

CHROMATIC DISPERSION IN OPTICAL COMMUNICATIONS

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Summary: This article deals with chromatic dispersion causes in optical fibres and with its effects on signal transmission. The ways of dispersion compensation are described and illustrated through simulations OptSim software.

Key words: Chromatic dispersion, DCF, MMSF, OptSim, Bragg grating (FBR), eye diagram

INTRODUCTION

Optical transmission systems have been managed to our demands to be able to transfer the required data volumes. Unfortunately, these requirements are increasing, forcing us to deal with problems, which we saw only in theory so far. Specifically, one of these is the chromatic dispersion influence.

Optical transmission system transmits information encoded in optical signal over long distances. The electrical signal in the transmitter at the fibre input is converted into light impulses that are transferred through the fibre to the receiver at the end of the fibre. In the receiver the light impulses are converted back to the original electrical signal. The transmission using the optical fibre has many advantages over traditional metallic (copper) transmission systems:

- optical signal propagating through fibre is attenuated less than the electric signal in the metallic line and so it can be sent over longer distances without repeaters
- optical transmission allows much greater data capacity
- optical signal is completely electrically isolated and it is resistant to RF interference and crosstalk

Characteristics of the optical transmission system are determined mainly by parameters of the optical fibre. The most important parameters are:

- Numerical aperture (NA) - Ability of fibre to absorb light into itself (specifically the optical power). Specifically, it is the sine of the angle under which a light ray may enter the fibre to ensure the total reflection of light will occur at the fibre surface.
- Attenuation - It is the analogy of attenuation in the case of copper cables. With increasing distance from the optical source, the power of optical signal decreases.
- Dispersion - It characterizes optical fibre in terms of maximum transmission speed. If a non-monochromatic light impulse is transmitted through an optical fibre, its shape

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changes along the fibre as a consequence of light wave speed dependence on various factors. The pulse width gradually increases and peak power of impulse is reduced. This fact limits information capacity at high transmission speeds. Dispersion reduces the effective bandwidth and at the same time it escalates the error rate due to an increasing intersymbol interference.

There are three main types of dispersion: modal dispersion, chromatic dispersion and polarization dispersion. We will focus only on one of them – on the chromatic dispersion.

1. CHROMATIC DISPERSION

1.1 The Components of Chromatic Dispersion

The primary cause of the chromatic dispersion (CR) is the fact that different spectral components of the light impulse (different wavelengths) propagate in the optical fibre at different speeds. As the consequence of different speeds the light impulse spectral components have different time of arrival to the end of fibre, impulse width increases and inter-bit spaces narrow (see the Fig. 1). The receiver cannot correctly recognize whether a transmitter in a specific bit interval sent a value of logical one or zero. The distortion of the transmitted information will then increase the bit error rate.

The chromatic dispersion consists of two components: the material dispersion and the waveguide one.

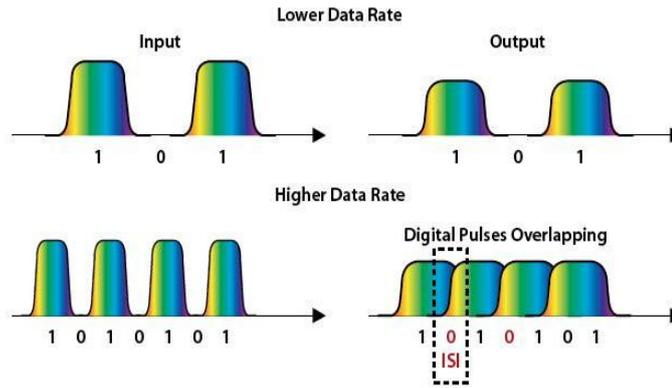
The material dispersion is caused by the dependence of the refractive index of the material used for fibre manufacturing on the light wavelength. Note that the refractive index is determined as a ratio of the speed of light in the material to the speed of light in vacuum. Then the speed of light v in the material is done:

$$v = \frac{c}{n} \quad (1)$$

where: c ... speed of light in vacuum,

n ... refractive index in a given environment

The waveguide dispersion is caused by boundary condition at the fibre surface which are influenced by geometrical parameters of the fibre. The geometrical parameters are mainly: the transversal profile of the refractive index and of the fibre core radius to the signal wavelength ratio. Consequently, the waveguide dispersion affects the speed of light passing through the fibre, too.



Source: (3)

Fig. 1 - The dependence of pulses overlap on transmission rate

The waveguide and material dispersion as a result have the same effect on signal transmission in optical fibre and therefore common term the chromatic dispersion is used.

1.2 The Parameters of Chromatic Dispersion

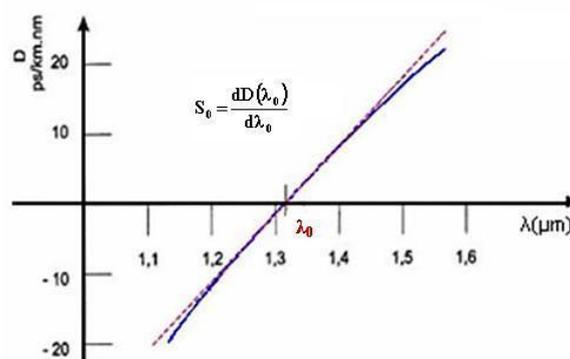
The chromatic dispersion coefficient is a primary parameter. It determines the size of the CD and it is described by the equation:

$$D(\lambda) = \frac{dt_g(\lambda)}{d(\lambda)}, \left[\frac{\text{ps}}{\text{nm} \times \text{km}} \right] \quad (2)$$

Chromatic dispersion coefficient $D(\lambda)$ expresses group delay t_g per km of the signal change per wavelength. The value of the chromatic dispersion coefficient $D(\lambda)$ is numerically equal to the Gaussian pulse (in ps) of an initial spectral half-width of 1nm width expansion after passing the fibre of a 1 km length. Pulse width increases with:

- an increasing coefficient of chromatic dispersion $D(\lambda)$
- a spectral width of the light source
- a length of the optical fibre

A typical wavelength dependence of the chromatic dispersion coefficient $D(\lambda)$ for a conventional single-mode fibre is shown in the Fig. 2.



Source: (4)

Fig. 2 - The wavelength dependence of the chromatic dispersion coefficient

This figure also shows the wavelength λ_0 [nm] of the zero chromatic dispersion and the dispersion characteristics slope S_0 [ps/nm² x km] at this point. The values of these parameters are provided by the manufacturer as catalog data and can be used for sufficiently accurate calculations of the chromatic dispersion coefficient in normal operating conditions. The image also shows that at longer wavelengths the coefficient of the chromatic dispersion $D(\lambda)$ is positive, i.e. the light components with longer wavelengths are delayed in the fibre comparing to those of the shorter wavelengths. The coefficient of chromatic dispersion $D(\lambda)$ for a particular wavelength is calculated using the graph in the Fig. 2 and the following equation:

$$D(\lambda) = \frac{S_0}{4} \times \left[\lambda - \left(\frac{\lambda_0^4}{\lambda^3} \right) \right], \quad \left[\frac{\text{ps}}{\text{ps} \times \text{km}} \right] \quad (3)$$

where all parameters are apparent in the Fig. 2.

The chromatic dispersion coefficient at wavelength 1550 nm is cca $D(\lambda) = 18$ [ps.nm⁻¹km⁻¹].

1.3 Chromatic Dispersion Influence on Transmission System

The transmitted optical pulse extension Δt at the end of an optical fibre is given by the eq. (4):

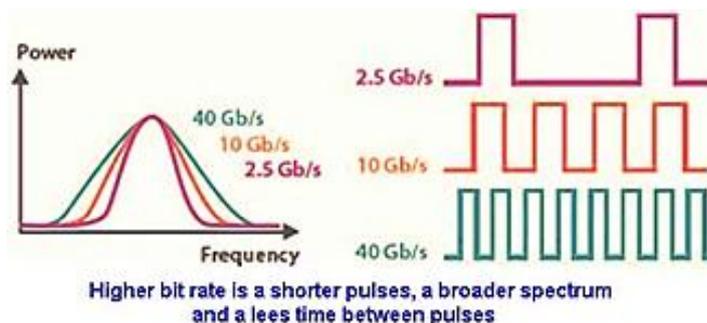
$$\Delta t = D(\lambda) \Delta \lambda L, \quad [\text{ps}; \text{ps}/(\text{nm} \times \text{km}; \text{nm}; \text{km})] \quad (4)$$

where:

$\Delta \lambda$... a spectral half width of the transmitted pulse source (LED diode $\Delta \lambda = 1$ nm),

L ... the fibre length

At the higher transmission speeds it is necessary to use narrower light pulses with shorter spaces (see the Fig. 3). The chromatic dispersion in this case is a very strongly limiting factor of the transmission. The chromatic dispersion influences the use of appropriate sources of optical signal.



Source: (3)

Fig. 3 - Effect of increasing the transmission speed on pulse width and the width of the bit space

The fibre without influence of chromatic dispersion (safe length) we can determine using the following equation:

$$L = \frac{1000 k}{B D(\lambda) \Delta\lambda}, \quad [\text{km}; \text{Gbit/s}; \text{ps}/(\text{nm} \times \text{km}); \text{nm}] \quad (5)$$

where:

$k \dots$ is a constant of resistance against the spread of impulses ($k = 0,5$ for the expansion of $\frac{1}{2}$ bit interval)

$B \dots$ is the signal transmission speed (Gbit/s)

$D(\lambda) \dots$ is the coefficient of chromatic dispersion

$\Delta\lambda \dots$ is the a spectral half width of the transmitted pulse source ($\Delta\lambda = \text{cca}1 \text{ nm}$ for LED diode)

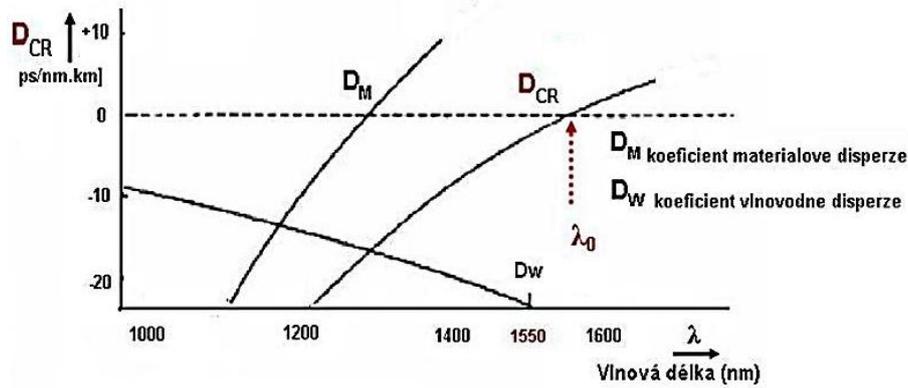
If we use a wavelength 1550 nm and LED as the light source the safe length (L) is only 22 km for transmission rate $B=2.5$ Gbit/s and only 5.5 km for transmission rate $B=10$ Gbit/s. These distances are too short. So we can change a source and instead of the LED we use a DFB laser with an external modulator based on the principle of Mach-Zehnder interferometer. This greatly reduces the spectral half width of the light source. It will be considerably smaller than the spectral width of modulation of the transmitted signal, $B \gg \Delta\lambda$. A length of fibre without the influence of chromatic dispersion can be determined from the equation now:

$$L = \frac{104\ 000 k}{B^2 D(\lambda)}, \quad [\text{km}; \text{Gbit/s}; \text{ps}/(\text{nm} \times \text{km}); \text{nm}] \quad (6)$$

The maximum distance without interference of the chromatic dispersion increases to 924 km (for bit rate $B=2,5$ Gbit/s) and to 58 km (for bit rate $B=10$ Gbit/s). Unfortunately, the safe distance decreases with quadrate of the transmission speed.

1.4 Chromatic Dispersion Compensation

Various methods allow for compensation of the chromatic dispersion. We have already described the possibility of the chromatic dispersion influence reduction using DFB laser diode as a suitable source of the optical signal. The chromatic dispersion comprises the material and the waveguide dispersion. The material dispersion is constant, but waveguide one depends on the fibre geometrical parameters (in the cross section). The manufacturers can modify a refractive index profile so as to set the zero chromatic dispersion coefficient at the desired operating wavelength λ_0 (for instance at 1550 nm - see **Chyba! Nenalezen zdroj odkazů.**).

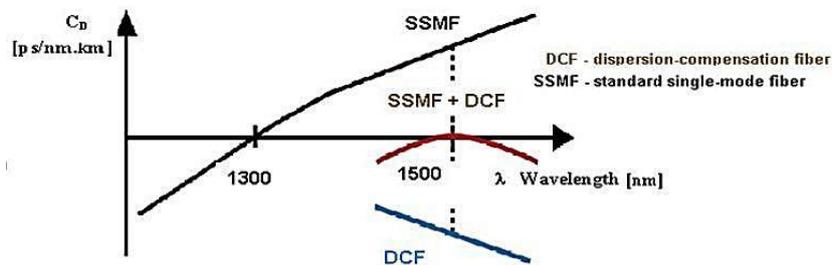


Source: (4)

Fig. 4 - Compensation of chromatic dispersion with DSF (SSMF) (from (4))

Then we talk about fibres with shifted dispersion characteristics DSF (Dispersion Shifted Fibre) or SSMF (Standard Single-Mode Fibre).

Another way to reduce chromatic dispersion is the application of an optical fibre with a high negative chromatic dispersion coefficient DCF (Dispersion Compensation Fibre). The DCF is then a part of a total fibre length usually of about 1/6 of the whole length of the fibre. DCF compensates delays of individual light impulse components at different wavelengths. These fibres have relatively high attenuation (about 0,5dB/km) and are susceptible to effects of nonlinear phenomena (Fig. 5).



Source: (3)

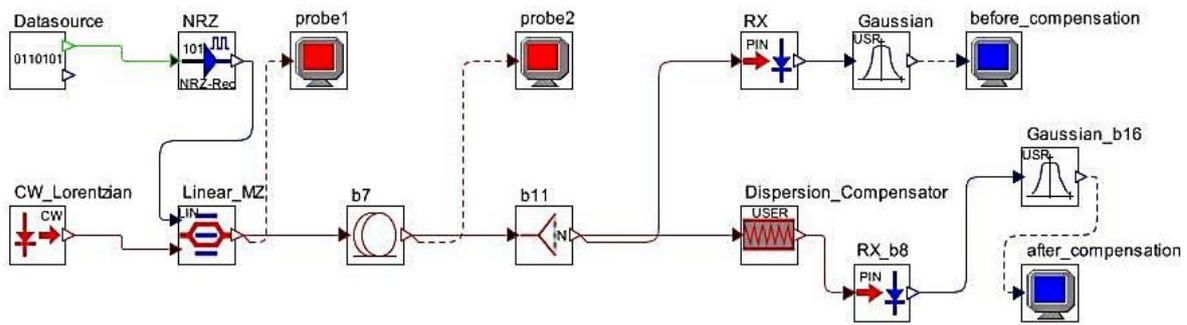
Fig. 5 - Dispersion compensation with DCF

We can reduce the chromatic dispersion by means of Bragg grating, but only for a narrow spectral region (6 nm).

2. SIMULATIONS USING OPTSIM SOFTWARE

2.1 Dispersion compensation using fibre Bragg grating (FBR)

OptSim is a software simulation tool for analysis of various optical communication systems and technologies.



Source: Author

Fig. 6 - FBR dispersion compensation – simulation diagram

where:

- Datasource ... pseudo-random or a deterministic logical signal generator
- NRZ ... non return to zero coding
- CW_Lorentzian ... a simplified continuous wave (CW) laser
- Linear MZ ... Mach-Zehnder amplitude modulator
- b7 ... optical fibre link
- b11 ... ideal optical splitter
- RX ... optical receiver (photodiode)
- Gaussian ... a generic user-defined electrical filter
- Electrical Probe ... an oscilloscope for electrical signals
- Optical Probe ... a probe for optical signals

In the Fig. 6 there is shown a diagram of the fibre Bragg grating (FBG) compensation method. In the simulation NRZ signal with a transmission speed of 10Gbit/s was used. Signal was transmitted through a standard 120 km long single mode fibre.

The results of simulation in the OptSim program - the eye diagram and the histogram without and with compensation - are shown in the next figures. In the Fig. there is an eye diagram with a not very good separation of signal levels. The Fig. shows corresponding histogram with a big number of values between the lowest and the highest levels what is the reason for the unclear eye diagram. The eye diagram is an important tool for qualitative analysis of signals used in digital communication. It provides a view on the assessment of transmission characteristics of the system and the simulator uses it to evaluate the error during the transmission of information. For the eye diagram in this first case the parameter Q is about 9 and the bit error rate (BER) is around $1 \cdot 10^{-3}$.

The Fig. 8 shows eye diagram and Fig. 8 shows the histogram after compensation using FBR.

The inserted FBG compensation significantly reduced the influence of the chromatic dispersion. We may see a sharp eye diagram in the Fig. 8 and the simulation shows that the parameter Q increased to Q=27.

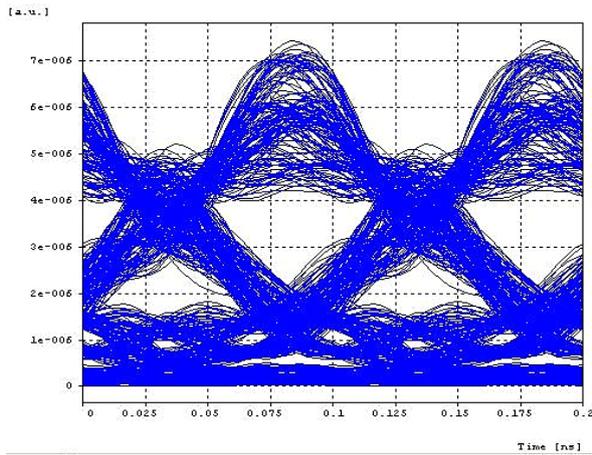


Fig. 7 - Eye diagram before compensation
Source: Author

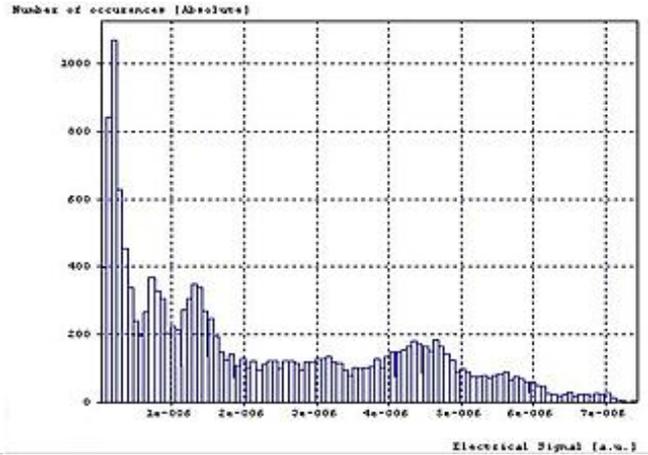


Fig. 8 - Histogram before compensation
Source: Author

BER values for FBG dispersion compensation are so small that the program OptSim failed to show them.

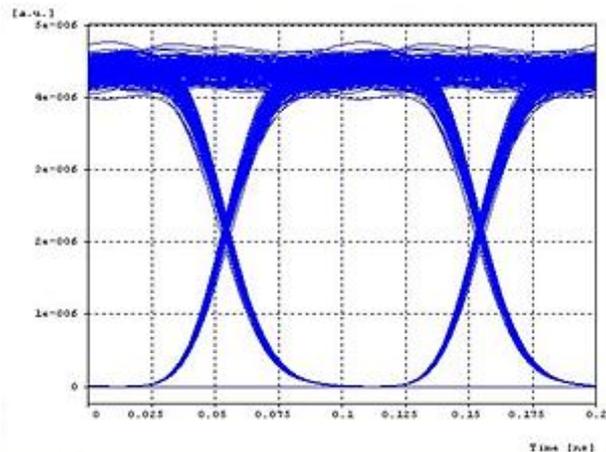


Fig. 8 - The eye diagram after FBG compensation; Source: Author

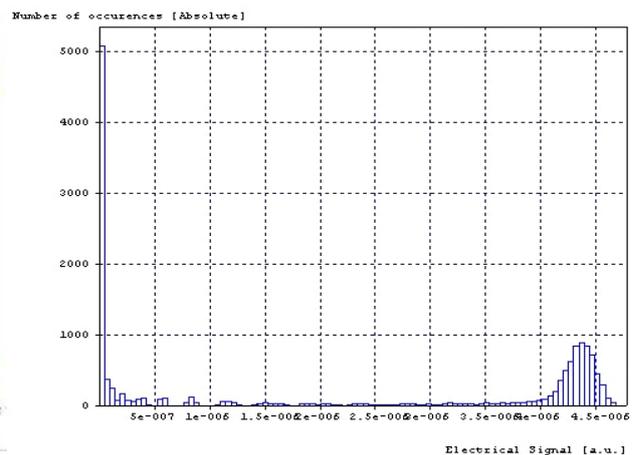


Fig. 8 - The signal histogram after FBG compensation; Source: Author

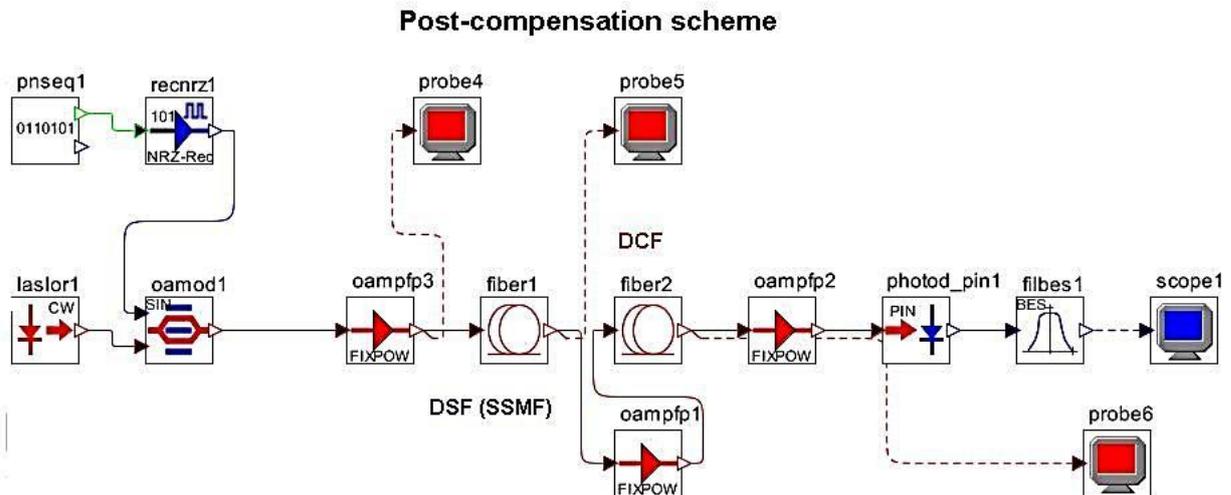
2.2 Dispersion compensation using dispersion compensation fibre (DCF)

Now we will compensate dispersion using an optical fibre DCF (Dispersion Compensation Fibre) with high negative value of chromatic dispersion coefficient. The communication link with a total length of 120 km we prepare consists of 20 km of DCF with negative chromatic dispersion coefficient ($D = -80\text{ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$) and of a 100 km single-mode classical fibre ($D = 18\text{ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$). We distinguish between the pre-compensation and the post-compensation method of chromatic dispersion. Pre-compensation model has the DCF at the link front end and in the post-compensation model the DCF is at the link far end. The simulation diagram of the post-compensation method is shown in the **Chyba! Nenalezen zdroj odkazů.** This example simulates a 10Gbit/s point to point communication link. The

link consists of three optical amplifiers (oampfp 1-3), that compensate the fibres attenuation mainly of the DCF.

The eye diagram and histogram of the electrical signal before compensation is the same as in the first case (see Fig. and Fig.).

Chyba! Nenalezen zdroj odkazů. shows the eye diagram and the **Chyba! Nenalezen zdroj odkazů.** shows the signal histogram after DCF compensation.



Source: Author

Fig. 11 - Post-dispersion compensation method with DCF

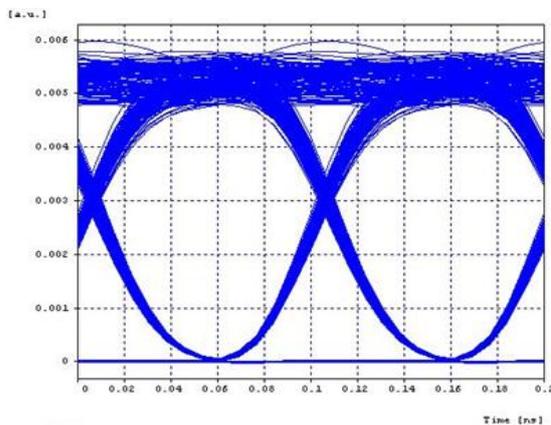


Fig. 10 - Post-compensation DCF eye diagram; Source: Author

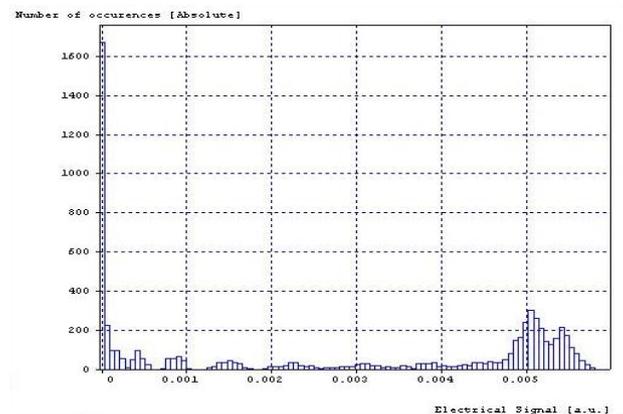


Fig. 10 - The signal histogram after the DCF compensation; Source: Author

The inserted fibre reduces a chromatic dispersion again. However, the curves of the eye diagram are not as sharp as in compensation with FBG and therefore Q parameter has now the value only $Q=22$.

Simulation of chromatic dispersion pre-compensation even got worse results. The Q parameter reached was $Q=18$. BER values for the both methods are again very small and the program did not display them.

Note

On long links over 300 km, we can also meet with a symmetrical full compensation method of chromatic dispersion. The principle of this compensation is an application of DCF fibres at both ends simultaneously. The compensation results are very good in this case and we save one optical amplifier.

3. CONCLUSION

The aim of this study was to describe the methods of the chromatic dispersion reduction in a classic single-mode optical fibre SMF at a transmission speed up to 10 Gbit/s and to illustrate it using simulation on the OptSim software.

There were performed two simulations – dispersion compensation using the FBG and the DCF dispersion compensation. Both simulations showed significant reduction of chromatic dispersion confirming the theoretical assumptions. The comparison of eye diagrams and Q parameters of the two mentioned compensation methods shows that the FBG is the better method for chromatic dispersion compensation than the DCF. Further, on the DCF shows a higher attenuation, which must be compensated by optical amplifiers and so this method is less applicable than the compensation using FBG.

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