Chromatic Dispersion Monitoring techniques in WDM optical Fiber Links

Karamjit Kaur, Anil Kumar*
Department of ECE, Amity University Haryana
Maneasar, Gurgaon, India

Abstract*—The optical fibers are the backbone of communication industry and are vastly studied in terms of their materials and propagation properties. These are necessary to decide the signal strength that need to be input so as to retrieve it successfully at the destination end. Among the different properties, dispersion plays a vital role as it spreads the optical pulse as the signal propagates along the length of fiber resulting in the signal delay. This is due to influence of refractive index on wavelengths travelling along the signal. The present work summarizes the different types of dispersion in optical fiber with a special focus on Group Velocity Dispersion or Chromatic Dispersion. The different technologies of dispersion monitoring are also summarized.

Keywords*—WDM network, chromatic dispersion, group velocity dispersion, dispersion monitoring.

I. Introduction

An Optical fiber is a glass or plastic fiber that carries light along its length. Optical fibers are widely used in fiber-optic communications, which permits transmission over longer distances and at higher bandwidths (data rates) than other forms of communications. Fibers are used instead of metal wires because signals travel along them with less loss, and they are also immune to electromagnetic interference. Light is kept in the core of the optical fiber by total internal reflection. This causes the fiber to act as a waveguide. Fibers which support many propagation paths or transverse modes are called multi-mode fibers (MMF), while those which can only support a single mode are called single-mode fibers (SMF). Multi-mode fibers generally have a larger core diameter, and are used for short-distance communication links and for applications where high power must be transmitted. Single-mode fibers are used for most communication links longer than 550 meters.

For modern glass optical fiber, the maximum transmission distance is limited not by direct material absorption but by several types of dispersion, or spreading of optical pulses as they travel along the fiber. Dispersion in optical fibers is caused by a variety of factors. Intermodal dispersion, caused by the different axial speeds of different transverse modes, limits the performance of multi-mode fiber. Because single-mode fiber supports only one transverse mode, intermodal dispersion is eliminated. In single-mode fiber performance is primarily limited by chromatic dispersion (also called group velocity dispersion), which occurs because the index of the glass varies slightly depending on the wavelength of the light, and light from real optical transmitters necessarily has nonzero spectral width (due to modulation). Polarization mode dispersion, another source of limitation, occurs because although the single-mode fiber can sustain only one transverse mode, it can carry this mode with two different polarizations, and slight imperfections or distortions in a fiber can alter the propagation velocities for the two polarizations. This phenomenon is called fiber birefringence and can be counteracted by polarization-maintaining optical fiber. Dispersion limits the bandwidth of the fiber because the spreading optical pulse limits the rate that pulses can follow one another on the fiber and still be distinguishable at the receiver. Some dispersion, notably chromatic dispersion, can be removed by a 'dispersion compensator'. This works by using a specially prepared length of fiber that has the opposite dispersion to that induced by the transmission fiber, and this sharpens the pulse so that it can be correctly decoded by the electronics.

Dispersion and losses in fibers:

Dispersion in the fiber means the broadening of the signal pulse width due to dependence of the refractive index of the material of the fiber on the wavelength of the carrier. If we send digitized signal pulses in the form of square pulses, they are converted into broadened Gaussian pulses due to dispersion. The dispersion leads to the degradation of the signal quality at the output end due to overlapping of the pulses.

There are two kinds of dispersion mechanisms in the fiber. Classification of dispersion is shown in Fig. 1:

(i) Intramodal dispersion
(ii) Intermodal dispersion.

The dispersion effects can be explained on the basis of behavior of group velocities of the guided modes in the optical fiber. Group velocity is the velocity at which the energy in a particular mode travels along the fiber.

The propagation constant $\beta = n_1 \frac{2\pi}{\lambda} = \frac{n_1 \omega}{c}$

Group velocity $V_g = \frac{d\omega}{d\beta} = \frac{d\lambda}{d\beta} . \frac{d\omega}{d\lambda}$

From (1)

$$\frac{d\beta}{d\lambda} = \frac{2\pi}{\lambda} . \frac{dn_1}{d\lambda} - n_1 \frac{2\pi}{\lambda^2}$$

Using $\omega = \frac{2\pi}{\lambda}$

$$\frac{d\omega}{d\lambda} = -\frac{2\pi c}{\lambda^2}$$

Therefore,

$$V_g = \frac{-\frac{2\pi c}{\lambda^2}}{\frac{2\pi}{\lambda} . \frac{dn_1}{d\lambda} - n_1 \frac{2\pi}{\lambda^2}} = \frac{c}{N_g},$$

Where, $N_g = n_1 - \lambda \frac{dn_1}{d\lambda}$ is called the group index of fiber. Thus the group velocity and phase velocity (v_p = (C/n_1)) are different in the optical fiber. Otherwise an optical fiber is a dispersive medium.

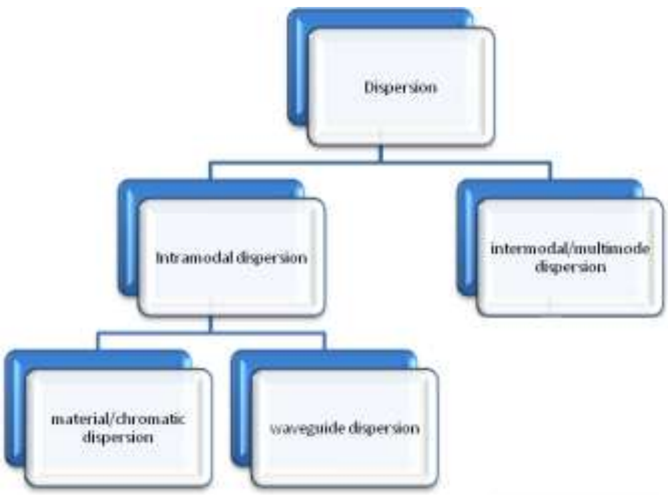

Fig. 1. Classification of dispersion

Intramodal dispersion arises due to the dependence of group velocity on the wavelength. Further it increases with the increase in spectral width of the optical source. This spectral width is the range of wavelengths emitted by the optical source. Thus the intramodal dispersion can be reduced in an optical fiber using single mode laser diode as an optical source. It can be further classified into two types:

1. Material dispersion(due to the dispersive properties of the optical fiber material)
2. Wave guide dispersion (due to and the guidance effects of the optical fiber).

(a) *Material dispersion* (*or*) *chromatic dispersion*: This dispersion arises due to the variation of the refractive index of the core material with the wavelength or frequency of light. It is directly proportional to the frequency bandwidth of the transmitted pulse. A material exhibits material dispersion when $\frac{d^2 n_1}{d\lambda^2} \neq 0$. For pure silica, the material dispersion tends to zero at the wavelength of 1300 nm. Further by using an optical source with a narrow spectral width, the material dispersion can be reduced. For shorter wavelengths around 600 nm to 800 nm, the material dispersion exponentially rises to a higher value.

(b)*Waveguide dispersion*: This dispersion arises due to the finite frequency bandwidth and the dependence of the mode group velocity on the frequency of light. Higher the frequency bandwidth of the transmitted pulse, higher will be the waveguide dispersion. The amount of waveguide dispersion depends on the fiber design like core radius, since the propagation constant 'β' is a function of a/λ. In the case of single mode fibers, waveguide dispersion arises when $\frac{d^2\beta}{d\lambda^2} \neq 0$. In the case of multimode fibers, most of the modes propagate far from the cut off value. Therefore then all are almost free from waveguide dispersion.

Intermodal dispersion (*or*) *multimode dispersion*: Intermodal dispersion or multimode dispersion arises due to the variation of group velocity for each mode at a single frequency. Different modes arrive at the exit end of the fiber at different times. So there is multimode dispersion and hence there is broadening of the signal pulses.

Based on the dispersion effects, one can get the following results:

(i) The multimode step index fibers exhibit a large value of dispersion due to the enormous amount of multimode dispersion which gives the greatest pulse broadening. At the same time the multimode graded index fiber exhibits an overall dispersion which is 100 times lesser than the multimode step index fiber's dispersion. This is due to the shaping of the refractive index profile in a parabolic manner.

(ii) In the case of single mode step index fibers, they have only intramodal dispersion. Further among the intramodal dispersions, the waveguide dispersion is the dominant one. The material dispersion in them is almost negligible due to axial ray propagation and small core radius. When we compare it with the dispersion in the multimode graded index fiber, the dispersion in the single mode fiber is negligible. That is why single mode fibers are highly useful in long distance communication systems.

1.1 Dispersion-shifted single mode fibers

Generally in single mode fibers, zero dispersion is obtained at a wavelength of about 1300 nm. Since there is a finite loss in the silica fiber at 1300 nm, today the fibers are designed such that there is zero dispersion at 1550 nm with a minimum loss. At 1550 nm, the material dispersion in single mode fiber is positive and large, while the waveguide dispersion is negative and small. So to increase the waveguide dispersion equal to that of material dispersion, the relative refractive index difference 'D' may be slightly increased by adding more Ge O2 in the core (which increases the refractive index of the core) or adding more fluorine in the cladding (which decreases the refractive index of the cladding) or instead of parabolic refractive index profile, a triangular refractive index profile can be designed. Thus the dispersion-shifted fibers have minimum loss and zero dispersion at 1550 nm.

1.2 Dispersion compensating fibers (DCF)

At present the installed fiber optic links are operating at the wavelength of 1300 nm using conventional single mode fibers. Instead of 1300 nm wavelength if one wants to use 1550 nm wavelength to reduce the transmission loss, then the whole fiber optic link should be replaced with the new dispersion-shifted fibers. This will require an enormous expenditure. The avoid this huge expenditure and to use the old fiber optic links dispersion compensating fibers were evolved. These fibers have a large negative dispersion at 1550 nm , while the conventional single mode fibers operating at 1300 nm have positive dispersion at 1550 nm . By suitably replacing 1 km length of conventional single mode fiber in the fiber optic link with the dispersion compensating fiber for every 100 km length of conventional single mode fiber optic link, one can achieve minimum loss and zero dispersion also.

1.3 Dispersion Monitoring:

Chromatic dispersion monitoring techniques are based on monitoring the magnitude of amplitude modulation pilot tones, nonlinear effects in highly nonlinear fiber, phase-shift detection, two-photon absorption, and analyzing the tap coefficients in electronic dispersion equalizers. When evaluating a dispersion-monitoring scheme, two design parameters that must be considered are the dispersion-monitoring window and the monitoring sensitivity. The dispersion-monitoring window is important because ambient-temperature changes can occur in a large residual dispersion variation. Also long-haul transmission links have large accumulated dispersion. Monitoring sensitivity is also important because for data rates equal to 40 Gb/s, a small change of 18 ps/nm in chromatic dispersion can cause a 1 dB power penalty.

Among the proposed CD monitoring schemes, sampling amplitude histogram method requires data signal to be sampled with sampling pulse width smaller than bit period and the imperfect sampling pulse will also affect the monitoring results. This can be challenging for high speed systems. The RF pilot tone techniques avoid the need for high speed components and could be used for in line service. However, they require modifications to the transmitter and the added pilot tones may affect the performance of data signal transmission. Coherent detection based schemes such as linear optical sampling requires complicated optical components. RF spectrum analysis for noise monitoring has been reported. However, the use of this method for CD monitoring has not been investigated. Recently, preliminary results for CD monitoring for non-return-to-zero (NRZ)-DPSK signals are represented by using signal power spectrum analysis. This scheme avoids modifications to the transmitter and potential degradations caused by pilot tones by utilizing the data signal itself for the purpose of monitoring. In this paper, the use of the RF spectrum of the received signal in a DPSK system is analyzed for CD monitoring. In particular, the total amount of RF power up to the signal bandwidth increases with CD and hence can be used for CD monitoring. Simulations as well as experiments are carried out to demonstrate the effectiveness of the proposed technique and they are in close agreement with theoretical predictions. CD monitoring technique for DPSK systems by measuring RF power spectra.

In particular, the spectral components up to the signal bandwidth were found to increase with CD in the transmission link, which can be used to monitor dispersion. The spectral power dependence on CD is presented and the derivations are in agreement with simulation as well as experimental results. As the proposed scheme utilizes transmitted data for CD monitoring, transmitter modifications are not required. In addition, high speed electronics are not required. The effects of OSNR, DGD, nonlinearity and chirp on the proposed monitoring technique have also been studied.

In [1] a novel post-detection method based on an optical delay-and-add filter (DAF) is proposed for dispersion monitoring at

40 Gb/s or beyond. The proposed method can be used with or without a pilot tone and works well even when there exists a residual chirp due to the finite direct current (DC) extinction ratio of a Mach–Zehnder (MZ) modulator or self-phase modulation (SPM). Several modulation formats, including conventional non-return to zero (NRZ), return to zero (RZ), carrier-suppressed RZ (CSRZ), RZ differential phase shift keying (RZ-DPSK), and CSRZ-DPSK are used to numerically demonstrate the feasibility of this technique without using a pilot tone. In a linear dispersion-compensation scheme, residual fiber dispersion could be fully compensated via either a pre-detection or a post-detection scheme in combination with a variable dispersion compensator (VDC) at a receiver. In a pre-detection scheme, a dispersion detector first detects the total chromatic dispersion in a transmission system, and followed by a VDC whose dispersion is adjusted to be the same as the measured total system dispersion but with a negative sign. Examples of pre-detection schemes include the use of an amplitude-modulation (AM) pilot tone and clock fading technique. In a post-detection scheme, a zero dispersion detector is used to monitor the residual dispersion. The zero-dispersion detector generates a VDC control signal so that the VDC can completely cancel the residual dispersion. Examples of post-detection schemes include phase modulation (PM) pilot tones offline alternating chirp and clock generation techniques. This paper proposes a novel post-detection technique that exhibits both sufficient monitoring window and high dispersion resolution. The technique uses an optical delay-and-add filter (DAF), in combination with (a) an AM pilot tone or (b) any modulation format that has a symmetric spectrum with respect to its optical carrier [e.g., NRZ, RZ, CSRZ, RZ differential phase shift keying (RZ-DPSK), CSRZ-DPSK, etc.]. A DAF is basically an asymmetric Mach–Zehnder interferometer (AMZI) with a differential optical delay τ between the two arms. The DAF used in this proposal has a nominal delay that is equal to a half period of an AM pilot tone or a half-bit/one-bit period of high-speed modulating data when there is no pilot tone.

[2] demonstrate a chromatic dispersion monitoring technique for systems using dual-drive Mach-Zehnder modulators. A RF monitoring tone, at switched frequencies, is phase modulated onto the optical signal with the existing modulator. Better monitoring sensitivity and range is achieved compared to conventional systems employing an amplitude-modulated tone. We have demonstrated a phase-modulated RF monitoring tone based dispersion monitoring technique for systems using dual-drive Mach-Zehnder modulators. The amplitude modulation of the baseband data signal and the phase modulation of the RF monitoring tones are achieved simultaneously using the single modulator. It experimentally demonstrated a monitoring range of 1300 *ps/nm* with negligible penalty due to the monitoring tone.

In [3] Chromatic dispersion limitations for FSK and DPSK systems using narrow line width lasers and direct detection receivers are found to depend strongly on the receiver configuration. The receiver must include an optical frequency discriminator, such as a Mach-Zehnder interferometer, and either a balanced photo-detector pair or a single photo-detector can be used at the interferometer output. For transmission at 1550 nm over 1310-nm optimized single-mode fiber, the distance for 1 dB eye closure penalty at 10 Gb/s ranges from 20 to 70 km, depending on the modulation format and the receiver configuration.

In [4], all-optical OFDM transmitter and receiver with 5×20Gbit/s are simulated. The 100-Gbits/s signal was successfully transmitted over 40-km-SMF without dispersion companion in the simulation experiment. From this paper we have analyzed the principle of orthogonal carrier generation, and obtained the optimal configuration for two, three and five orthogonal carriers. Through designing proper system parameters, the clearly eye diagrams were obtained. The BER curves of five orthogonal signals were detected. We deduce the principle that the MZM modulator generates optical orthogonal carriers and the optical DFT. Through adjusting the amplitude of the cosine driving voltage and the DC bias voltage,2,3,5 optical orthogonal carriers are generated and throng scanning the phase of the optical gate the optimal phase point is found. Paper simulate a 5×20 Gbit/s all optical OFDM transmission system under the environment of back to back transmission and 40km transmission.

[5] proposed a simple method for measuring the chromatic dispersion and the time delay of optical fiber by using bidirectional modulation of a Mach–Zehnder modulator. To demonstrate the performance of the proposed method, we have measured the chromatic dispersion of optical fiber with length of 2.235 km by using this method over wavelength of 1500–1580 nm. The difference between the measured and the given chromatic dispersion is less than 0.19 ps/nm/km over the measured wavelength range.

In [6] detailed computer simulation of optical FSK and DPSK transmission systems is carried out with the direct detection receivers using Mach-Zehnder interferometer (MZI). The performance degradation of the systems due to the combined effect of the fiber chromatic dispersion and receiver noise is evaluated. The simulation results show that the DPSK system is less sensitive to fiber chromatic dispersion and for a dispersion penalty of 1 dB, the maximum allowable fiber length is around 80 Km for FSK and 250 Km for DPSK using a dispersion index of 0.05.

[7] characterized a dual-gate single-modulator ADORE with RZ-ASK data signals at 42.65 Gb/s, showing a receiver sensitivity variation of ~2 dB with automatic channel selection for an input signal with 40 dB OSNR and zero dispersion. It was shown that the device operates automatically without errors over the full range of relative phases between the input signal and local clock. This ADORE can tolerate input OSNR degradation to 30 dB and 14 ps/nm CD for a 3 dB receiver sensitivity variation between best- and worst-case values of the relative phase. It offers a practical solution for retiming burst or packet-switched optical data signals at gateway interconnections between networks.

[8] propose a chromatic dispersion monitoring technique by analyzing the tap coefficients in electronic dispersion equalizers using tapped delay lines without needing additional hardware. This technique is robust to varying optical signal-to-noise ratio. The successful chromatic dispersion monitoring is demonstrated by simulation and experiment.

[9-10] discuss the impact of dispersion on quality of service in terms of BER and q-factor. The impact of not only second order, but the higher orders are presented. The mathematical model for third, forth, fifth order dispersion is obtained and the impact is visualized through eye diagrams.

In [11] a novel dispersion monitoring method based on four-wave mixing (FWM) or parametric amplification effect in optical fiber is proposed. The signal pulse stream, which is used as a parametric pump, is mixed with a weak continuous wave light at a different wavelength in a fiber. Due to the FWM effect, a so-called idler light is created at a wavelength symmetric in respect to the pump. The output idler power can be measured and is dependent on the pulse width and, therefore, accumulated residual dispersion of the input signal. The concept was successfully demonstrated with 40-Gb/s return-to-zero signal. This approach potentially works for data rates up to terabits per second and can be applied to provide a feedback for automatic dispersion compensation.

In [12] a novel method that uses a post-detection method of dispersion and Q factor measuring to enlarge the monitoring window. The method was able to calculate accumulated dispersion of the order of 2040 ps/nm using a different OSNR higher than or equal to 9 dB. The method shows very good behavior using the RZ and CSRZ formats. We also show results with the NRZ format, although the results are not so good because the NRZ format only has a residual component at the clock frequency and the noise superposes itself to the clock component. The method also shows a high monitoring sensitivity, 0.33 dB/ (ps/nm), using a low launch power. When compared with other ways of increasing the monitoring window, this method has advantages of high monitoring sensitivity and do not have difficulties in controlling the temperature-dependent variations to maintain quadrature and is suitable for long distances.

II. Conclusion

The different techniques for chromatic dispersion monitoring presented in the literature are summarized. Considering the importance of optical communication networks in today's telecomm industry, it has became need of the hour to put an effort to enhance the present monitoring window for efficient monitoring and quality transfer of signal. The monitoring of CD is equally crucial without losing the monitoring sensitivity and range of implementation. To achieve this, a monitoring scheme for RZ and its variant CSRZ system need to be developed for CD monitoring through eye diagrams with high-speed electro-optical sampling. By this, it is possible to have monitoring windows up to 2040 ps/nm at 40 Gb/s, using the RZ and CSRZ modulation formats with high monitoring sensitivity of 0.3363 dB/ (ps/nm).

References

[1] Kuen Ting Tsai and Winston I. Way, "*Chromatic-Dispersion Monitoring using an Optical Delay-and-Add Filter*" Journal of Lightwave Technology, Vol. 23, No. 11, pp. 3737-3740, November 2005.

[2] Andrew Liu, G. J. Pendock, and Rodney S. Tucker, "*Chromatic Dispersion Monitoring for Systems using Dual-Drive Mach-Zehnder Modulators*" 0-7803-9217-5/05/$20.00©2005 IEEE, pp. 892-892, 2005.

[3] A. F. Elrefaie and R. E. Wagner, "*Chromatic Dispersion Limitations for FSK and DPSK Systems with Direct Detection Receivers*" IEEE Photonics Technology Letters, Vol. 3, No. 1, pp. 71-71, January 1991.

[4] Shumin Zou, Nan Chi et. al, "*Performance monitoring on the orthogonality among the multi-subcarriers of an all-optical OFDM system*" Proc. of SPIE-OSA-IEEE Asia Communications and Photonics, SPIE Vol. 7632, 763209, 2009.

[5] Keum-Soo Jeon et.al, "*Optical Fiber Chromatic Dispersion Measurement using Bidirectional Modulation of an Optical Intensity Modulator*" IEEE Photonics Technology Letters, Vol. 14, No. 8, pp. 1145-1147, August 2002.

[6] Satya P. Majumder and Mohammad S. Alam, "*Performance Analysis and Simulation of Optical Direct Detection FSK and DPSK Systems*" IEEE CH35934-9610000-0686, pp. 687-690, 1996.

[7] R. Weerasuriya et. al, "*Performance characterization of 42.65 Gbit/s dual-gate asynchronous digital optical regenerator using single MZM*" Electronics Letters 4th June 2009, Vol. 45, No. 12.

[8] Xingwen Yi et. al, "*Chromatic dispersion monitoring in electronic dispersion equalizers using tapped delay lines*" Optics Express, Vol. 15, No. 2, 312-316, January 2007.

[9] Karamjit Kaur et. al., "*Impact of Higher Order Impairments on QoS Aware Connection Provisioning in 10 Gbps NRZ Optical Networks*" CCIS 712, pp. 283–293, 2017. DOI: 10.1007/978-981-10-5780-9_26.

[10] Karamjit Kaur et. al., "*A Unified Approach for Calculating Error Rates of 10 Gbps WDM Network in Presence of Higher Order Dispersion*" Journal of Optical Communication, Vol. 31, No. 1, pp. 117-122, 2018.

[11] Shenping Li and Dmitri V. Kuksenkov, "*A Novel Dispersion Monitoring Technique Based on Four-Wave Mixing in Optical Fiber*" IEEE Photonics Technology Letters, Vol. 16, NO. 3, pp. 942-945, March 2004.

[12] Ribeiro *et. al.*, "*Chromatic-Dispersion-Monitoring Scheme using a Mach-Zehnder Interferometer and Q-Factor Calculation*" J. Opt. Commun. Netw. , Vol. 2, NO. 1, pp. 10-20, January 2010.