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Realization of Combined Chromatic Dispersion Compensation Methods in High Speed WDM Optical Transmission Systems

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Introduction

Chromatic dispersion (CD) has an important role on a quality of transmitted optical signal in high-speed fiber optic transmission systems. As a result chromatic dispersion limits the maximum transmission distance. Dispersion is a second most important optical fiber characteristic after attenuation or transmission loss [1]. As shown in Fig. 1, the three main dispersion types are modal, chromatic, and polarization mode dispersions. Chromatic dispersion can be divided into two components - material and waveguide dispersion [2].

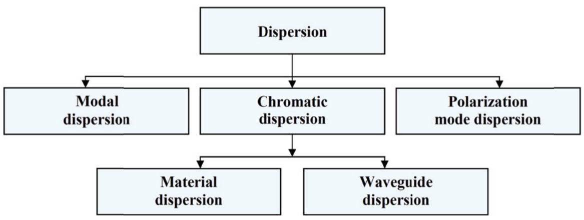

Fig. 1. Types of dispersion [1]

Waveguide dispersion is caused by physical structure of optical fiber core and cladding (refractive index profile), and as a result different wavelengths propagate at different velocities in the core and cladding. Material dispersion is dominant part of CD, and is caused by change of optical fiber refractive index n with wavelength λ [3]. Waveguide dispersion is relatively small compared to material dispersion (Fig. 2).

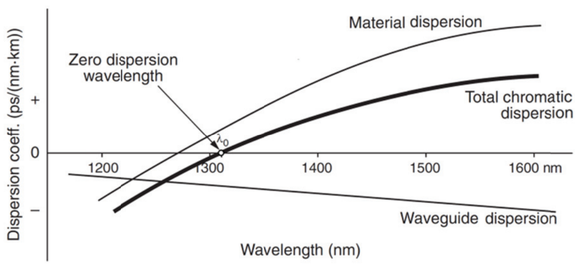

Fig. 2. Total chromatic dispersion of SSMF fiber containing material and waveguide dispersions [3]

Modal dispersion can be observed in multimode optical fibers, where multiple modes of the same signal pulse propagate at different velocities along the optical fiber and cause pulse broadening. Generally modal dispersion does not occur in a singlemode fiber because there is only one fundamental mode propagating [4, 5].

The dispersion of standard singlemode optical fiber (SSMF) for wavelength range from 1200 nm to 1625 nm can be calculated using the following empirical formula [1]

$$D \approx \frac{S_0}{4}\left(\lambda_c - \frac{\lambda_0^4}{\lambda_c^3}\right), \quad (1)$$

where D – dispersion in ps/(km·nm); S_0 – zero dispersion slope in ps/(nm^2·km); λ_c – the laser center wavelength in nm; λ_0 – zero dispersion wavelength in nm (Fig. 2).

Zero dispersion slope S_0 is a dispersion parameter that describes the rate of change of dispersion with wavelength at zero dispersion wavelength λ_0. Real dispersion representing curve is not straight and has a slope (Fig. 2). It means that at two different wavelengths there will be two various dispersion slope values.

Zero dispersion wavelength λ_0 is wavelength where material and waveguide dispersion cancel each other. Typically zero dispersion wavelength of SSMF (ITU G.652) fiber is near the wavelength of 1310 nm.

Dispersion causes optical signal pulses to broaden and lose their shape as they travel along optical fiber. When pulses become wider, they have tendency to interfere with an adjacent pulses. Eventually this limits the maximum achievable data transmission rate and transmission distance [2, 5].

The broadening of signal pulses causes intersymbol interference (ISI). As example, if the light source transmits a "1" (light pulse) into an optical fiber then different parts of this pulse will travel along the fiber at different speeds due to dispersion. It means that some parts of the transmitted "1" may spread into the adjacent bit slots as shown in Fig. 3. Due to influence of ISI there occur problems to restore transmitted information. In this case it is difficult to separate transmitted bit sequence at receiver side and it is resulting bit errors (high BER) or even failure of fiber optical transmission system [5]

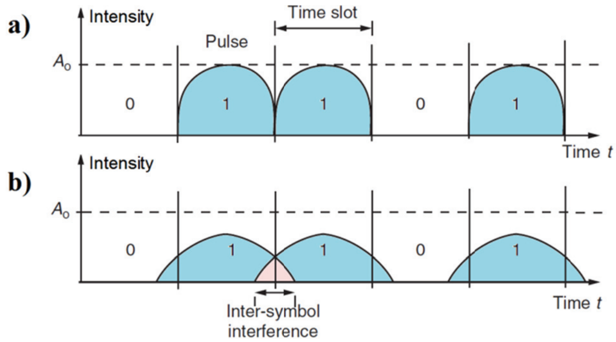

Fig. 3. Intersymbol interference: a – input bit sequence; b – output bit sequence affected by ISI [1]

Chromatic dispersion compensation methods

In fiber optical transmission systems dispersion compensation modules (DCM) (also called dispersion compensation units - DCU) can be used for chromatic dispersion compensation. These modules can provide a fixed or tunable amount of compensating dispersion value. A dispersion compensating module is often placed between two fiber amplifiers in fiber optical transmission link, for example, erbium-doped fiber amplifiers (EDFA) [3, 5].

Dispersion compensating fiber (DCF), fiber Bragg grating (FBG) and optical phase conjugator (OPC) can be used in chromatic dispersion compensation modules. Typically DCM is specified by what length, in km, of standard single mode fiber will be compensated or by the total compensation value of dispersion over a specific wavelength range, specified in ps/nm [3].

Dispersion compensation module containing DCF typically has a high fiber attenuation and accordingly insertion loss resulting from the insertion of a device in fiber optical transmission line will be high. These DCM optical losses can be compensated by optical amplification.

The effective core area (A_{eff}) of a DCF is much smaller than standard ITU-T G.652 single mode fiber thereby dispersion compensating fiber experience much higher optical signal distortions caused by nonlinear optical effects (NOE) [3]. Typical dispersion compensating fiber has small effective core area $A_{eff} = 12\ \mu m^2$ whereas standard single mode optical fiber has $A_{eff} = 80\ \mu m^2$, and DCF has attenuation coefficient up to $\alpha = 0.6$ dB/km whereas standard single mode optical fiber has $\alpha = 0.2$ dB/km. The effective core area A_{eff}, is optical fiber parameter which determines how tightly light is confined to the core. As mentioned above, the nonlinear effects are stronger in fibers with smaller values of A_{eff}. Impact of nonlinear optical effects can be reduced by lowering optical power [2, 5]. DCF has large negative dispersion (D = -80 ps/(nm·km) that helps to compensate chromatic dispersion. Such an optical fiber with negative dispersion is achieved by developing a complex refractive index profile. It must be considered that DCF adds polarization mode dispersion (PMD) to the fiber optical transmission link, whose value typically is 0.1 ps/√km [3]. The reason of PMD is that different frequency components of pulse which has different polarization states propagate with different velocity, resulting pulse broadening. Polarization mode dispersion becomes a limiting factor for high speed optical communication systems [5].

Dispersion compensation modules with chirped fiber Bragg grating (FBG) for compensation of chromatic dispersion is also available. Chirped fiber Bragg grating is suitable for WDM systems. It has grating period which is not constant but changes linearly over the length of the grating with the shorter grating period located at the beginning of the grating [3].

FBG grating period is distance between two adjacent maximum values of the refractive index (Fig. 4).

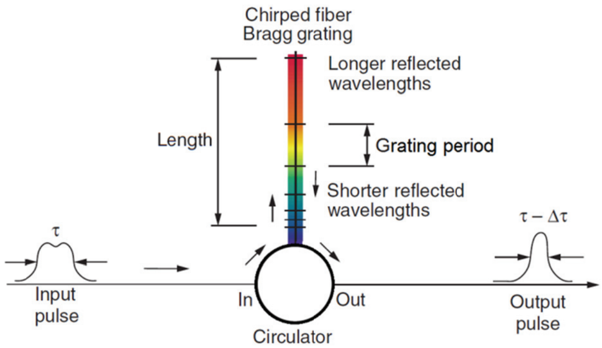

Fig. 4. Chirped fiber Bragg grating [3]

The fiber grating reflects a narrow spectrum of wavelengths that are centered at reflected wavelength (λ_B) and passes all the other wavelengths. Reflected wavelength λ_B can be obtained by following equation

$$\lambda_B = 2\Lambda n_g, \qquad (2)$$

where λ_B – reflected wavelength, nm; Λ – grating period, nm; n_g – fiber's effective group refractive index.

As shown in Fig. 4, dispersion affected input pulse with width τ is passing Chirped fiber Bragg grating and at output its width is decreased by $\Delta\tau$ and shape is restored.

Chirped fiber Bragg grating has shorter grating periods at beginning but over the length of the grating these periods linearly increase. Therefore shorter signal wavelengths are reflected sooner and have less propagation delay through the FBG but longer signal wavelengths travel further into the fiber grating before they are reflected back and accordingly have more propagation delay through the FBG. Chirped fiber Bragg grating impact is exactly opposite of optical fiber chromatic dispersion where longer signal wavelengths are affected most of all. Typically the length of the fiber grating is from 10 to 100 cm. [3].

A significant advantage of using a fiber Bragg grating dispersion compensation modules over DCF fiber is its relatively small insertion loss resulting from the insertion of a device in fiber optical transmission system. For comparison, commercial DCF specified to compensate accumulated chromatic dispersion of 100 to 120 km standard single mode fiber span have about 10 dB of insertion loss, whereas a FBG based dispersion compensation module, capable to compensate the same fiber span length, insertion loss is only up to 4 dB.

In contrast to DCF DCM, FBG based dispersion compensation module can be used at higher optical powers without inducing nonlinear optical effects [5].

Besides DCF DCM and FBG DCM, the accumulated chromatic dispersion also can be compensated by optical phase conjugator (OPC) which realizes inversion of optical signal phase. The idea to use optical phase conjugation for dispersion compensation was proposed in 1979, but only in 1993 this technology was implemented experimentally [5].

Optical phase conjugator, sometimes referred to as spectral inversion, is a promising technology able to compensate accumulated chromatic dispersion and impairments caused by nonlinear optical effects (NOE) such as Kerr nonlinearities (for example, four wave mixing - FWM) and self phase modulation (SPM) in long-haul fiber transmission systems [7].

Since the dispersion accumulates linearly along the fiber-optic transmission link, OPC DCM must be placed exactly in the middle of link to obtain full dispersion compensation. This way the distortion that occurred in the first part of the transmission link before the OPC DCM are canceled by distortion that occur in the second part of the link after the OPC DCM. It should be mentioned that it is not always possible to place OPC DCM exactly in middle of fiber transmission link. Therefore an extra DCF module can be employed to obtain full chromatic dispersion compensation [5, 7].

The optical phase conjugator (OPC) is a nonlinear optical chromatic dispersion compensation method in contrast of dispersion compensating fiber (DCF) and fiber Bragg grating (FBG) [5].

For WDM operation with high conversion efficiency OPC is implemented with different frequency generation (DFG) and a second harmonic generation (SHG) in periodically poled lithium-niobate (PPLN) waveguide - $LiNbO_3$. Basic idea of phase conjugation of data signal is illustrated in Fig. 5 and the principle of the cascaded SHG and DFG processes is illustrated in Fig. 6 [7].

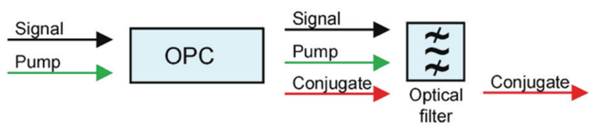

Fig. 5. Realization of phase conjugation of a data signal

Optical data signal at frequency ω_{signal} is combined together with a pump signal at frequency ω_{pump} and then passes in OPC unit. At the output of the OPC there are data signal, pump signal and conjugated signal at frequency $\omega_{conj} = 2\omega_{pump} - \omega_{signal}$. Afterwards the conjugated signal is separated from the pump and original data signals by an optical filter.

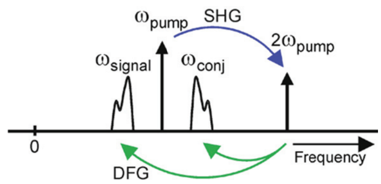

Fig. 6. Principles of SHG and DFG [7]

SHG and DFG effects are used together to realize the optical phase conjugation of data signal. Under influence of second harmonic generation (SHG) the pump signal at frequency ω_{pump} is up-converted to the frequency $2\omega_{pump}$ (Fig. 6). At the same time different frequency generation (DFG) occurs and the second harmonic at frequency $2\omega_{pump}$ interacts with the input signal at frequency ω_{signal} to generate a phase conjugated optical signal at frequency $\omega_{conj} = 2\omega_{pump} - \omega_{signal}$. This way the phase conjugated data signal with inverse optical spectrum relative to input data signal is obtained on the output of OPC DCM unit [7].

Due to wide conversion bandwidth (typically more than 50 nm) one OPC unit with periodically poled lithium-niobate (PPLN) waveguide is capable to conjugate multiple WDM channels. Japanese scientists are experimentally demonstrated a simultaneous phase conjugation of up to 103 DWDM channels with the data rate 10 Gbit/s per channel and NRZ coding. These input data signal channels located in C-band (1531 – 1551 nm) were phase conjugated to the output signal at L-band (1559 – 1579 nm) using only one PPLN waveguide. The pump signal wavelength was 1555 nm, and at the output of PPLN waveguide the phase conjugated DWDM channels were present mirrored relative to the pump signal.

Measurement technique

The accepted research method of combined chromatic dispersion compensation methods in 4 channel WDM system is a mathematical simulation using OptSim software where complex differential equation systems are solved using Split-Step algorithm. Optical fiber is affected by linear and nonlinear effects and the change of electromagnetic field is characterized by Maxwell's equations. In order to study the nonlinear effects in optical fiber, it is used a separate case of Maxwell's equation - the nonlinear Schrödinger equation (NLS) [5].

Except certain cases this equation cannot be solved analytically. Therefore, OptSim simulation software is used for fiber optical transmission system simulations where it solves complex differential equations using Time Domain Split-Step (TDSS) method. This Split-Step method is being used in most commercial optical system simulation tools [6]. The principle of the method is illustrated by fiber propagation equation, which can be written as follows

$$\frac{\partial A(t,z)}{\partial z} = \{L+N\}A(t,z), \quad (3)$$

where $A(t,z)$ – optical field; L – linear operator responsible for dispersion and other linear effects; N – non-linear operator that accounts for the Kerr effect and other nonlinear effects like Stimulated Raman scattering (SRS).

Using the Split-Step method, it is assumed that linear L and nonlinear N effects affect the optical signal independently, if span (step) of simulated optical fiber if enough small (Fig. 7).

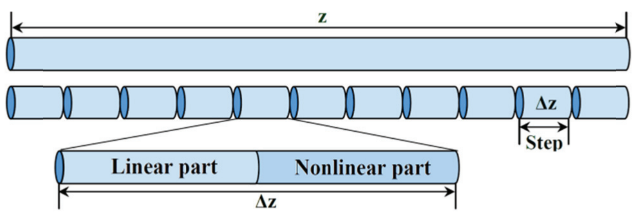

Fig. 7. Split-Step method [6]

Each step (Δz) consists of two half steps. In the first half step only linear effects (linear part) are taken into account, but in the second half step only nonlinear effects (nonlinear part) are taken into account, see Fig.7. All fiber length z is divided into such a steps Δz, and by turns linear and nonlinear effects are considered [6]. For the most accurate results, it is necessary to carefully choose a step Δz (Fig. 7). If this step Δz is chosen too small, it will increase the time necessary to perform calculations, but if the step is too large it will decrease accuracy of the calculations.

Simulation models

For studying a combined chromatic dispersion compensation methods we realized three simulation schemes in OptSim software and each 4 channel WDM simulation scheme`s performance were evaluated by the obtained BER value of each WDM channel in the end of fiber optical link. In the present work, we show eye diagrams only of the second channel of realized WDM systems for the compact representation of the results obtained. Eye diagrams are fast way how we can approximately evaluate a performance of fiber optical transmission system. It should be noticed that ITU recommended BER value for fiber optical transmission systems is less than 10^{-9} [9].

As shown in Fig. 8, each WDM system simulation scheme has 4 optical channels. Channel interval is 100 GHz equal to 0.8 nm. The transmitter section consists of data source, NRZ driver, continuous wavelength (CW) laser and external Mach-Zehnder modulator (MZM).

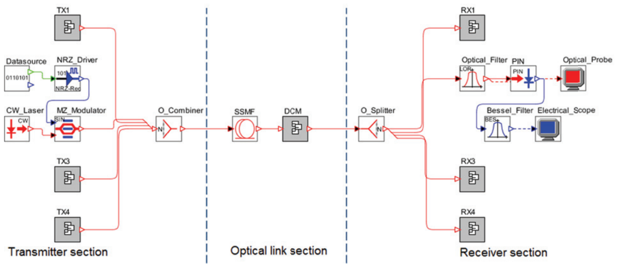

Fig. 8. Simulation model of WDM system with dispersion compensation module (DCM)

Each data source generate data stream with data rate 10 Gbit/s. This stream represents the information needed to transmit over fiber optical transmission link. As modulation method intensity modulation or on/off keying (OOK) is chosen where the strength (intensity) of the carrier optical wave is varied to represent 1 or 0 pulses. In OOK modulation high amplitude represents a 1 and a low amplitude represents a 0 [2]. Generated bit sequence from data source is sent to NRZ driver where it forms NRZ pulses. Afterwards formed electrical NRZ pulses are sent to Mach-Zehnder modulator. Finally, the CW laser light beam is modulated via the Mach-Zehnder modulator and optical pulses are formed [8]. These formed optical pulses are coupled by optical coupler from all WDM channels and sent into standard single mode fiber (SSMF).

Optical link section consists of standard SMF length of 160 km and dispersion compensation module – DCM.

The used standard optical single mode fiber (ITU-T G.652) has a large effective core area A_{eff} = 80 μm^2, attenuation α = 0.2 dB/km, dispersion D = 16 ps/(nm·km) and dispersion slope D_{sl} = 0.07 ps/(nm^2·km) at the reference wavelength λ = 1550 nm. At the end of optical link section, after DCM unit there is a 1x4 optical splitter where optical signal is split into four optical streams and sent to receiver section. In receiver section each channel is analyzed separately due to optical filtering.

Receiver section consists of PIN photodiode (sensitivity = -17 dBm), optical Lorentzian filter (-3dB Two-Sided bandwidth B_{wO} = 12.5 GHz), Bessel electrical filter (4 poles, -3 dB Bandwidth B_{wE} = 7.5 GHz), optical and electrical probes. Optical filters are necessary to separate each WDM channel from common optical signal, after that each channel using PIN photodiode is converted to electrical signal filtered by electrical filter [2].

Results and discussions

In this chapter three different combined chromatic dispersion compensation methods are described that can be implemented in DCM module: FBG-DCF, FBG-OPC and OPC-DCF. The aim of this chapter is to numerically evaluate the performance of these methods for 4 channel WDM system.

If dispersion compensation is not used in developed WDM simulation model, shown in Fig. 8, then system performance is seriously affected by accumulated dispersion, as we can see in Fig. 9, where the “eye” of eye diagram of second channel is almost closed.

Fig. 9 shows that without dispersion compensation the BER value is high (there are many bit errors) and we can assume it is because of inter-symbol interference (ISI), which causes pulse overlapping and receiver has difficulties to separate transmitted bit sequence.

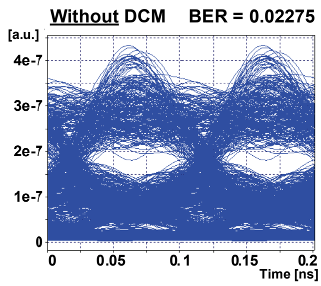

Fig. 9. Output eye diagram for the second channel of 10 Gbit/s 4 channel WDM system without dispersion compensation module

In this case BER > 10^{-9}, system performance is poor and fiber optical WDM transmission system is not able to qualitatively transmit information over distance of 160 km, until CD compensation will not be realized.

The first realized combined compensation method includes the common implementation of fiber Bragg grating (FBG) and dispersion compensating fiber (DCF) in fiber optical link section. This combined CD compensation method will be named as FBG-DCF (Fig. 10). The user defined realistic FBG, used in simulated fiber optical transmission system scheme, can compensate accumulated CD of 100 km long SSMF fiber span. For compensation of

CD accumulated by remaining 60 km of fiber optical line, DCF fiber is used.

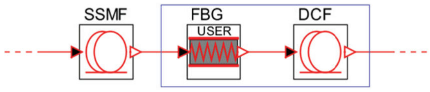

Fig. 10. Combined chromatic dispersion compensation scheme employing combined FBG-DCF method

We found that the optimal required DCF fiber length to reach optimal system performance is 3.5 km.

The employed DCF has a small effective core area A_{eff} = 18 μm^2, large attenuation coefficient α = 0.55 dB/km, large negative dispersion D = -80 ps/(nm·km) and dispersion slope D_{sl} = 0.19 ps/(nm^2·km) at the reference wavelength λ = 1550 nm.

By realizing fiber optical transmission system simulation with FBG-DCF combined dispersion compensating scheme, we found that BER value decreased and system performance improved (Fig. 11, a).

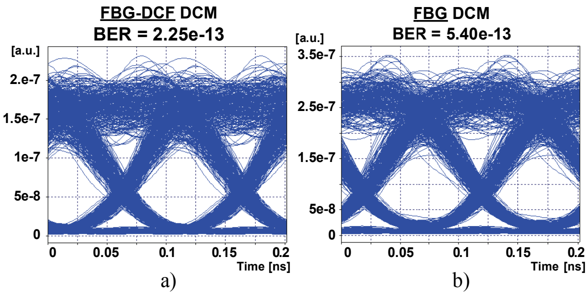

Fig. 11. Output eye diagram of the second channel for dispersion compensation method employing: a – FBG-DCF; b – FBG alone

It can be seen from obtained BER values that in our case, the use of FBG-DCF gives better result than using FBG alone for CD compensation (Fig. 11, b).

Fiber Bragg grating together with optical phase conjugator (FBG-OPC) was used as the second solution for combined chromatic dispersion compensation, see Fig.12.

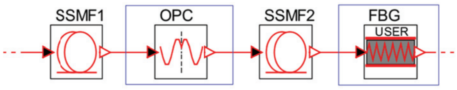

Fig. 12. Combined chromatic dispersion compensation scheme employing combined FBG-OPC method

Optical phase conjugator is characterized by its efficiency η and the phase shift (φ). The OPC used in simulation has signal amplitude efficiency parameter η=1 and constant phase shift φ = π/2 = 1.57079. To obtain full CD compensation OPC must be placed exactly in the middle of fiber-optic transmission link, but it is not always possible. Therefore, we inspected two OPC location variants. In the first case OPC unit was placed exactly in the middle of 160 km long fiber span (L_{SSMF1} = L_{SSMF2} = 80 km), while in the second case OPC was placed asymmetrically after the first 45 km of fiber link (L_{SSMF1} = 45 km and L_{SSMF2} = 115 km). FBG is placed at the end of the optical link section prior to optical splitter.

By realizing simulation of fiber optical transmission system with both OPC-FBG combined dispersion compensation schemes (FBG-OPC (80/80) and FBG-OPC (45/115)), it was obtained that BER value significantly decreased and system performance improved when asymmetric OPC placement was used (Fig. 13, b), but in case when OPC device is used symmetrical in the midline (Fig. 13, a) the performance increase is much smaller.

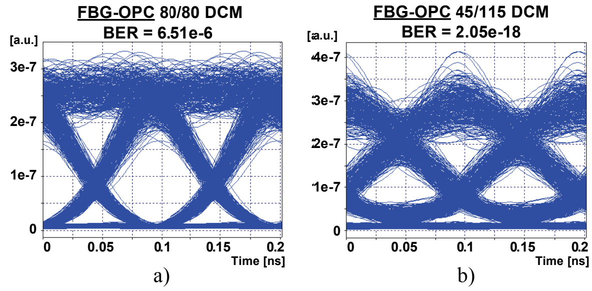

Fig. 13. Output eye diagram of the second channel for dispersion compensation method employing: a – FBG-OPC (80/80); b – FBG-OPC (45/115)

We can conclude that in the case of symmetric OPC placement (Fig. 13, a) together with fiber Bragg grating our system will not work because BER > 10^{-9}.

The third inspected combined dispersion compensation method includes the common implementation of optical phase conjugator and dispersion compensating fiber in fiber optical link section. This combined chromatic dispersion compensation method will be named as OPC-DCF (Fig. 14).

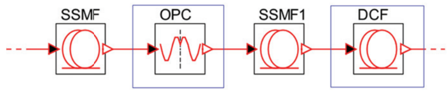

Fig. 14. Combined chromatic dispersion compensation scheme employing combined OPC-DCF method

The OPC were placed exactly in the middle of fiber-optic transmission link and extra DCF fiber span length of 0.5 km for CD compensation was used in this realization.

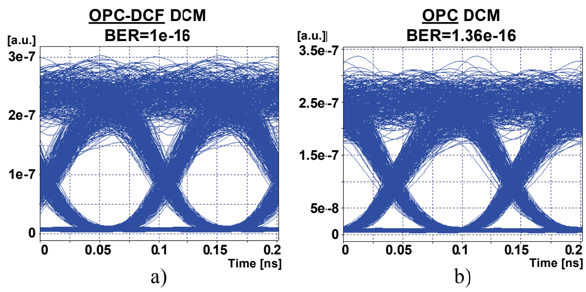

Fig. 15. Output eye diagram of the second channel for dispersion compensation method employing: a – OPC-DCF; b – OPC alone

Usage of extra 0.5 km DCF together with OPC let us to improve performance of the first and the second (Fig. 15, a) WDM system channel, but the performance of the third and the fourth channel became worth. If OPC is used without DCF for chromatic dispersion compensation it was found that performance improved on the third and the fourth channel, but performance of the first and the second channel (Fig. 15, b) became worth.

Conclusions

Chromatic dispersion compensation is an important premise to achieve higher performance of fiber optical system and increase the maximum transmission distance.

In this work using OptSim simulation software we have realized an experimental high-speed WDM fiber optic communication system model with new combined dispersion compensation mechanisms where DCF, FBG and OPC were used together.

The performance of realized fiber optical transmission system without CD compensation was very poor, but it has been shown that using described combined compensation methods (FBG-DCF, FBG-OPC, and OPC-DCF) system performance can be improved greatly.

Combined FBG-DCF dispersion compensation scheme showed small performance increase for all four WDM system channels while OPC-DCF scheme has increase of performance only for the first and the fourth channel. The best results were obtained by using FBG-OPC dispersion compensation scheme which showed the lowest BER value. Basis of the results we recommend avoiding the use of DCF for CD compensation where it is possible and use FBG instead.

Acknowledgement

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Chromatic dispersion (CD) has a significant impact on a quality of transmitted optical signal in high-speed fiber optic communication systems with data rates up to 10 Gbit/s, and as a result CD limits the maximum length of transmission distance. In order to operate fiber optic communication system with a sufficiently low bit error ratio (BER) and minimize the performance degradation caused by pulse distortion and broadening, dispersion compensation is needed. In this work using OptSim simulation software we realize an experimental high-speed WDM fiber optic communication system model with a new combined dispersion compensation mechanism where a conventional dispersion-compensating fiber (DCF), fiber Bragg grating (FBG) or optical phase conjugator (OPC) are used together. The best results were obtained by using FBG-OPC dispersion compensation scheme which showed the lowest BER value. Basis of the results we recommend avoiding the use of DCF for CD compensation where it is possible and use FBG instead. Ill. 15, bibl. 9 (in English; abstracts in English and Lithuanian).

S. Spolitis, V. Bobrovs, G. Ivanovs. Chromatinės dispersijos didelės greitaveikos WDM optinėse perdavimo sistemose tyrimas, taikant kombinuotus kompensavimo metodus // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 7(113). – P. 101–106.

Pažymėtina, kad plačiajuosčių iki 10 Gbit/s optinių perdavimo sistemų kokybę lemia chromatinė signalo dispersija. Esant apibrėžtam klaidų koeficientui, sistemos patikimą darbą užtikrina dispersijos mažinimo metodai. Panaudojus modeliavimo programų paketą „OptSim" įrodyta, kad gerokai sumažėja plačiajuosčių WDM optinių perdavimo sistemų signalų dispersija ir sukuriama naujų dispersijos kombinuotosios kompensacijos metodų. Il. 15, bibl. 9 (anglų kalba; santraukos anglų ir lietuvių k.).