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Mitigation of Chromatic Dispersion using Different Compensation Methods in Optical Fiber Communication: A Review

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ABSTRACT

Fiber-optic communication systems are light wave systems that employ optical fibers for information transmission to increase several orders of magnitude the bit rate distance product. However the performance of optical fiber communication system is limited by fiber dispersion. Dispersion compensation is the most important and challenging aspect of the optical fiber communication to maintain a high optical signal to noise ratio for good quality of the signal. Different techniques available in the literature to compensate dispersion are dispersion compensating fiber, optical filters, fiber Bragg grating, and electronic dispersion compensation. Among all these techniques of dispersion compensation electronic dispersion compensation is preferred because electronic equalizer cost can be almost negligible. The processing of opticalfield in the electronic domain has the potential to efficiently increase the dispersion tolerance. A review of the work done by researchers to compensate the dispersion has been presented in this paper.

Keywords—Dispersion Compensating Fiber (DCF), Directly Modulated Laser (DML), Electronic Dispersion Compensation (EDC), Group Velocity Dispersion (GVD)

I. INTRODUCTION

Optical communication system use high carrier frequencies in the visible or near infrared region of the electromagnetic spectrum. Directly modulated distributed feedback lasers have attracted much attention recently for application in metropolitan areas systems due to their compact size, low cost, low power dissipation and high output optical power in comparison to externally modulated transmitters. However the frequency chirp characteristics of directly modulated lasers (DMLs) significantly limit the maximum achievable transmission distance over standard single mode fibers [1]. Special fibers with negative dispersion can enhance the transmission limit to over 100km [2].

However this solution requires replacing the existing optical network. Another is dispersion supported transmission (DST) which has tunable low pass electrical filter at the receiver to compensate the chirp and enhance transmission limit to over 250km [3]. The same transmission limit can be achieved by directly modulating a chirp managed laser, which uses an optical filter at the transmitter output [4]. A more adaptive solution is to compensate for dispersion in the electronic domain at the transmitter or receiver because a processing of optical field in electronic domain has the potential to efficiently increase the dispersion tolerance. The organization of this paper is laid out as follows: this paper discuss theory of dispersion in section II, methods of dispersion compensation in section III, literature review in section IV, and a short conclusion in section V.

II. THEORY OF FIBER DISPERSION

Dispersion in the transmitted optical signal causes distortion for both digital and analog transmission along optical fibers. Dispersion within the fiber cause broadening of the transmitted light pulses as they travel along the channel. Due to broadening of pulses, these pulses overlap with their neighbouring pulses and become indistinguishable at the receiver input which is shown in Fig.1.

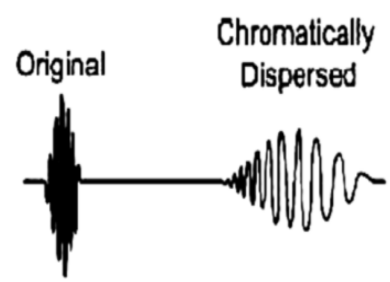

Fig.1 Optical Pulse Broadening caused by chromatic dispersion [5].

Dispersion in multi mode fiber also called intermodal dispersion occurs due to different paths followed by different rays. Single mode fiber has intramodal dispersion which is due to group velocity associated with the fundamental mode is frequency dependent. The group velocity dispersion effects can be minimized using a narrow line width laser and operating close to the zero dispersion wavelength (λ_{ZD}) of the fiber. However, it is not always practical to match the operating wavelength λ with λ_{ZD} .

System performance can be improved considerably by using an external modulator and thus avoiding spectral broadening induced by frequency chirping. Directly modulated distributed feedback lasers are preferred in metropolitan areas systems due to their compact size, low cost, low power dissipation and high output optical power. The advantages of optical systems are realizable in an efficient manner if the dispersion, which is the major enfeeblement in optical fibers, is compensated.

III. METHODS OF DISPERSION COMPENSATION

A. Dispersion compensating fiber

For long haul systems the dispersion compensating fiber (DCF), provides an all optical technique that is capable of compensating the fiber group velocity dispersion (GVD) completely if the average optical power is kept low enough that the nonlinear effects inside the fiber are negligible.

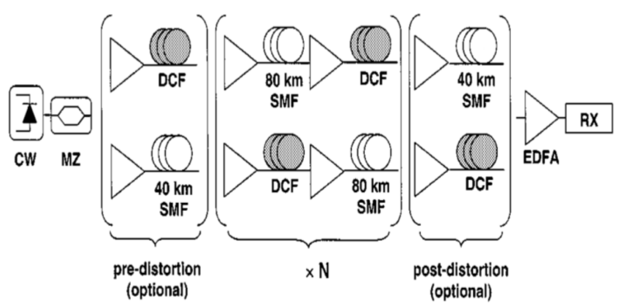

Fig.1 Block diagram of (top) post and (bottom) pre compensation systems using DCF [17]

Fig.1 shows the block diagram of post and pre compensation systems using DCF. For a single channel, the transmission limit of 100km can be achieved using DCF in the system. For the perfect dispersion compensation using dispersion compensating fiber, the DCF must have normal GVD in case standard single mode fibers have anomalous dispersion. The use of DCF is an efficient way to upgrade installed links made of single mode fiber (SMF) [6].

B. Optical filters

The GVD affects the optical signal through the spectral phase $\exp(i\beta_2 z\omega^2/2)$. So, the optical filter whose transfer function cancels this phase can restore the signal. But no optical filter has a transfer function suitable for compensating the GVD exactly. The transmission distance of 250km can be achieved by using optical filter at the output of the transmitter. An optical filter can be combined with optical amplifiers such that both fiber losses and GVD can be compensated simultaneously. The optical filter can also reduce the amplifier noise if its bandwidth is much smaller than the amplifier bandwidth.

C. Fiber Bragg gratings

A fiber Bragg grating acts as an optical filter because of the existence of a stop band, the frequency region in which most of the incident light is reflected back. The stop band is centered at the Bragg wavelength $\lambda_B = 2\hat{n}\Lambda$ where Λ is the grating period and $\hat{n}$ is the average mode index. A fiber grating acts as a reflection filter which is used for dispersion compensation .The device uses a thin metal film as a distributed on-fiber heater to shift the FBG wavelength by changing he applied current through the film [7]-[10]. A compact tunable fiber Bragg grating for post dispersion compensation enables the system to operate over a much wider range of launch power than with simple, fixed compensation using the DCF. Although a tunable fiber Bragg grating cannot completely restore a signal that is distorted by nonlinear effects but it can reduce much of the incurred penalty. The multi channel chirped fiber Bragg grating can be used as dispersion compensator which has a small module size and has fixed insertion loss that is less than 3.5dB. In addition, it can operate over a wide bandwidth and can compensate chromatic and third order dispersion of each individual channel. Multi- channel chirped fiber grating (MC-CFBG) also has greatly reduced nonlinearity when compared to conventional DCF [11]-[13].

D. Electronic dispersion compensation

In the early 1990s, studies were initialized on the application of electronic signal processing for distortion equalization in optical transmission systems [14]. Adaptive electronic dispersion compensation in the receiver can mitigate dispersion without special coding in the transmitter and without foreknowledge of the fiber span length or other characteristics. This makes Electronic dispersion compensation (EDC) especially attractive for networks with dynamic wavelength routing in which the optical path length may change when wavelength are rerouted. The prototype EDC can consists of a multi tap feed forward equalizer which is based on analog signal processing, an error calculator, weight update signal generator and a digital controller. The Feed Forward Equalizer (FFE) section includes parallel implementation of n tap delay lines with tap spacing at the symbol rate. The filter coefficients are computed by a decision directed process based on the widely used least mean square algorithm or any other algorithm.

The chromatic dispersion tolerance at 2dB optical signal to noise ratio (OSNR) penalty has been improved by 40% using FFE as compared the system without equalizer.

The combination of feed forward equalizer and decision feedback equalizer (DFE) can improve the dispersion tolerance of about 60% as compared to receiver without equalizer. In this structure FFE consists of about five fractionally spaced feed forward taps and only one feedback tap. The maximum likelihood sequence estimator (MLSE) is the first digital signal processing (DSP) equalizer using Viterbi algorithm to compensate any kind of optically distorted detected by the photodiode. But the ADC requirements for an MLSE equalizer are less demanding than for other equalizing schemes that use DSP. The MLSE can improve 160% dispersion tolerance as compared to receiver without EDC using non- return to zero format. Full field based MLSE can approximately 50% improve the transmission reach as compared to conventional direct detection MLSE. A novel electronic pre compensation scheme for a directly modulated laser can enhance transmission limit and needs less launch power as compared to inline compensation systems.

IV. LITERATURE REVIEW

The work done by researchers to compensate the dispersion has been summarized as under in literature review.

M.I. Hayee and A. E. Willner [15] analyzed 10 Gb/s non dispersion managed and dispersion managed wavelength division multiplexed system that use pre compensation, post compensation or dual compensation of each channel to minimize dispersion and nonlinear effects. They find that dual compensation gives the minimal penalty for each dispersion managed WDM systems. Furthermore, they find that the optimal amount of pre or post compensation depends upon the specific dispersion map used in the wavelength division multiplexing (WDM) system.

T.N. Nielsen et al. [16] proposed a compact tunable fiber Bragg grating (FBG) that uses distributed thin film heaters on the surface of the fiber to dynamically optimize the post dispersion compensation at 40 Gb/s non return to zero transmission system. They have demonstrated first dispersion compensating FBG at long pseudorandom bit sequence pattern lengths. They find that a device itself requires only a Bragg grating and a tapered thin metal film coating to shift and chirp the FBG wavelength by changing the applied current through the film which optimize time varying dispersion maps and can reduce power penalty associated with nonlinear transmission impairments and other variations.

C. Peucheret et al. [17] performed a systematic numerical optimization of pre and post normalized sections using standard and dispersion compensating fibers for non return to zero 10 Gb/s single channel systems. They discover that by independently varying the power at the different types of fiber inputs and compensation ratio, the post compensation performs better than pre compensation at the expense of more stringent parameter tolerance. They also show that by introducing pre distortion the performance of both pre and post compensation schemes can be significantly improved.

I. Tomkos et al. [18] demonstrated error free transmission distance over 100km of negative dispersion fiber for a 10Gb/s 1.55μm directly modulated signal over a single fiber link without using any dispersion compensation and that was the largest distance ever reported for this kind of laser sources. The achieved dispersion length product for a Q- factor greater than 9.4dB was about 750ps/nm. The fiber that enabled such long transmission distance with high dispersion tolerance was a nonzero dispersion shifted fiber that has negative dispersion in the entire usable bandwidth and was optimized for operation with directly modulated laser. The results presented in this paper were not universal since the actual performance depends on the particular DML device and its driving conditions, but this shows that negative dispersion always increase the transmission distance of 10Gb/s DMLs.

M. D. Feuer et al. [19] demonstrated substantial enhancement of maximum transmission distance using a newly developed electronic dispersion compensator in combination with a directly modulated distributed feedback laser source. They find that for pseudorandom data at the OC-192 rate, the EDC roughly doubles the usable fiber span for a given dispersion penalty. This paper demonstrated when the transmission distance extended to 25km, the eye becomes fully closed and severe error floor was observed even with EDC.

B. Franz et al. [20] proposed a receiver comprising a 5 tap feed forward and a novel 1 tap decision feedback equalizer to mitigate chromatic dispersion and polarization mode dispersion. This paper predicted that the DFE increases considerably the performance of the single FFE, specifically if an OSNR system penalty of 2dB or more was allowed. The combination of FFE and DFE has been successfully tested to enable an enhanced 43 Gb/s data transmission with 50% higher PMD tolerance and 60% higher CD tolerance respectively at 2dB OSNR penalty.

H. Bulow et al. [21] discussed the performance of different electronic equalization and processing schemes for 40 and 10 Gb/s optical transmission over single mode fiber, from the point of their ability to compensate CD and PMD. In addition this paper investigated the impact of fiber non linearity and modulation format on equalization. They demonstrated a DSP based processing of the optical field in the electronic domain enables an extension of the CD tolerance by more than one to two orders of magnitude. Although all these techniques have the potential to realize DCF free transmission, they require one to operate with reduced launch power in the fiber as compared to dispersion managed optical line systems to minimize impairments from fiber non linearity.

J. Zhao et al. [22] investigated full field detection based likelihood sequence estimation for chromatic dispersion compensation in 10 Gb/s on–off keyed optical communication systems. This paper confirmed that approximately 50% improvement in transmission reach can be achieved compared to conventional direct detection MLSE without significantly increasing the electronic compensation complexity. They demonstrated that full field MLSE was more robust to the noise and the associated noise amplifications in full field reconstruction and consequently exhibits better tolerance to non optimized system parameters than full field feed forward equalizer.

R. Pawase et al. [23] investigated the performance of negative dispersion fiber used as a dispersion compensating module. In this paper the DCF was tested on a single span, single channel system operating at a speed of 10Gb/s with the transmitting wavelength of 1550nm over 120km of conventional single mode fiber. Furthermore, the performance of the system at 240km, 480km, 720km, 960km, 1200km were also used to examine the results for the over and under compensation links respectively. This paper concluded that for a single channel, single span optical communication system, the dispersion distance limit increased by introducing dispersion management into the network.

A. S. Karar et al. [24] proposed electronic pre compensation for a 10.7 Gb/s system employing a directly modulated laser. The nonlinear distortion resulting from the direct modulation of the laser can be mitigated by pre compensation based on the reversal of the large signal rate equations and use of DSP to generate an approximate modulating current. This paper extended this concept in a novel look up table optimization scheme for EDC. This paper shows that a 42.8GSa/s digital to analog converter was sufficient for exploiting the full potential for electronic pre compensation using a DML.

K. Khairi et al. [25] investigated experimentally the performance difference between using multichannel chirped fiber Bragg grating as dispersion compensator in pre compensation and post compensation configuration for long span optical transmission system. They demonstrated that even though both methods compensate for chromatic dispersion, the effects of SPM on the signal were most effectively avoided in the pre compensation case.

A. S. Karar and J. C. Cartledge [26] presented a novel electronic dispersion post compensation algorithm and experimentally demonstrated the short reach optical links employing a directly modulated laser as a transmitter with subcarrier modulation and digital signal processing enabled direct detection receiver. The proposed algorithm utilizes the functional relationship between the DML output optical power and chirp in deducing the received optical phase, which was normally lost under direct detection. This paper performed frequency domain equalization to mitigate the link dispersion. A 3dB and 5dB improvement in received optical power was achieved as compared to uncompensated system for 56 Gb/s and 112 Gb/s signals at bit error rate (BER) of $1.0x10^{-3}$ respectively.

V. CONCLUSION

This paper presented a review of different techniques available in the literature to compensate dispersion such as dispersion compensating fiber, optical filters, fiber Bragg grating, and electronic dispersion compensation. Among all these techniques dispersion compensating methods electronic dispersion compensation is preferred because electronic equalizer cost can be almost negligible, the processing of optical field in the electronic domain has the potential to efficiently increase the dispersion tolerance, mitigation of non linear distortion with electronic processing allows non linear processing functions which are not possible for linear optical processing by DCF.

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