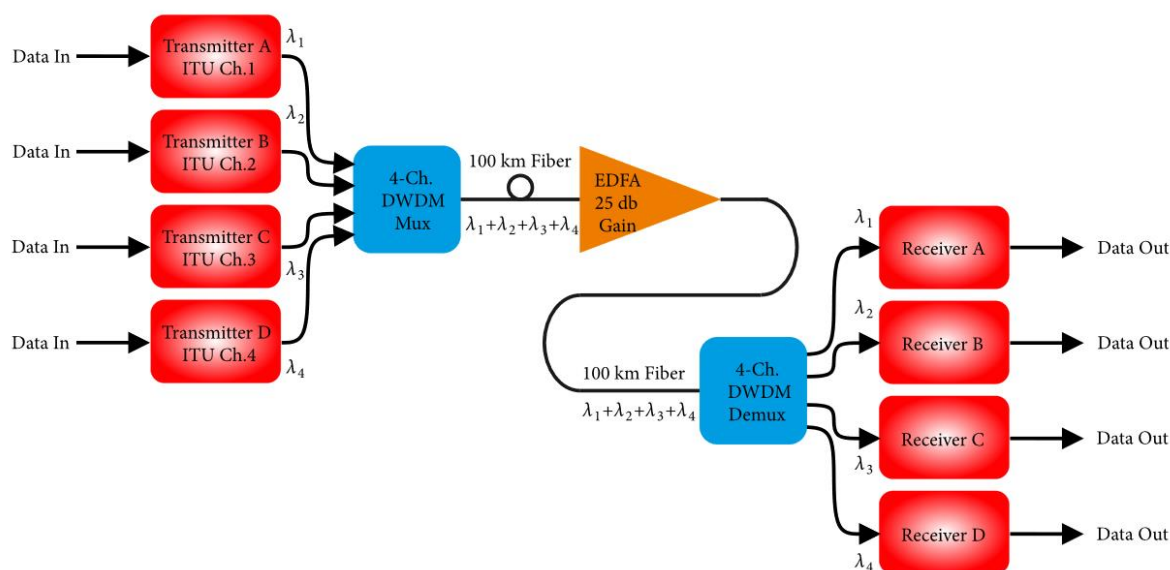


Fig. 1: 4-channel DWDM.

of the individual channels in the range of 100 GHz (0.8 nm), 50 GHz (0.4 nm), 25 GHz (0.2 nm) (UDWDM) and 12.5 GHz (0.1 nm) depends on the frequency. The distance between wavelengths and frequencies is given by the equation

$$\Delta\lambda = \frac{\lambda \Delta f}{f}, \tag{1}$$

where $\Delta\lambda$ represents the wavelength spacing, Δf is the frequency spacing value, λ represents each wavelength and f represents frequency [6], [7]. For a high quality of transmission and the correct operation it is necessary that the wavelength deviation from the designed wavelength will not exceed 0.2, representing tolerance ± 0.16 nm for 100 GHz channel spacing [8-11]. For usage of DWDM technology in access and metropolitan networks it should be appropriate to narrow wavelength range to the band "C" only, which is the area from 1530 nm to 1565 nm. For this band, the components (EDFA amplifiers, etc.) are suitable and affordable.

3 Self-Phase Modulation

Self-phase modulation is a nonlinear phenomenon caused by the interaction of light and material. If the light pulse propagates in a nonlinear optical medium, a change in refractive index is induced due to the optical Kerr phenomenon [4]. This causes a dependence of the pulse phase on the intensity, and it leads to a change in the pulse spectrum. The frequency is in the middle of the pulse approximately linear [12-15]. Phase changes with

time in the same way as the optical signal. Different parts of the pulse go through various phase shifts due to fluctuations in phase. This results in the frequency chirping. The primary phenomenon of self-phase modulation is broadening the pulse. SPM effect is more pronounced in systems with high transmission power as chirping effect is proportional to the signal transmission power. Phase is expressed as follows

$$\phi = \frac{2\pi}{\lambda} nL, \tag{2}$$

where λ is the wavelength of the optical fiber of the transmitted pulse having a refractive index n , and nL is called optical length [4]. The fiber used for high transmission power can be replaced with n_{eff} and L_{eff} respectively i.e.

$$\phi = \frac{2\pi}{\lambda} n_{eff} L_{eff}, \tag{3}$$

or

$$\phi = \frac{2\pi}{\lambda} (n_l + n_{nl}I)L_{eff}, \tag{4}$$

where the right part of the first relationship is a linear portion of a constant phase (ϕ_l) and the second relationship is a nonlinear portion of the constant phase (ϕ_{nl}).

If the intensity is time dependent and the wave is modulated in time, then the phase ϕ is also time dependent. Substitution phase in time causes a change in the frequency spectrum which is given by

$$\omega = \frac{d\phi}{dt}. \tag{5}$$

In dispersion, the medium in the spectrum changes temporarily and the pulse changes the nature of variations. It is necessary to take into account the Gaussian pulse, which modulates the carrier frequency ω and the new instantaneous frequency becomes

$$\omega' = \omega_0 + \frac{d\phi}{dt}. \quad (6)$$

The sign of the phase shift is SPM negative due to a minus sign in the expression for the phase ($\omega t - kz$)

$$\phi = -\frac{2\pi}{\lambda} L_{eff}(n_l + n_{nl}I), \quad (7)$$

and, therefore ω is

$$\omega' = \omega_0 - \frac{2\pi}{\lambda} L_{eff} n_{nl} \frac{dI}{dt}. \quad (8)$$

Thus the leading edge pulse $\frac{dI}{dt} > 0$ is

$$\omega' = \omega_0 - \omega(t), \quad (9)$$

and the rear edge $\frac{dI}{dt} < 0$ so,

$$\omega' = \omega_0 + \omega(t), \quad (10)$$

where

$$\omega(t) = \frac{2\pi}{\lambda} L_{eff} n_{nl} \frac{dI}{dt}. \quad (11)$$

This shows that the pulse is chirp and the frequency is varied across the pulse. This phenomenon called chirping is caused by SPM leading to an extent pulse spectrum.

4 Erbium Doped Fiber Amplifier

These amplifiers consist of optical fiber several tens of metres long which is doped with rare earth with Erbium Er^{+3} . The EDFA principle was initially discovered in 1960 but only further progress and economic gains enabled the up until then prohibitively expensive laser lamps to be used commercially in optical networks in the 1990s. The EDFA systems allowed the start of a new generation of optical communication and systems. The benefit of EDFA is to strengthen the optical signal simultaneously at several wavelengths [8]. This increases the system's transferring capacity and uses the technology of WDM optical multiplexing thanks to the option of transferring more wavelengths in one one-mode fiber. EDFA helped to lower the

prices of long distance lines and increased their capacity. Instead of one expensive optical amplifier for one wavelength it uses one optical amplifier for a whole range of wavelengths in one fiber. From the 1990's the WDM systems with EDFA support the capacity increase in optical networks and today the capacity of the optical fiber is at the level of tens of Gbps [8]. The admission of EDFA amplifiers ushered in undesirable effects connected with high transfer speed. Today the EDFA amplifiers are most widely used in optical communications. They also ensure the transatlantic data transfer and elsewhere where there are thousands of optical cables and the signal is considerably absorbed and it needs to be amplified.

The scheme of EDFA connection is pictured in Fig.2. The intake laser diode is of 980 or 1480 nm wavelength and currently available diodes have a power of 450 mW, bound into single-mode fiber. The filter absorbs the spontaneous emission noise and the optical isolator removes the undesirable light reflections [14]. The optical isolator is an opto-fiber component allowing the light flow only in one direction. The optoelectronic feedback node directs the amplifiers gain and the intake power. In optical communication EDFA's are used for the regeneration of the signal absorbed by absorption and the dispersion in the transfer fiber. They are inserted into long distance transfer lines approximately every 70 – 100 km.

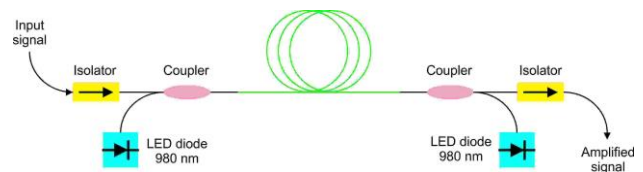


Fig.2: The operating principle of a single EDFA.

5 BER and Q-factor

Q-factor expresses the analogue quality of the digital signal considering the gap between the signal and noise. It contains all physical worsening that degrades the signal and cause bit error. The higher the Q-factor's value, the lower the bit error [8], [14]. The calculation of the Q-factor is given as

$$Q = \frac{I_1 - I_0}{\sigma_1 - \sigma_0}, [-] \quad (12)$$

where I_1 is logic level „1“, I_0 is logic level „0“, σ_1 is standard variance of logic level „1“ and σ_0 is standard variance of logic level „0“. Bit error bE can be computed as the ratio between received error

bits and the overall number of received bits p during time t .

$$BER = \frac{bE}{vp \cdot t}, \quad (13)$$

where v is the transfer's speed. Bit error shows quality of the whole optical system. In real digital communication systems there is a nonzero likelihood of error decision whether the patterned value represents the value of the logical "0" or logical "1" [8]. The calculation of bit error with the Q-factor recognition is denoted by:

$$BER = \frac{1}{2} \operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp\left(-\frac{Q^2}{2}\right)}{Q \cdot \sqrt{2\pi}}. \quad (14)$$

The distribution of the likelihood level of the received signal is on the Fig.3. Levels of signal $\log.1$ are represented by the mean value σ_1 , levels of signals $\log.0$ are represented by the mean value σ_2 . $P(1|0)$ and $P(0|1)$ mark the likelihood of $\log.1$ evaluation while the transmitter transmitted signal $\log.0$ and vice versa.

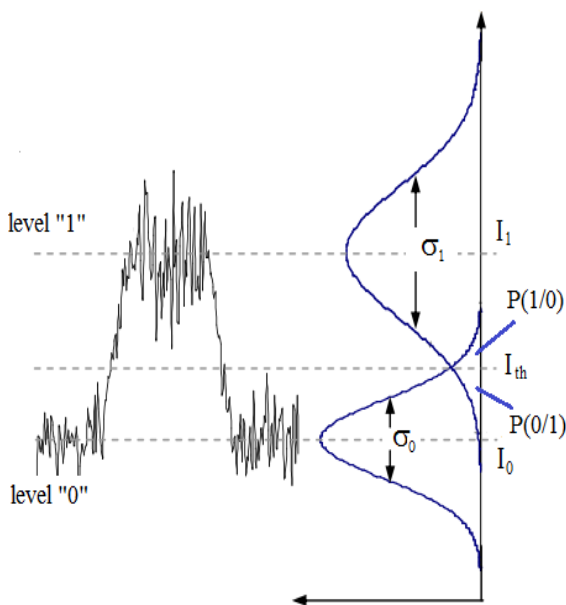


Fig.3. Received optical signal with marked noise dispersion [8].

6 Experimental verification of the SPM in DWDM system

OptSim is a programming environment that is used to design and simulate optical communication systems at the level of propagation. Conducting simulation in the programming environment OptSim is very convenient, especially for verification of

functionality gaps, or suppression of undesirable phenomena during the transmissions. OptSim is comprehensive software for the simulation of communication systems prior to implementation in practice, which ultimately can save considerable funds. It is designed for professional research of WDM, DWDM, CWDM, time division multiplexing TDM, television access CATV, LAN, parallel optical bus and other emerging optical systems. OptSim can create a fully optical communication system that represents interdependent set of blocks, each block represents a component or subsystem in a communications system. Each component could be customized according to their own requirements, users enter various numeric values, and the results could be checked with the virtual measurement instruments.

In our case, for the DWDM system the 'Sample mode' was used. In this mode, the data are transferred between components at any point in time during the entire simulation. These transfers are called samples and the advantage of this approach is that the simulation can be performed an unlimited number of times. In this mode, the signal processing is carried out only in the time domain. Design of optical communication system in this mode is easy, as each component is represented by its own icon.

The DWDM communication system was also created based on the ITU-T G.694.1.

6.1 Realization of DWDM system

The Fig. 1 illustrates the four-channel DWDM system. This DWDM system contains 3 parts: transmitting part, optical part and receiving part.

6.1.1 Transmitting part

It consists of four DWDM channels. These channels include a data source. It generates a pseudo-random sequence of bits at a rate of 10 Gbps. This sequence of bits is encoded in the block NRZ (Non-Return to Zero). The block generates the encoded NRZ electrical signal. The signal is modulated by Mach-Zehnder modulator for optical carriers which source is a laser CW_Lorentzian (6 dBm). The sources, i.e. laser diodes emit frequencies from 193.000 to 193.150 THz.

6.1.2 Optical part

The optical signal is amplified and transmitted by a single-mode optical fiber (standard G.652.D) [16], [17]. The amplifier amplifies the input signal by 10 dB. The OptSim indicates a non-linear effect SPM. At the output of the optical transmission part is the signal deprecated due to SPM and dispersion and furthermore it is sent towards the recipient.

6.1.3 Receiving part

The output optical signal is converted to the electrical. The eye diagram, BER analysis, Q-factor, eye openness and jitter can be evaluated by the probes. The probe labelled as *Input* senses the signal before being transmitted through the optical communication system, with no SPM or dispersion impact.

In this simulation, it will be a reference probe, and obtained results will be compared with the signal received at the output of the system. At the output of the probe is placed *Scope*. With this probe eye diagram, BER (Bit Error Rate), Q-factor, eye openness and jitter can be analyzed.

6.2 Results of simulation

The eye diagrams are shown in Fig. 4, 5 and 6. In each case, there are two graphs, one without the SPM phenomenon and the other one with the SPM phenomenon. These charts show the change of the optical dispersion value affected by the SPM the transmission quality. The values of the dispersion are as follows: -10, 0 and 10 ps/nm/km.

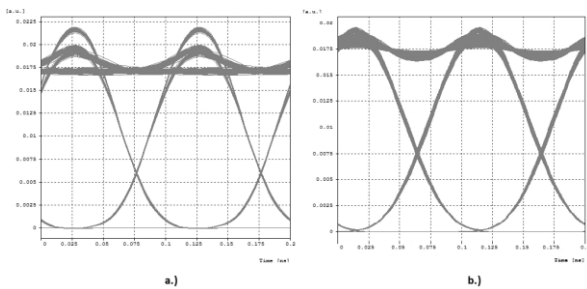


Fig. 4: The eye diagram for the optical dispersion $D=-10$ (ps/nm/km) a) After the SPM (output) b) Before the SPM (input).

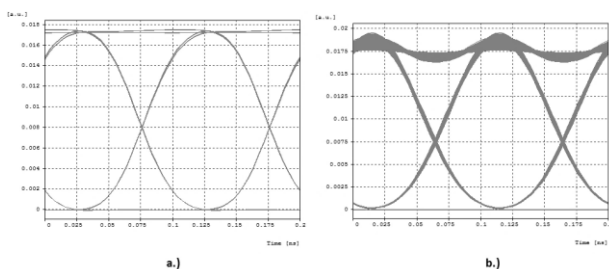


Fig. 5: The eye diagram for the optical dispersion $D=0$ (ps/nm/km) a) After the SPM (output) b) Before the SPM (input).

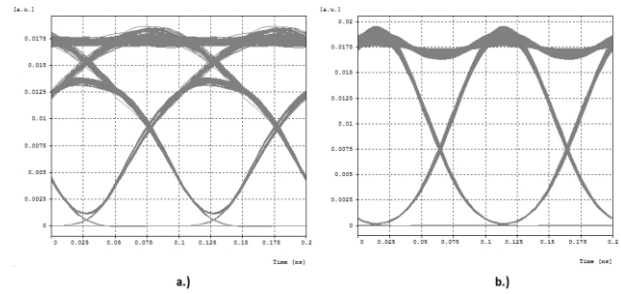


Fig. 6: The eye diagram for the optical dispersion $D=10$ (ps/nm/km) a) After the SPM (output) b) Before the SPM (input).

The resulting values are in Table 1 where the dispersion is changed with the increment 5.

Table 1: Values of four transmitters used

Dispersion (ps/nm/km)		10	5	0	-5	-10
Q (dB)	Without SPM	30.33816				
	With SPM	18.235	29.630	40	30.89	26.64
BER	Without SPM	10^{-40}				
	With SPM	1.8×10^{-17}	10^{-40}			
Jitter (ns)	Without SPM	0.00333483				
	With SPM	0.024	0.0243	0.02	0.015	0.017

7 Conclusion

The aim of this article was to demonstrate the SPM non-linear effect which occurs in WDM systems. For implementing an optical communication system, it is necessary to take into account this phenomenon already in the proposal itself. In the simulation, the DWDM system was altered as it affects the SPM phenomenon dispersion. As it can be seen in Fig.4, 5 and 6, the Q-factor became non-linear due to the SPM influence. The transmission quality characterized by the Q-factor was before the SPM phenomenon constant: 30.33816. By changing the value of the dispersion, the Q-factor, jitter and BER have changed. The values of these parameters are shown in Table 1.

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