International Journal of Advanced Academic Research | Sciences, Technology & Engineering | ISSN: 2488-9849
Vol. 4, Issue 6 (June 2018)

ANALYSIS OF LINEAR AND NON LINEAR EFFECT OF DISPERSION IN A SINGLE MODE OPTICAL FIBER TRANSMISSION SYSTEM

[1]Sani Abdullahi Mohammed, [2]Hamza Abdullahi, [3]Muhammed Mahmud Babangida, [4]Mariya Garba Mustapha

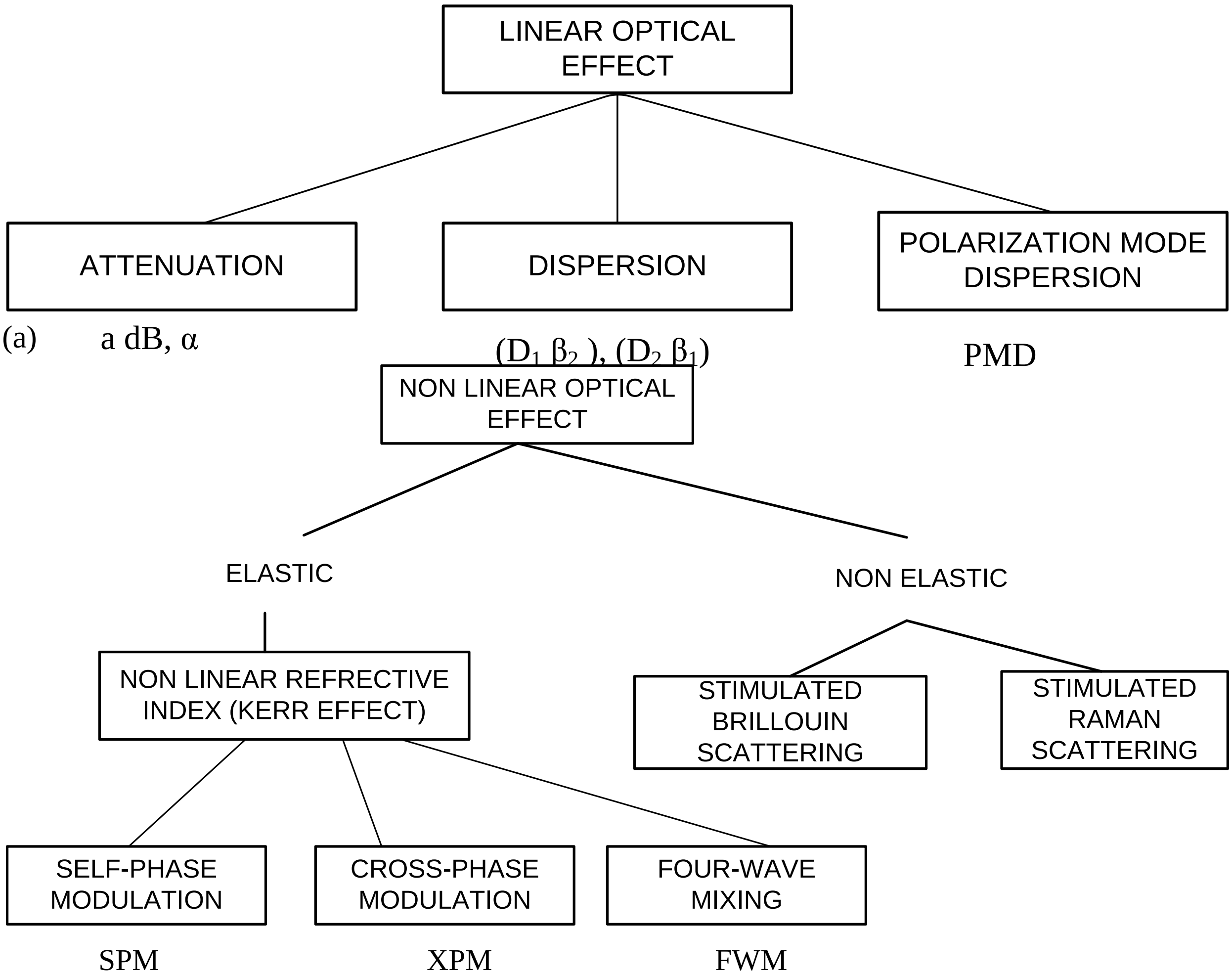
[1] Department of Computer Engineering, Kano State Polytechnic, School of Technology, Kano, Nigeria.
[2 3 4]Department of Electrical Engineering, Kano State Polytechnic, School of Technology, Kano, Nigeria.
[1]samohd3@yahoo.co.uk, [2]hamzaadm2015@gmail.com,
[3]muhammadmahmud76@yahoo.com,[4]mariyamustapha@gmail.com

Co-author's (Sani Abdullahi Mohammed) phone number: +2348034034331

ABSTRACT
A comprehensive study of the various linear and nonlinear effects have been discussed which helps to increase data rate, to overcome dispersion effects and various non-linear effects in the fiber. This work aims to understand the time dispersion in optical communication systems and to find its solution. We start by presenting a brief introduction regarding dispersion and its constituents for a single-mode fiber. We derive the pulse propagation equation, in the linear regime, and show the influence and consequences of the dispersive effects, such as the group velocity dispersion and the higher-order dispersion in different pulses. In order to avoid dispersive effects on the pulse transmission in the linear regime, two dispersion compensation schemes are presented; compensation scheme based in dispersion compensation fibers (DCFs) and compensation dispersion based in fiber Bragg gratings (FBGs). Finally, the influence of the nonlinear effects in pulse propagation of optical fiber systems is presented and analyzed.

1.0 Introduction

Optical fiber communication is a method of transmitting information from one place to another by guiding pulses of light through optical fiber. Optical communication system faces problems like dispersion, attenuation and non-linear effects. Among them dispersion affects the system the most. Dispersion is a pulse spreading in an optical fiber which increases along the fiber length. The categories of dispersion include Modal dispersion which is Pulse spreading caused by time delay, Chromatic dispersion which is Pulse spreading caused by different wavelength of light propagate by different velocities, Material dispersion which is Wavelength dependency on index of refracting of glass, Waveguide dispersion which is Due to physical structure of the waveguide and Polarization mode dispersion which occurs due to Birefringence (Agrawal, 2010). Dispersion compensation is the most important feature required in optical fiber communication system because absence of it leads to pulse spreading that causes the output pulses to overlap (Agrawal, 2007). The nonlinear effects in optical fiber occur either due to intensity dependence of refractive index of the medium or due to inelastic-scattering phenomenon. Various types of nonlinear effects based on first effect such as self-phase modulation, cross-phase modulation and four-wave mixing. Their thresholds, managements and applications are also discussed and comparative study of these effects is presented.



(b)

Figure 1.0 fiber properties in single-mode optical fibers (a)Linear (b)and nonlinear(Nguyen, 2015).

Transmission of signal information through optical fibers rapidly improved due to quality of transmission and broad bandwidth. This contribution covers modulation techniques employed in the optical transmission medium. The focus is on negative influences of the optical environment. We will introduce simulation program which simulate chosen modulation techniques through optical communication path. Each optical fiber represents a transmission system, which is frequency dependent. Pulse propagation inside this transmission system can be described by the nonlinear Schrödinger equation (NLSE) and this NLSE is derived from Maxwell equations.

1.1 Modeling of Pulse Propagation in a Single Mode Fiber

The propagation of light in a guided medium is generally described by Maxwell equations which leads to the wave equation

$$\nabla^2 E + n_0^2 \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 P}{\partial t^2} \tag{1.1}$$

Where

$\nabla = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$, Laplacian operator

E is the electric field vector,

μ_0 is the vacuum permeability,

n_0 is the refractive index of the medium.

P is the polarization density field.

ε_0 is the vacuum permittivity,

The Nonlinear Schrodinger (NLS) wave equation is used to model pulse propagation in a single mode fiber, and for long lengths of fiber, the NLS wave equation is typically derived under a few approximations on the waveguide properties of the guiding medium (Dike, and Ogbe, 2013). The pulse envelope in time t at the spatial position z, $A(z,t)$ propagating from transmitting to the receiving end of an optical fiber communication system is described by the non-linear Schrodinger equation 1.2

$$\frac{\partial}{\partial z}A(z,t) = -\frac{\alpha}{2}A(z,t) + \beta_1 \frac{\partial}{\partial z}A(z,t) - j\frac{\beta_2}{2}\frac{\partial^2}{\partial t}A(z,t) + \frac{\beta_3}{6}\frac{\partial^3}{\partial t^3}A(z,t) - j\gamma\left|A(z,t)\right|^2 A(z,t) + j\gamma T_R \left|A(z,t)\right|^2 A(z,t) + \frac{\gamma}{\omega_0}\left|A(z,t)\right|^2 A(z,t) \tag{1.2}$$

Where

A is the pulse envelop in spatial position *z* and in time *t*

γ is the Propagation constant $=\alpha + j\beta$

β_1 in the first order dispersion parameter causes pulse delay due to polarization mode dispersion,

β_2 is the second order dispersion parameter causes pulse broadening due to chromatic dispersion.

α is the attenuation coefficient of the fiber and

α_0 is the non-linearity coefficient of the fiber and it is a function of the light strength.

$-\frac{\alpha}{2}A(z,t)$ Linear attenuation

$-j\frac{\beta_2}{2}\frac{\partial^2}{\partial t}A(z,t)$	Second order dispersion
$+\frac{\beta_3}{6}\frac{\partial^3}{\partial t^3}A(z,t)$	Third order dispersion
$-\mathrm{j}\gamma\left\|A(\mathrm{z},\mathrm{t})\right\|^2 A(\mathrm{z},\mathrm{t})$	Kerr effect
$+\mathrm{j}\gamma T_R\left\|A(\mathrm{z},\mathrm{t})\right\|^2 A(\mathrm{z},\mathrm{t})$	Stimulated Raman Scattering
$+\frac{\gamma}{\omega_0}\left\|A(\mathrm{z},\mathrm{t})\right\|^2 A(\mathrm{z},\mathrm{t})$	Self-steepening effect

When the pulse width is greater than 1ps, equation 1.2 can be considerably simplified (as indicated below) because the Raman effect term and the self - steepening effect term are negligible compared to the Kerr effect term

$$\frac{\partial A}{\partial z}+\frac{\beta_1\partial^2 A}{\partial t}-\frac{i}{2}\frac{\beta_2\partial^2 A}{\partial t^2}+\frac{\alpha}{2}A=-i\alpha_0\ /\ A/^2\ A \qquad (1.3)$$

From the equation we can obtain effects in optical fibers and we can classify them as:

(a) Linear effects, which are wavelength depended

(b) Nonlinear effects, which are intensity (power) depended.

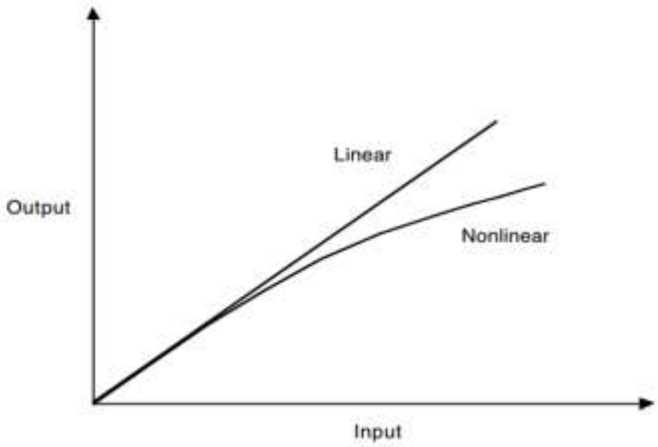


Figure 1.1 Linear and nonlinear interactions.

1.2 Linear effects

The majority losses of optical transmission signal through optical fibers are caused by linear effects. These linear effects are dispersion and optical signal loss called attenuation. The attenuation represents transmission loss, which means the decreasing level of the signal power with increasing length. Two types of dispersion occur in the optical fibers, modal and chromatic. This research paper deals with single mode fibers and therefore modal dispersion, which occurs only in multi-mode fibers, is not examined. The chromatic dispersion is caused by different traveling speed through fiber for different wavelength and it depends on the spectral width of the pulse. The broadening and phase shifting occur in optical fibers due to the chromatic dispersion (Kaminow et al., 2008).

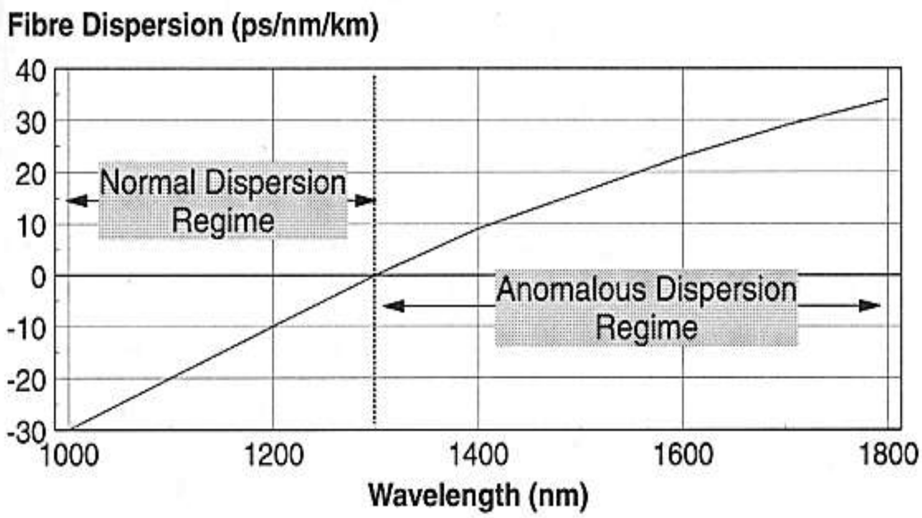


Fig 1.2 Material dispersion of a single mode fiber (Nguyen, 2015).

1.3 Nonlinear effects

These effects play an important role in transmission of optical pulses through optical fiber. We can classify nonlinear effects:

(a) Kerr nonlinearities, which is self-induced effect in which the phase velocity of the wave depends on the wave's own intensity. Kerr effect describes change in refractive index offiber due to electrical agitation. Due to Kerr effect, we are able to describe the following effects:

i. Self-phase Modulation (SPM) - effect that changes the refractive index of the transmission medium caused by intensity of the pulse.

ii. Four Wave Mixing (FWM) - effect, in which mixing of optical waves rise a fourth wave, which can occur in the same wavelength as one of the mixed wave.

iii. Cross-phase effect (XPM) is effect where wave of light can change the phase of another wave of light with different wavelength. This effect causes spectral broadening.

(b) Scattering nonlinearities, which occur due to inelastic scattering of a photon to lower energy photon. We can say that the energy of light wave is transferred to another wave with a different wavelength. Two effects appear in optical fiber:

i. Stimulated Brillouin Scattering (SBS) and

ii. Stimulated Raman Scattering (SRS) – effects that change variance of light wave into different waves when the intensity reaches certain threshold (Nguyen, 2015)

Nonlinear effects in the glass fiber, such as four-wave mixing (FWM), self-phase modulation (SPM), and cross-phase modulation (XPM) would also adversely affect the transmission quality to a significant degree. Higher-level modulation methods reduce the modulation bandwidth and thus provide a way out of this dilemma. In the subsequent section we discuss the various ways to increase spectral efficiency and different modulation formats to increase capacity.

Nonlinear effects in optical fibers have become an area of academic research and of great importance inthe optical fiber based systems. The employment ofhigh bit rate multi wavelength systems together with optical amplifiers creates major nonlinear effects such as SRS, SBS, SPM, XPM and FWM. Presence of these nonlinear effects in the optical fiber communication systems like wavelength division multiplexed (WDM) systems can adversely affect the communication between two receiving ends (Chopra and Chaubey 2013). The situation is different when the nonlinearity and dispersion are considered together. In some circumstances, the nonlinearity could counteract the dispersion. In addition, when multiple channels are considered, the fiber nonlinearity results in interactions among channels. These nonlinear effects can be managed through proper system design. By increasing information spectral efficiency, which can be done by increasing channel bit rate, decreasing channel spacing or the combination of both, the effects of fiber non linearity come to play even more decisive role (Manpreet and Himali 2015). Fundamental investigations have demonstrated the usefulness of Standard Monomode Fiber (SMF) for transmission of bit rate higher than 10Gb/s over a single channel. In the last few years, both dispersion and optical Kerr's effects have been studied together creating path ways to techniques called dispersion compensation techniques. The combined use of SPM and joint optimization of the bias and modulation voltages to increase the dispersion limited transmission distance at 10Gb/s. Numerical and experimental studies gave first ideas about the design of an appropriate passive dispersion compensation scheme for upgrading the existing SMF communication systems. High-speed transmission over SMF at 1.55 µm suffers severely from the combined interaction of Kerr nonlinearity and dispersion. Several techniques have been developed to overcome these limitations. The use of dispersion compensating fibers (DCF) has emerged as one of the most practical techniques to compensate for the chromatic dispersion in long-haul optically amplified standard fiber transmission systems. The performance of a WDM communication system has been evaluated in presence of nonlinear effect SPM (Rekha and Mritunjay 2016).

1.4 Signal Distortion in Optical Fibers

The broadening of light pulses in fiber optics communication system is called dispersion. The dispersion increases when length of fiber increases. We have a mathematical relationship between chromatic dispersion and optical phase. The rate of change of optical phase with respect to optical frequency is called group delay. The rate of change of change of Group delay with respect to optical frequency is called chromatic dispersion.

1.5 Material Dispersion

Material dispersion arises because of the variation in the refractive index n(λ) as a function of wavelengths. This implies that the group velocity of any given mode is dependent on the wavelength. The refractive index of silica as a function of wavelength is shown in Figure 3.3. The refractive index is plotted over the wavelength region of 1.0-2.0µm, which is the most important range for silica-based optical communication systems as the loss is lowest at 1300 and 1550 nm windows.

The propagation constant β of the fundamental mode guided in the optical fiber can be written as:

$$\beta(\lambda) = \frac{2\pi n(\lambda)}{\lambda} \qquad 1.4$$

The group delay t_{gm} per unit length of can be obtained as

$$t_{gm} = \frac{d\beta}{d\omega} \qquad 1.5$$

1.6 Effect of dispersion

Dispersion of transmitted optical signal causes distortion for both digital and analog transmission along optical fiber. When considering the major implementation of optical fiber transmission which involves some form of digital modulation, the dispersion mechanism within the fiber cause broadening of transmitted light pulses as they travel along the channel (Bjarklev, A. et al., 2003). It may be observed from the figure that each pulse broadens and overlaps with its neighbors, eventually becoming indistinguishable at the receiver input. The effect is known as inter symbol interference (ISI) Thus, an increasing number of errors may be encountered on the digital optical channel as the ISI becomes more pronounced.

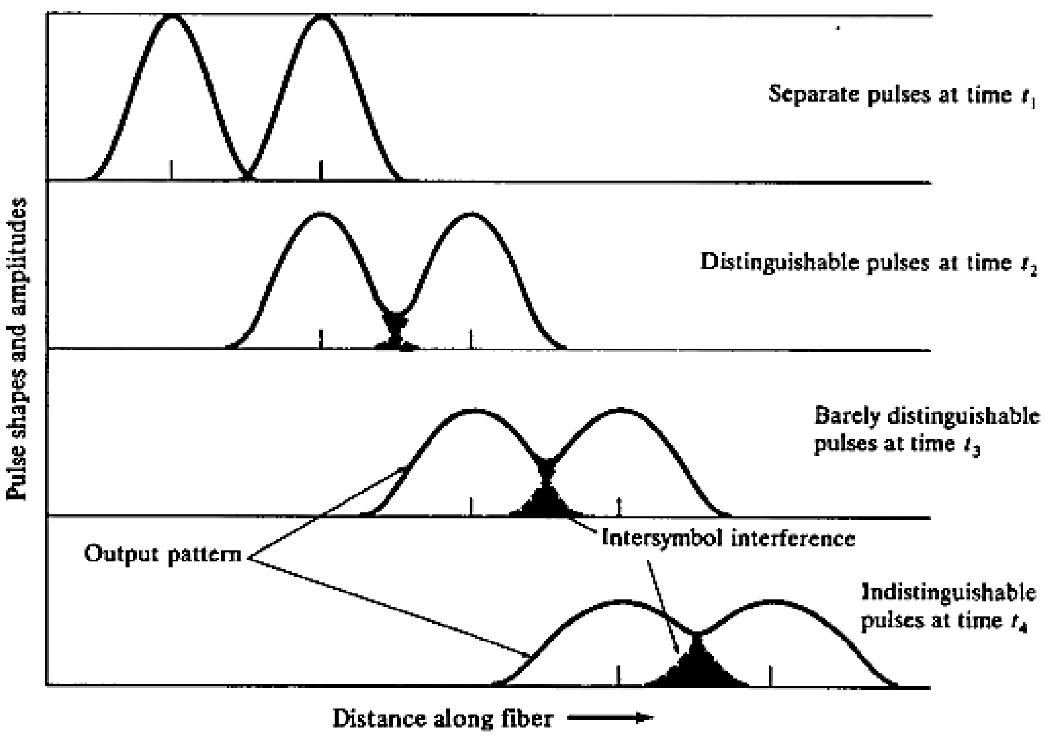


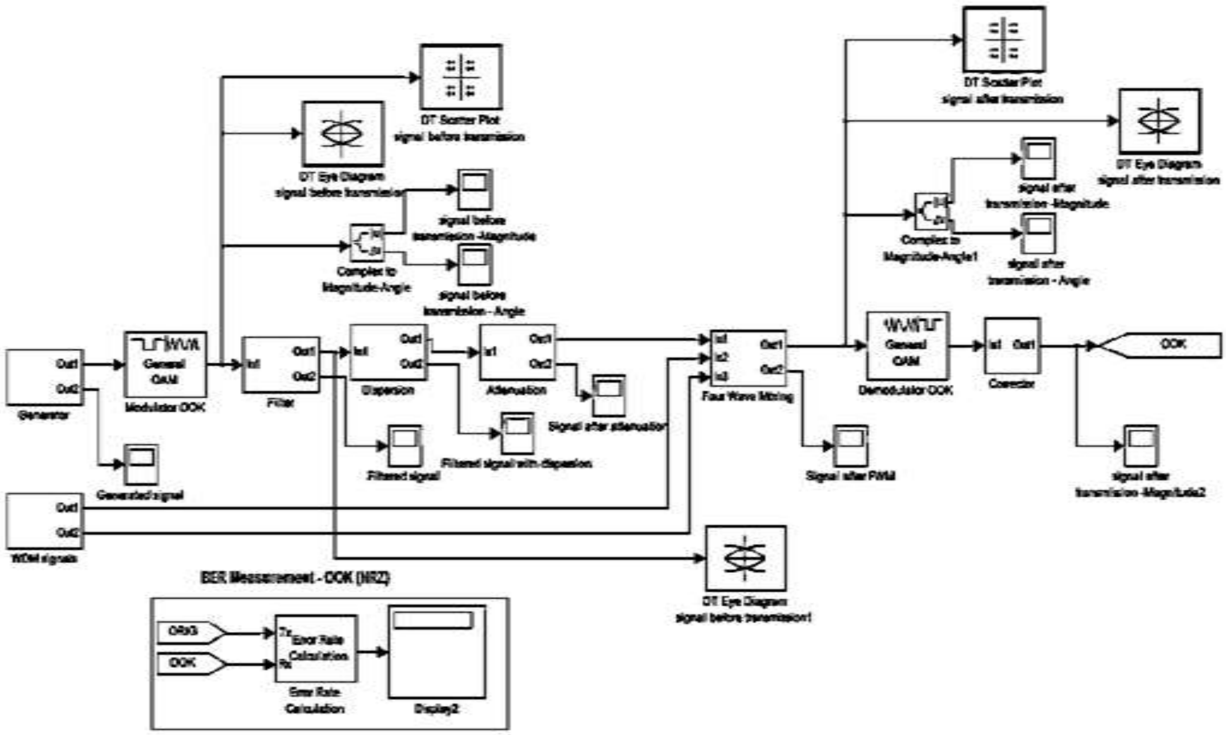
Fig.1.3 *Pulse overlap (Keiser, 2013).*

2.0 SYSTEM CONFIGURATION AND ANALYSIS

The system is designed and investigated by using MATLAB Version: 8.3.0.532 (R2014a) programs. The simulation of different modulation techniques through optical fiber with given parameters and system performance is allowed (Certik & Roka. 2012). To run the simulation, the input parameters and power parameter of four wave mixing must be set. In this section we will show how the signal change as it passes through the system. For this purpose we will consider these parameters of the system, three source generator with the power 1mW at wavelengths of 1550.5nm, 1551nm and 1551.5nm, the fiber length 10 km, the dispersion coefficient 18 ps/nm/km, the attenuation 0.21 dB/km. To simulate a realistic optical transmission medium we used four effects that influence the transmission path attenuation, limited bandwidth, dispersion and four wave mixing effect. The design of the simulation which simulates OOK modulation is shown on figure 2.

Figure 2.0: The OOK modulation

We used a Bernoulli generator as a source which generates two pulses "1" and "0". The original model also used a Bernoulli generator, but it was used in framework mode, which did not work with the dispersion part. To compare the input signal with output, both signals must be brought to the corrector, which delay the original signal with the transmitted signal.



The graph of generating signal with the involvement scheme is shown on figure 2.1. The blocks responsible for the delay are filter and dispersion.

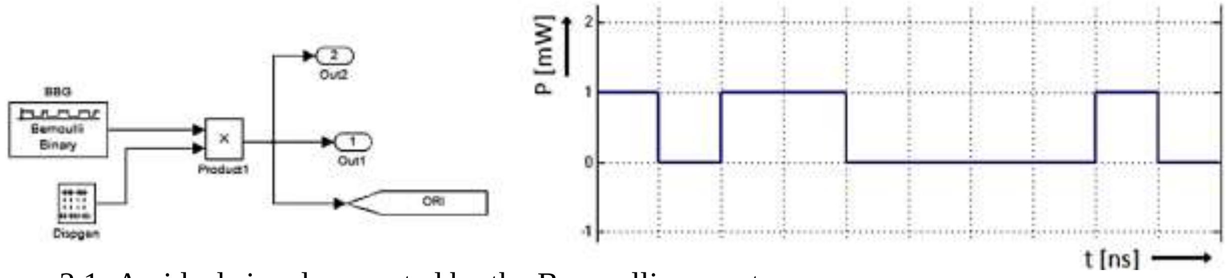


Figure 2.1: An ideal signal generated by the Bernoulli generator

After being generated, the ideal signal is modulated by the OOK modulation, which is shown on figure 2.2 and the course of the signals is shown on figure 2.3. These modulations are part of the MATLAB Simulink. The aim of this program is to show the realistic optical fiber in the realisticsystem without infinity bandwidth. Assuming finite bandwidth, we filtered signal with the appropriate filters and the scheme of filter is shown on figure 2.4. The program involves two options for filtering; the first filtration changed the signal with higher rise and fall edge. This kind of signal is mostly generated with expensive sources used in core networks. The second option is a signal with slower riseand fall edges. This kind of signal can be generated with LED diode and both filtrations are shown on figure 2.5.

Figure 2.2: modulator and demodulator blocks

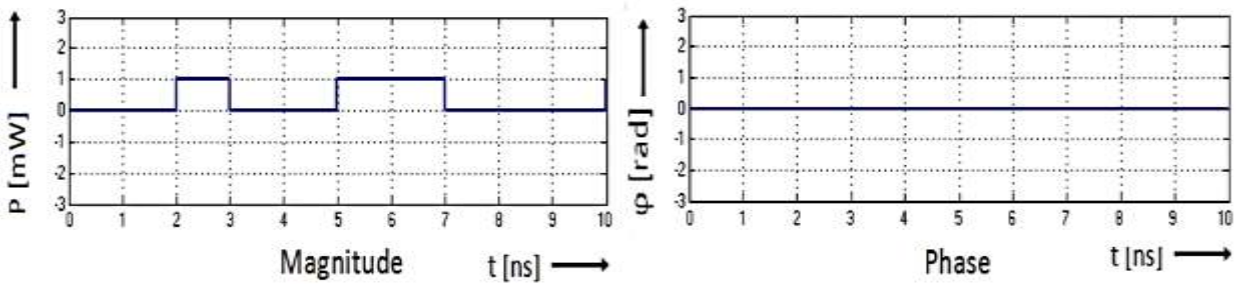


Figure 2.3: The modulated OOK signal

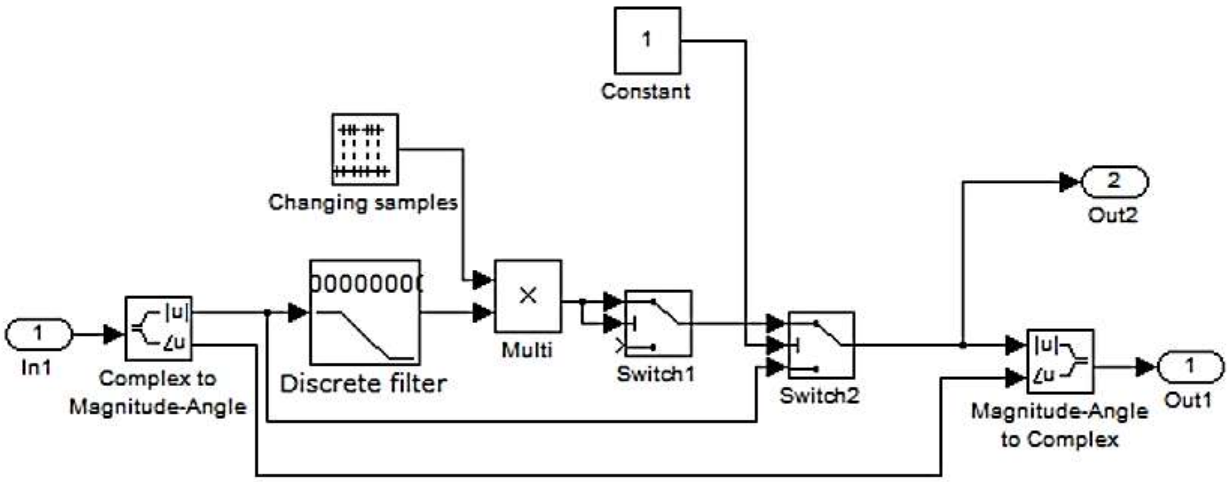


Figure 2.4: A scheme of the filter block

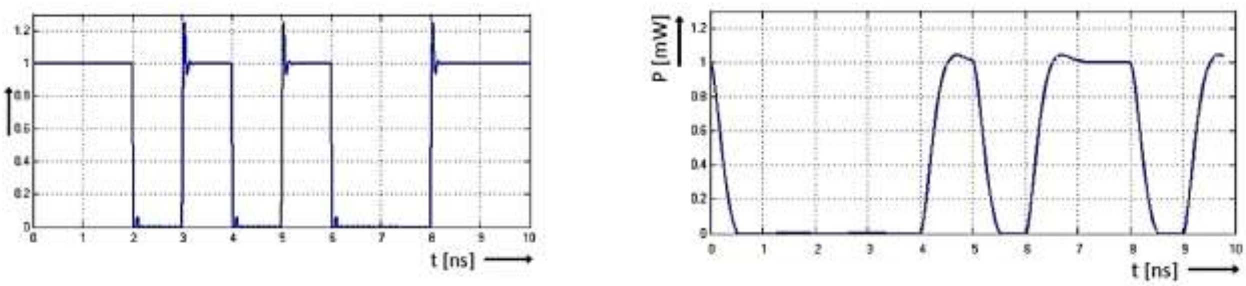


Figure 2.5: The OOK filtered signal – a laser diode (left) and a LED diode (right)

We use the dispersion block after we filter the signal with an appropriate filters. This dispersion block causes the original signal to expand in the time domain and phase shift occurs due to chromatic dispersion. The dispersion scheme is shown on figure 2.6. In this system, the value of dispersion is given by 18 ps/nm/km. Because we are using this 10 km system the signal will broader by value of 180 ps/nm/km. The influence of dispersion is shown on figure 2.7. On this figure we compare magnitudes between the signal without dispersion and signal with dispersion. The power of signal on figure 9 is attenuated due to bordering of pulse and pulse energy.

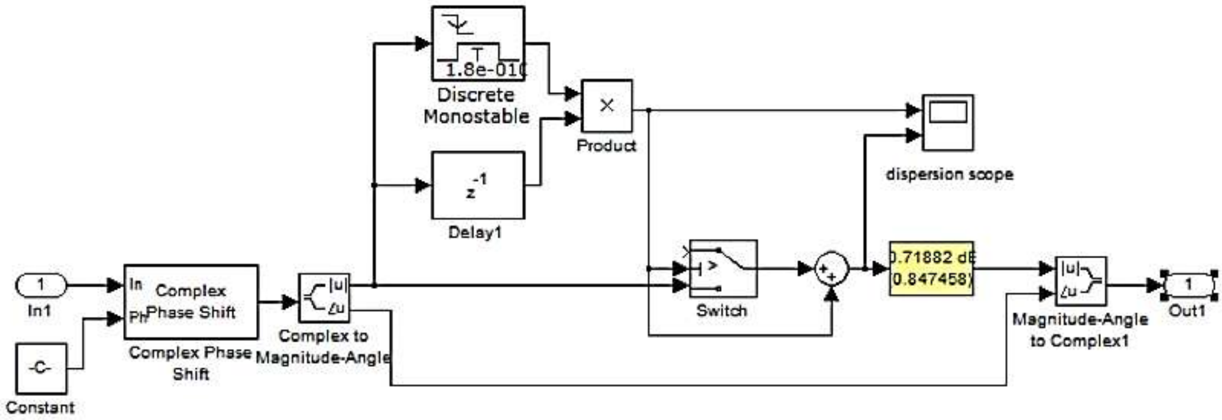


Figure 2.6: A scheme of the dispersion block

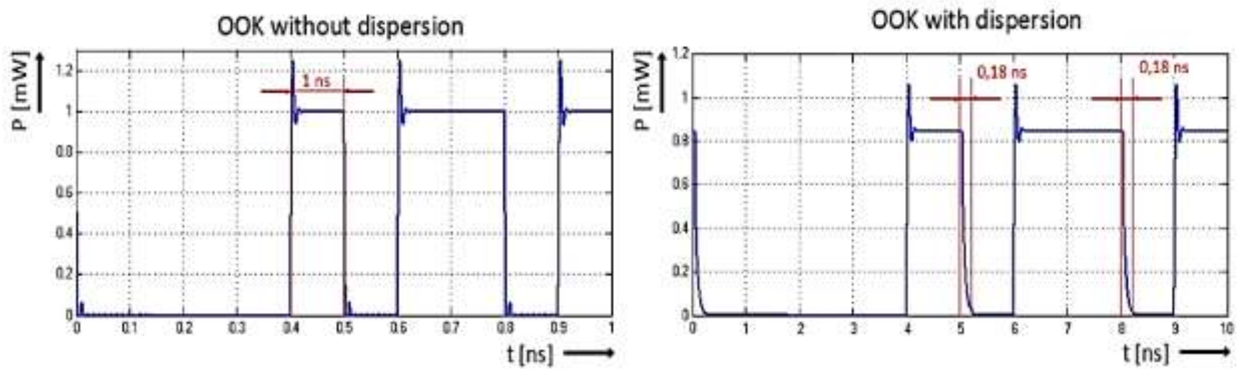


Figure 2.7: A comparison of the OOK signal with and without the dispersion

The next effect we use is attenuation. For this effect we used block which is already part of MATLAB Simulink. The scheme for attenuation is shown on figure 2.8. In the realistic system, the attenuation decreases the amplitude (magnitude) of the signal. For our fiber, the attenuation is 0.21 dB/km and because we are using the 10 km distance, our total signal attenuation is 2.1 dB.

A comparison of the signal with attenuation and the signal without attenuation is shown on figure 2.9.

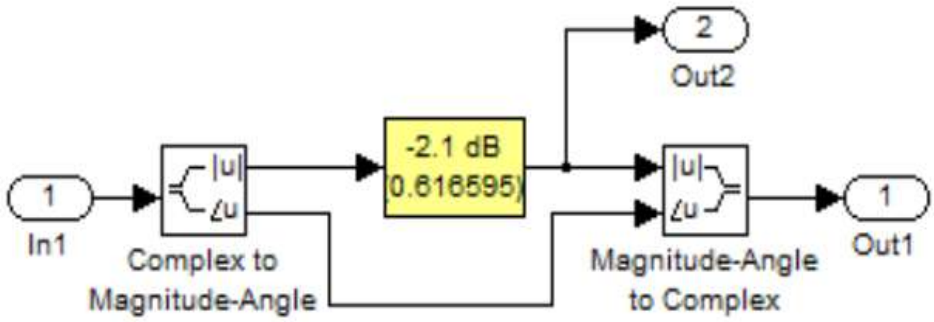


Figure 2.8: A scheme of the attenuation block

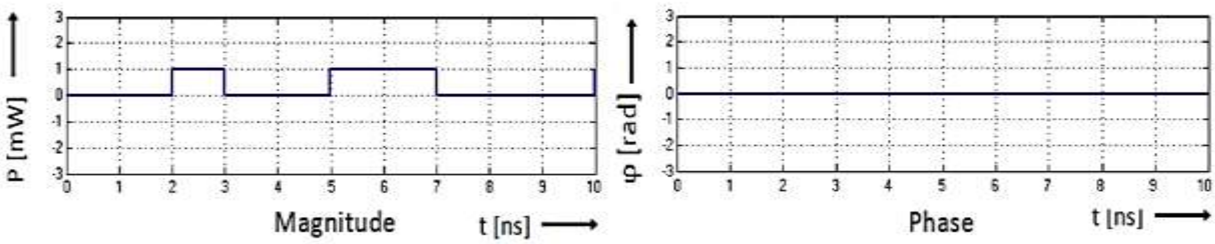


Figure 2.9: A comparison of the signal with and without the attenuation

The last effect of the simulation is the Four Wave Mixing. The FWM block is inserted after linear effects. This FWM effect occurs only in WDM systems and therefore we generate additional two signals with same modulation techniques. Generated signals are brought into the FWM block where all the signals are mixed and new generated FWM signal is created with the power given by parameters introduce in the main screen. The FWM schemas are shown on figure 2.10. The FWM effect differs depending on the power of the fourth wave and transmission rates of all mixed signals. The FWM effect on the OOK modulation with the quick rise/fall edge and the FWM effect on the OOK modulation with the slow rise/fall edge are shown on figure 2.11. We assume that a power of the FWM has only real part and therefore it affects only the magnitude. We observe that if a dispersioncoefficient value of SSMF optical fibers is higher than the 10 ps/nm/km and the channel spacing is more than 0.5 nm, then the FWM signal power is negligible compared to the optical signal power. These values are typical for Standard Single-Mode Fibers (SSMF), which used for long distances. However, when we use these dispersion values then the speed per channel is limited to 1 – 10Gbit/s.

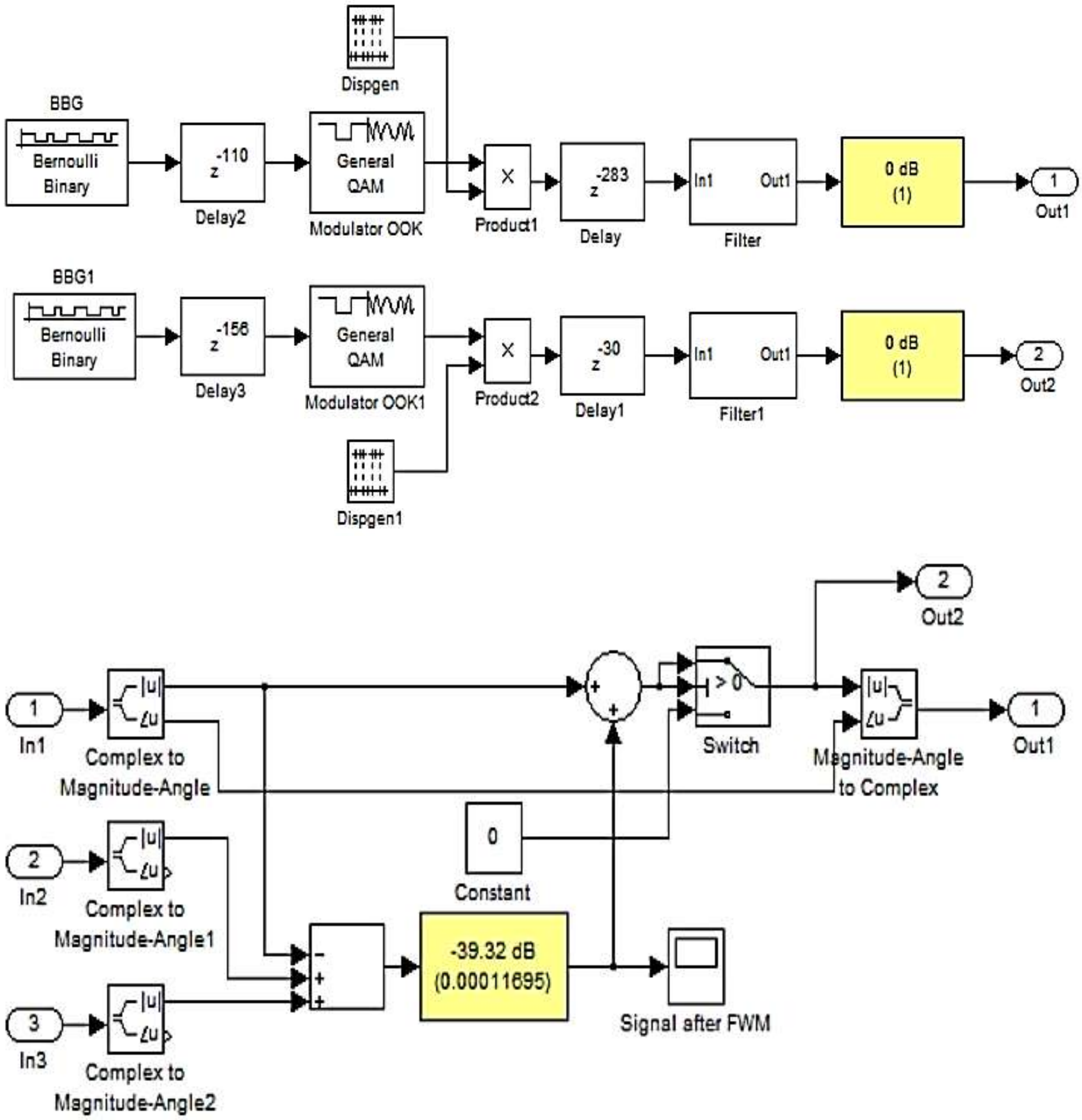


Figure 2.10: FWM blocks

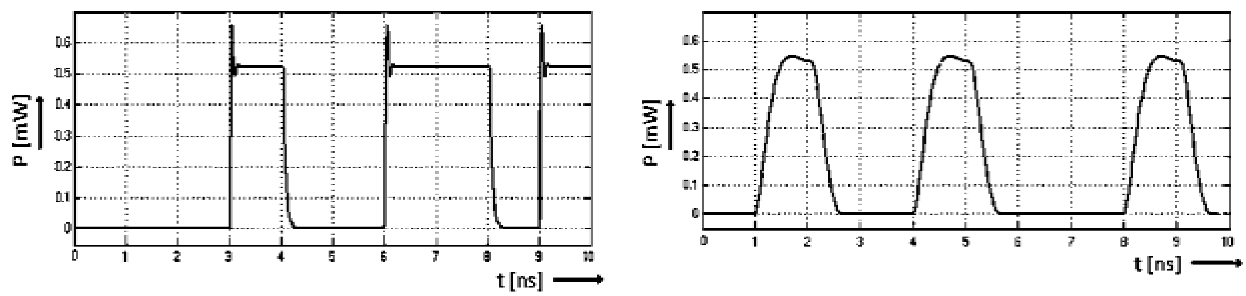


Figure 2.11: The OOK signal (quick rise/fall edge) and the OOK signal (slow rise/fall edge) with the FWM effect for the SSMF

Many optical transmission systems used Non-Zero Dispersion Shifted Fibers (NZDSF) with dispersion values are from 0.1 to 6 ps/nm/km. The FWM effect on these kinds of fibers has higher values than in the SSMF. This causes the lower SNR ratio as shown on figure 2.12.for the OOK modulation with quick rise/fall edges and for the OOK modulation with slow rise/fall edges. The signal shape depends on the modulation format used by neighboring signals and on the transmission rate. We assume that the neighboring signals are using the same modulation format as examined signal.

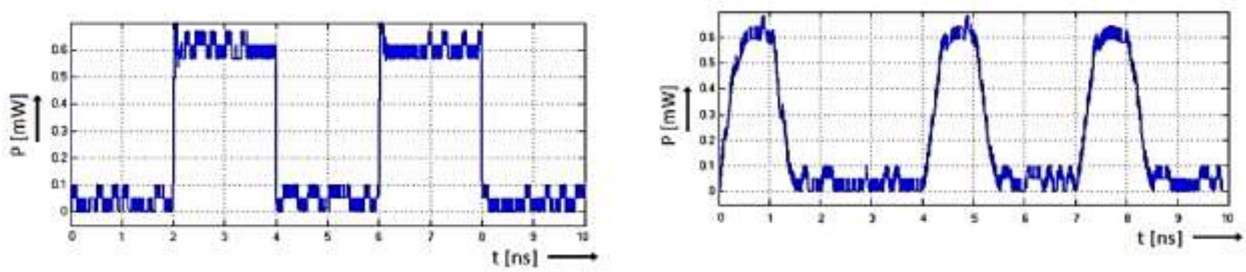


Figure 2.12: The OOK signal (quick rise/fall edge) and the OOK signal (slow rise/fall edge) with the FWM effect for the NZDSF.

After the signal pass through fiber, it gets delayed. To compare the input and the output signal, both signals must be delayed with same time. For this reason we add a corrector block which delays the input signal and then we compare the signals in comparison block. The schemes of these blocks are shown on figure 2.13. The simulation shows the Bit Error Rate (BER) of the system by comparing the input with the output signal bit by bit. The number of compared bits can be set in main screen.

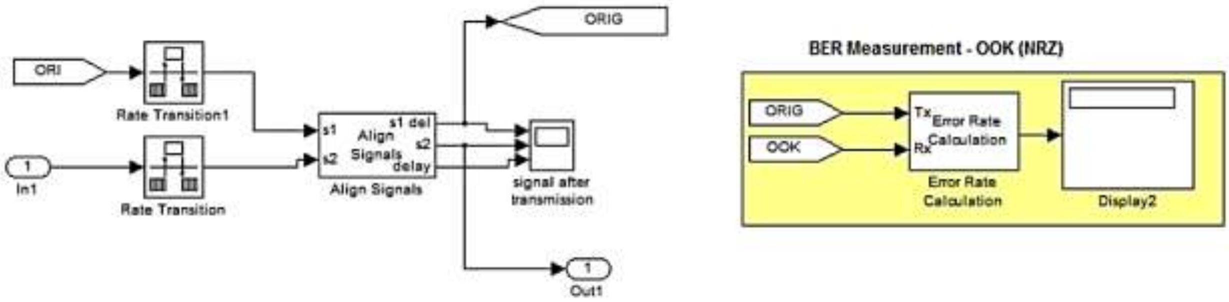


Figure 2.13: Schemes of the corrector and comparison block

The simulation part includes eye diagrams which allow the calculation of the BER and make it easier to view the signal. The eye diagram is an oscilloscope display of the transmitted digital signal, which is repetitively sampled to get a good representation of its behavior. The eye diagram is often used to look at the signal before transmission, to assure that the signal is generated properly, but mostly it is used to look at the received signal to evaluate the signal quality. Careful analysis of this visual display can give the user a first-order approximation of signal-to-noise. Eye diagrams before and after transmission for OOK modulation are shown on figure 2.14.

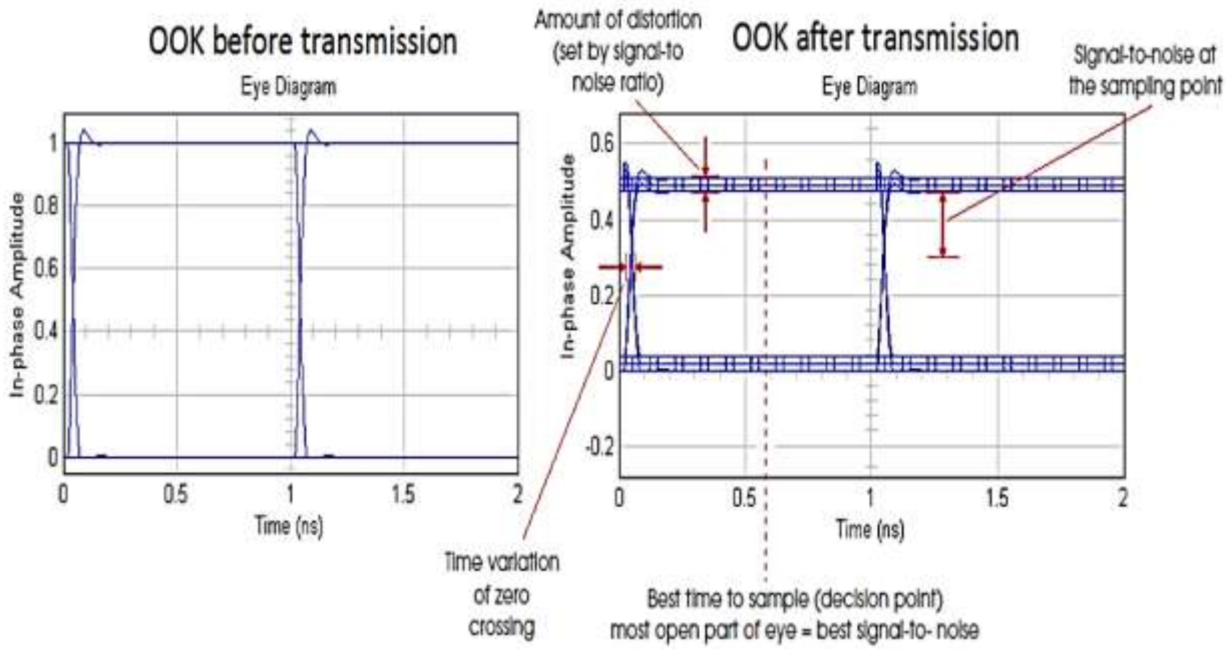


Figure 2.4: OOK eye diagrams before and after transmission

CONCLUSION

Fiber-optic communication because of its advantages over electrical transmission, have largely replaced copper wire communications in core networks in the developed world. But it is also marred by many drawbacks: dispersion, attenuation and nonlinear effect. From this study it is clear that different researchers have used different techniques for dispersion compensation in optical system. Our main aim is to present various courses for the OOK modulation technique through optical transmission medium. Linear effects and the FWM nonlinear effect are included in this simulation, but in the near future we would like to encompass this simulation for other nonlinear effects and thus results will be closer to real systems. Such a program would allow an overview of the possibilities of modulation. Another task would be adding other modulation techniques such as MSK, QAM and Manchester modulation, which propagate the signal in a different way. Additionally the program allows a further understanding of the issues of nowadays optical transmission systems. Though these effects degrade nature, they are also useful for many applications such as SPM in solitons and pulse compression, CPM inoptical switching, and FWM in squeezing and wavelength conversion.

REFERENCES

Agrawal, G. P. (2010). *Fiber-Optic Communication Systems. 4th ed.*, John Wiley &Sons, Inc, New York.

Agrawal, G.P. (2007). *Nonlinear Fiber-Optic,*4thed. Boston: Academic press.

Bjarklev, A., Broeng, J., and Bjarklev, A. S. (2003). *Photonic Crystal Fibres,* Kluwer Academic Publishers, ISDN:1-4020-7610-X.

Certik, F. & Roka, R. (2012).*Analysis of Modulation Techniques Utilized in the Optical Transmission Medium*, ELEKTRO 2012 – 9th International Conference, Žilina (Slovakia), 21.-22.5.2012, ISBN 978-1-4673-1178-6.

Chen, M.; He, L.; Yang, S.; Zhang, Y.; Chen, H.; Xie, S. (2007). Chromatic sispersion and PMD monitoring and compensation techniques studies in optical communication systems with single channel speed 40Gbit/s and CSRZ format.*Optics Express,* Vol.15, No.12, (June 2007) 7667-7676.

Chen, M.; Yang, Q.; Li, T.S.; Chen, M.S.; He, N. (2010). New high negative dispersion photonic crystal fiber. *Optik*, Vol.121, No.10, (June 2010) 867-871.

Chopra, k. and Chaubey, V. K. (2013).International Journal of Electrical, Electronics and Data Communication, ISSN: 2320-2084

Hong, I. W. (2002). *Dispersion compensation in fiber optic communication systems*. Thesis for the Degree of Master of Science, San Jose State University, San Jose, California, USA.

Kaminow, I. P.; Li, T., Willner, A. E. (2008). *Optical Fiber Telecommunictions V B: Systems and Networks,* Elsevier Inc., ISDN:978-0-12-374172-1.

Kaminow, I. P. and Li, T. (2002). *Optical Fiber Telecommunictions IV B: Systems and Impairments,*Academic Press, ISDN:0-12-395173-9.

Kashyap, R. (2009). Fiber Bragg Gratings, 2nd Ed., Acdemic Press, ISDN:0-12-372579-8. Ibsen, M.; Durkin, M. K.; Cole, M. J.; Laming, R. I. (1998). Sinc-sampled fiber Bragg gratings
for indential multiple wavelength operation. *IEEE Photonics Technology Letters,* Vol.10, No.6, (June 1998) 842-845.

Kaushal, K. Jaiswal, A.K.Mukesh, K. and Nilesh A. (2014).Performance Analysis of dispersion compensation using Fiber Bragg Grating (FBG) in Optical Communication. *International Journal of Current Engineering and Technology.*

Kayser S. F., Roy, S. Khatun, M. T.(2016). Design of a Highly Nonlinear Single Mode Hexagonal Photonic Crystal Fiber for High Negative Dispersion.*19th International Conference on Computer and Information Technology, North South University, Dhaka, Bangladesh.*

Keiser, G. (2013). *Optical fiber communication*.Fifth edition McGraw-Hill Education pvt Ltd.

Manpreet, K.and Himali, S. (2015).Analysis on Dispersion Compensation with Dispersion Compensation Fiber.*SSRG International Journal of Electronics and Communication Engineering.volume 2 issue 2.*

Nguyen, L. B. (2015). *Optical Fiber Communication Systems with MATLAB and Simulink Models Second Edition,* CRC Press Taylor & Francis Group

Pan, Z. Q. (2003). Overcoming fiber dispersion effects in high-speed reconfigure wavelength division multiplexing optical communication systems and networks. Dissertation for Ph.D, University of Southern California, Los Angeles, California, USA.

Rekha and Mritunjay K. R.(2016).Analysis and Comparison of Dispersion Compensation by DCF Schemes & Fiber Bragg Grating.I J C T A, 9(41), 2016, pp. 165-176

Sukhoivanov, I. A.; Guryev, I. V. (2009). *Photonic Crystals: Physics and Practical Modeling, Springer-Verlag,* ISDN:978-3-642-02645-4.

Sun, J.; Dai, Y. T.; Chen, X. F.; Zhang, Y. J.; Xie, S. Z. (2006). Thermally tunable dispersion compensator in 40Gb/s system using FBG fabricated with linearly chirped phase mask. *Optics Express,* Vol.14, No.1, (January 2006) 44-49.