Dispersion Compensation In Optical Communication - A Review.

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ABSTRACT

Dispersion is defined as - the phenomenon in an optical fiber whereby light photons arrive at a distant point in the different phase then they entered the fiber. Dispersion causes signal distortion that ultimately limits the bandwidth and usable length of the fiber cable. Therefore dispersion compensation (management) becomes an essential part to study in optical communication for better transmission. In this paper we have reviewed the various techniques (schemes) that are used for dispersion compensation.

General Terms

Dispersion Compensation Schemes (techniques), Dispersion, Dispersion Compensation.

Indexing terms

Dispersion Compensation Schemes, Dispersion, High Speed Optical Communication System.

INTRODUCTION

Dispersion is defined as - the phenomenon in an optical fiber whereby light photons arrive at a distant point in the different phase then they entered the fiber. Dispersion causes signal distortion that ultimately limits the bandwidth and usable length of the fiber cable. Dispersion compensation is used to avoid the chromatic dispersion of optical element. This goal can be achieved by avoiding excessive temporal broadening of the pulse or the distortion of signals. Dispersion compensation is an important issue for fiber –optic links. Strong dispersive broadening of modulated signal can occur in cases with higher data rates. Without dispersion compensation, each signal would be broadened so much that it would strongly overlap with a number of neighboured symbols. Even for moderate broadening, significant inter-symbol interference can strongly distort the detected signal. Therefore, it is essential to compensate the dispersion before detecting the signal.

DISPERSION COMPENSATION SCHEMES

1) Precompensation Scheme:- To avoid the effect of dispersion this scheme modifies the characteristics of input pulses at the transmitter before they are sent into the fiber link. Precompensation techniques are:-

a) Prechirp Technique.
b) Novel Coding Technique.

a) Prechirp Technique:- It modifies the characteristics of input pulse before sending into the fiber link. If input pulse is Gaussian then by prechirping (chainging amplitude) the amplitude of this pulse is given by [1]-

$$A(0,t) = A_0 \exp\left[\frac{1+iC}{2}\left(\frac{t}{T_0}\right)^2\right]$$

where C is the chirp parameter.

A suitably chirped pulse (β_2 C<0) can propagate over longer distances before it broadens outside its allocated bit slot.

Assuming pulse broadening factor is tolerable by $\sqrt{2}$ then the transmission distance is given by:-

$$L = \frac{C \pm \sqrt{1+2C^2}}{1+C^2}L_D$$

where $L_D = \dfrac{T_0^2}{|\beta_2|}$ is the dispersion length.

If C=1 then L increases by 36%. And if C=$1/\sqrt{2}$ then maximum improvement by a factor of $\sqrt{2}$ accurs.

Prechirp technique was used in 1980s with directly modulated semiconductors lasers [2]-[5]. These lasers have chirp parameter which is negative. Also chirp parameter is negative for standard fibers. Therefore condition for chirping is not satisfied (which is β_2 C<0) [1]. The chirp induced during the direct modulation increases GVD induced pulse broadening and due to this transmission distances decreases. To increase the transmission distance without effecting the current pulse shape several technique were used in 1980s [3]-[5].

By using external modulator at the transmitter side for prechirping , then optical pulse are nearly chirp-free and prechirp technique in this case uses positive value of chirp parameter C. So that condition for chirping is satisfied (β_2 C<0). Many techniques used for this purpose [6]-[12].

*b) Novel Coding Technique (FSK):-*In novel coding technique, frequency shifted keying (FSK) format is used for transmission of signal. In it the FSK signal is generated by switching the wavelength of laser between 1 and 0 bits by a constant amount $\Delta\lambda$ .The 1 and 0 are transmitted with different carrier wavelengths. Two wavelengths travel at different speeds inside the fiber. The wavelength shift $\Delta\lambda$ determines the time delay between 1 and 0. The time delay is given by-

$$\Delta T = \text{DL} \, \Delta\lambda$$

$\Delta\lambda$ is chosen such that ΔT =1/B.

This scheme is known as dispersion-supported transmission. Because of fiber dispersion FSK signal is converted into the amplitude modulated signal .At the receiver side this signal is decoded using an electrical integrator with decision device [13].

If the system is properly designed then FSK technique is used for longer distance transmission with better performance [14].

The transmission distance can also be increased by using **Duobinary Coding**. Dispersive effects are reduced for smaller bandwidth signal. And Duobinary Coding reduces the signal bandwidth by 50% [15]. Therefore it increases the transmission distance.

Two successive bits in the digital bit stream summed to form a three level duobinary code at half bit rate.
1+1=2; 0+0=0; 0+1=1; 1+0=1

At the reciever side phase information is used to distinguish the two. By using duobinary coding in optical communication system instead of using binary coding then 10Gbps signal was transmitted over 30km to 40 km [16]. Also by duobinary coding with an external modulator (frequency chirp with C>0) then 10Gbps signal was transmitted over 160km of a standard fiber [16].

c) Nonlinear Prechirp Techniques:- In this technique transmitter output is amplified by using a semiconductor optical amplifier (SOA). SOA operates in gain saturation region. Due to gain saturation region time dependent variation takes place in carrier density, which chirps the amplified pulse. SOA not amplifies the input pulse but also chirp (chirp parameter C>0) it. Due to this chirp, the input pulse is compressed in the fiber with β_2 <0. An input pulse of 40-ps is compressed to 23-ps and it can propagate over 18 km of standard fiber [17]. This technique is used for transmitting a 16-Gb/s signal, obtained from a mode-locked external cavity semiconductor laser, over 70km of fiber [18]. This technique is used for simultaneous compensation of fiber loses and GVD if SOAs are used as in-line amplifiers [19]. A nonlinear medium is also used to prechirp the pulse by self phase modulation of pulse.

SPM Induced Prechirping – It uses self phase modulation for chirping the pulse. In it transmitter output is passed through a fiber of suitable length before passing into the fiber link. The input signal at the fiber input is given by [1]-

$$A(0,t) = \sqrt{P(t)} \exp[i\gamma L_m P(t)] \longrightarrow (1)$$

where P(t) is the power of pulse, L_m is the length of nonlinear medium, γ is the nonlinear parameter.

In case of Gaussian pulse
$$P(t) = P_0 \exp\left(\frac{-t^2}{T_0^2}\right).$$

Then equation (1) can be written as:-

$$P(t) = \sqrt{P_0} \exp\left[-\frac{1+iC}{2}\left(\frac{t^2}{T_0^2}\right)\right]\exp(-i\gamma L_m P_0)$$

where C= $2\gamma L_m P_0$ is the chirp parameter, C is positive and suitable for dispersion compensation.

Transmission fiber itself is used for chirping the pulse because γ >0 for silica fiber. This technique was used in 1986 [20].

2) Postcompensation Technique:- This technique is used to manage the GVD at the receiver side .It uses an electronic technique at the receiver side. It is an easy technique for dispersion compensation with the use of heterodyne receiver for signal detection. Heterodyne receiver first converts data (optical signal) into microwave signal, it preserves both amplitude and phase information. A microwave filter cancels the effects of GVD. This technique has a

great importance for dispersion compensation in coherent light wave system [21]. A 31.5cm long microstrip line is used for dispersion equalization [22]. By using this 8-Gbps signal was transmitted over 188 km of standard fiber having dispersion of 18.5ps/km-nm. To avoid the GVD of light wave system using fiber length of 4900km having bit rate 2.5Gbps microstrip lines were used [23]. If the phase information of the optical signal is lost then it is difficult to avoid the effect of GVD in this technique.

An **optoelectronic equalization** technique is also used to compensate the GVD which is based on transversal filter [24]. In this technique power splitter used at the receiver splits the received signal into several branches. Fiber optic delay line introduces delays in different branches. A variable- sensitivity photodetector converts the optical signal of each branch into photocurrent and the summed photocurrent is used by the decision circuit. The transmission distance of light wave system operating at 5Gbps is extended by a factor 3 by using this technique.

3) Dispersion Compensating Fibers:-The precompensation and postcompensation scheme extends the transmission distance of dispersion limited system by a factor of 2 and these schemes are not suitable to avoid the GVD dispersion of long hall system [1]. To avoid these limitations a special kind of fiber is used, known as Dispersion Compensating Fiber (DCF). The dispersion compensating fiber uses an all-optical technique , fiber based solution to compensate the fiber GVD completely if the average optical power kept low enough that the non- linear effect insibe the optical fibers are negligible.

Process of dispersion compensation by DCF- Let us take an example in which each optical pulse propagates through two fiber segment, the second segment is DCF.
Optical power after the each fiber section is given by-

$$A(L,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} A(0,\omega) \exp\left[\frac{i}{2}\omega^2(\beta_{21}L_1 + \beta_{22}L_2) - i\omega t\right] d\omega$$

where L= $L_1 + L_2$, β_{2j} is the GVD for the fiber segment of length L_j (j=1,2).

The pulse recover its original shape at the end of DCF if ω^2 phase term vanishes for DCF. Therefore condition for dispersion compensation is

$$\beta_{21}L_1 + \beta_{22}L_2 = 0$$

$$\text{Or } D_1L_1 + D_2L_2 = 0 \longrightarrow (2)$$

The equation (2) shows that the DCF must have normal GVD at 1.55 μ m for D_2 <0. Because D_1 >0 for standard communication fiber.
The length of DCF should satisfy the relation

$$L_2 = -\left(\frac{D_1}{D_2}\right)L_1$$

L_2 should be as small as possible. This is possible only when DCF has a large negative value of D_2 .

DCF module (6-8 km) with optical amplifiers spaced apart by 60-80 km is used to upgrade the old light wave system of standard fiber [1] .The DCF compensates GVD and amplifier removes the fiber loses. But this scheme has two problems. 1) insertion losses of a DCF module typically exceed 5 dB. 2) DCFs have small mode diameter therefore effective mode area is only 20 μm^2 . DCF has large optical intensity at the given input power due to this nonlinear effects increase [25].

The problems of DCF is solved by using two mode fiber (V $\approx$ 2.5) such that higher-order is near cutoff. The loss of these fiber is same as of single-mode fiber but dispersion parameter D for higher order mode has large negative value [26]-[29]. Two –mode DCF requires a mode-conversion device. Mode-conversion device converts the energy from fundamental mode to higher-order mode. All -fiber devices are used used for mode -conversion. Mode conversion devices use a two-mode fiber with a fiber grating. Fiber grating provides the coupling betweem two modes. Grating period $\Lambda \Box 100\mu m$ is chosen two match the index difference $\overline{\delta n}$ between two modes

($\Lambda = \lambda / \overline{\delta n}$). Figure below shows the two-mode DCF with two long period gratings.
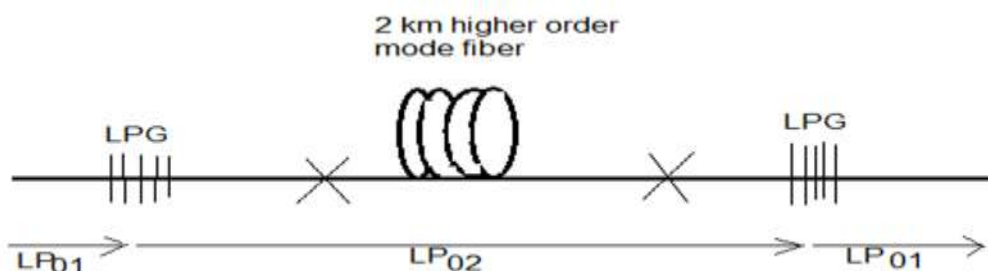
Figure: Two-mode DCF design with two long period gratings.

First grating transfers power to higher mode and second mode transfers power back into fundamental mode. Measured dispersion characteristics of such a 2-km-long DCF shows that parameter D has a value of -420ps/(km-nm) near 1550 nm. This feature allow it to use for broadband dispersion compensation [29].

4) Optical Filters:- The limitations of DCFs is that in order to compensate the GVD over 50km of standard fiber it needs long length DCF (>5km). Due to this, link loss increases in long-haul applications. These limitations are removed by using optical filters.

The pulse propagation in linear case is given by-

$$\frac{\partial A}{\partial Z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} = 0 , \longrightarrow (3)$$

where A is the pulse-envelope amplitude.

Using fourier transform method the solution of the equation (3) is given by-

$$A(Z,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(0,\omega)\exp\left(\frac{i}{2}\beta_2 Z\omega^2 + \frac{i}{6}\beta_3 Z\omega^3 - i\omega t\right)d\omega$$

where $\tilde{A}(0,\omega)$ is the fourier transform of $A(0,t)$.

GVD affects the optical signal through the spectral phase of $\exp(i\beta_2\omega^2 z/2)$.

If an optical filter has property that its transfer function cancels this phase then it will restore the signal. No optical filter has the property to compensate the GVD exactly (expect for an optical fiber).

Optical signal after the filter if this filter is placed after a fiber length L is given by-

$$A(L,t)= \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(0,\omega)H(\omega)\exp\left(\frac{i\beta_2\omega^2 L}{2} + \frac{i\beta_3\omega^3 L}{6} - i\omega t\right)d\omega$$

Expanding the phase of $H(\omega)$ in a Talyor series-

$$H(\omega) = |H(\omega)|\exp[i\phi(\omega)] \approx |H(\omega)|\exp\left(i\phi_0 + i\phi_1\omega + \frac{i\phi_2\omega^2}{2} + \frac{i\phi_3\omega^3}{6}\right)$$

The constant phase ϕ_0 and time delay ϕ_1 are ignored because they do not effect the pulse shape. The dispersion compensation takes place when $\phi_2 = -\beta_2 L$ and $\phi_3 = -\beta_3 L$.

If $|H(\omega)| = 1$ and higher-order terms in the expansion are negligible then signal is restored perfectly.

Dispersion management is shown in figure a) by optical filters. Filters compensate for GVD and also reduce amplified noise.
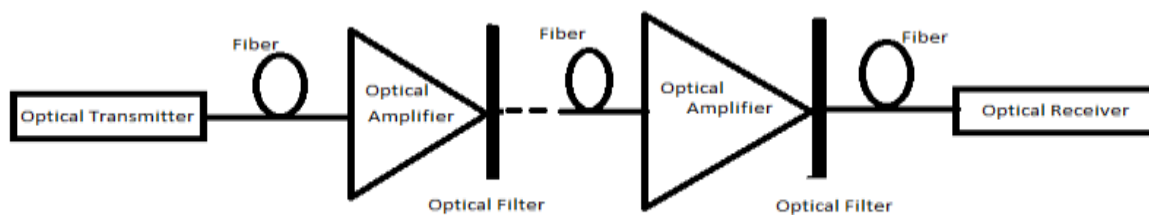

Figure a) : Dispersion management in a long-haul fiber link using optical filters after each amplifier [1].

5) Fiber Bragg Gratings:- Fiber Bragg Grating acts as an optical filter because of a stop band in it. Stop band is the frequency region in which most of the incident light reflected back [30]. Stop band is centered at the Bragg wavelength $\lambda_B = 2\bar{n}\text{A}$, where $\bar{n}$ is the average mode index and A is the grating period. For $1.55\mu m$ Grating period is $\text{A} \approx 0.5\mu m$. A holographic technique is used for making Bragg gratings. Use of grating for dispersion compensation was proposed in 1980s [31]. But their use became practical after1990.

a) Uniform period Gratings:- It is the type of grating in which refractive index varies along the length periodically as

$$n(Z) = \bar{n} + n_g\cos(2\pi z/A)$$

where n_g is the index modulation depth 10^{-4}.

Coupled-mode equations are used to analyze the Bragg Grating and written as [52]

$$\frac{dA_f}{dz} = +i\delta A_f + i\kappa A_b$$

$$\frac{dA_b}{dz} = -i\delta A_b - i\kappa A_f$$

where A_f and A_b are the spectral amplitude of two waves and

Detuning from the Bragg wavelength is $\delta = \frac{2\pi}{\lambda_0} - \frac{2\pi}{\lambda_B}$, Coupling coefficient $\kappa = \frac{\pi n_g \Gamma}{\lambda_B}$, and Γ is the confinement

factor.

Transfer function of the grating is [53] given as

$$H(\omega) = r(\omega) = \frac{A_b(0)}{A_f(0)} = \frac{i\kappa \sin(qL_g)}{q\cos(qL_g) - i\delta \sin(qL_g)}$$

where $q^2 = \delta^2 - \kappa^2$ is the dispersion relation, L_g is the grating length.

Grating –induced Dispersion:- Dispersion of the grating is related to the frequency dependence of the phase of $H(\omega)$. Grating induced dispersion exists mostly outside the stop band. In this region ($|\delta| > \kappa$) and the dispersion parameters are-

$$\beta_2^g = -\frac{\mathrm{sgn}(\delta)\kappa^2 / v_g^2}{(\delta^2 - \kappa^2)^{3/2}}, \beta_3^g = \frac{3|\delta|\kappa^2 / v_g^3}{(\delta^2 - \kappa^2)^{5/2}}$$

where v_g is the group velocity of the pulse with carrier

frequency $\omega_0 = 2\pi c / \lambda_0$.

Grating dispersion become normal ($\beta_2^g > 0$) on "red" side of the stop band (used for dispersion compensation). A single 2-cm long grating is used to compensate the GVD dispersion of 100-km fiber.

Apodization technique:- This technique is used to improve the grating response in which the index change n_g is

made non uniform across the grating, resulting in a z- dependent κ. An ultraviolet Gaussian beam is used to write the apodization grating holographically [30]. The reflectivity spectrum of an apodized is 7.5-cm long grating.

In some grating κ varies linearly over the length. A 11-cm long grating is used to compensate the GVD acquired by a 10Gbps signal transmitted over 100 km of standard fiber [32].

 b) *Chirped Fiber Gratings:-* These gratings have broad stop band and are used for dispersion compensation [33].

The optical period $\bar{n}\Lambda$ of chirped grating is non -uniform over its length [30]. Bragg wavelength $\lambda_B = 2\bar{n}\Lambda$ also varies

along grating length, therefore different frequency component of an optical pulse are reflected at different points. Operation of chirped fiber grating fiber is shown in figure-
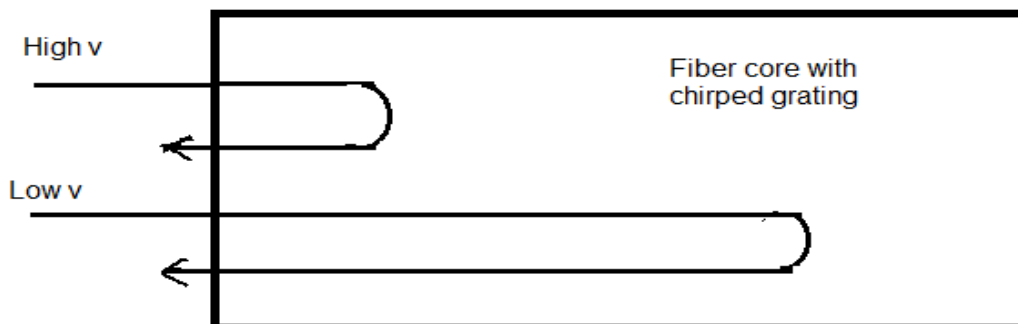
The low-frequency components of a pulse are delayed more because of increasing optical period. It provides anomalous GVD. The same grating provides normal GVD if it is flipped. Thus the optical period $\bar{n}\Lambda$ of the grating should decrease for it to provide normal GVD. Dispersion magnitude is determined by the rate at which $\bar{n}\Lambda$ decreases.

Calculation of dispersion parameter- Dispersion parameter D_g of a chirped grating of length L_g is given by using relation-

$$T_R = D_g L_g \Delta\lambda$$; where T_R is the round –trip time and $\Delta\lambda$ is the difference in the Bragg

wavelengths of the ends of grating.

Also $T_R = \dfrac{2\bar{n}L_g}{c}$ therefore grating dispersion is given by $D_g = \dfrac{2\bar{n}}{(c\Delta\lambda)}$

Limitation of chirped fiber bragg grating- The main limitation of the chirped fiber bragg gratings is that they work as a reflection filter. It uses 3dB fiber coupler to separate the reflected signal from the incident one. The use of 3-dB fiber coupler increases the insertion losses. These insertion losses are reduced by using optical circulator.
Low insertion losses are achieved by combining two or more fiber gratings as a transmission filter [34].

C) Chirped Mode Coupler:- A chirped mode fiber coupler is an all-fiber and it is based on the concept of chirped distributed resonant coupling [35]. Figure below shows the operation of two devices.
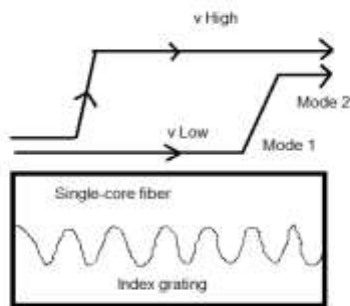

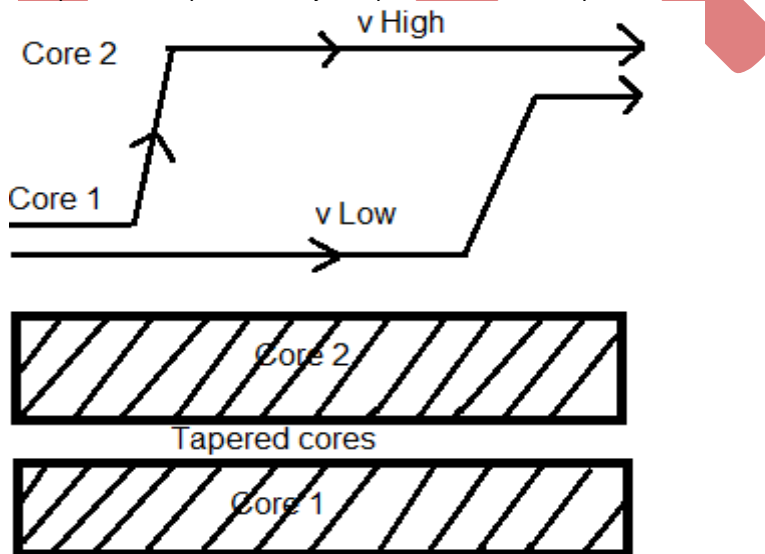**Figure:** Dispersion compensation by Chirped dual-mode coupler.

Figure: Dispersion compensation by tapered dual-core fiber.

The chirp grating couples the two spatial modes of dual fiber core. The grating transfers the signal from the fundamental mode to a higher-order mode, but different frequency components travel different length before being transferred. If grating period increases along the coupler length the coupler can compensate for the fiber GVD. The signal remains propagating in the forward direction but ends up with in a higher-order mode of the coupler. The signal is reconverted back into the fundamental mode by uniform-grating convertor.
If the two cores are close then transfer of energy from one core to another takes place because of evanescent-wave coupling between the modes. When the spacing between the core is linearly tapered (close), such transfer takes place at different points along the fiber, according to frequency of propagating signal. Thus, a dual core fiber with the linearly tapered core spacing can compensate for fiber GVD.

6) Optical Phase Conjuction:-
OPC is a nonlinear technique. It was implemented in 1993.
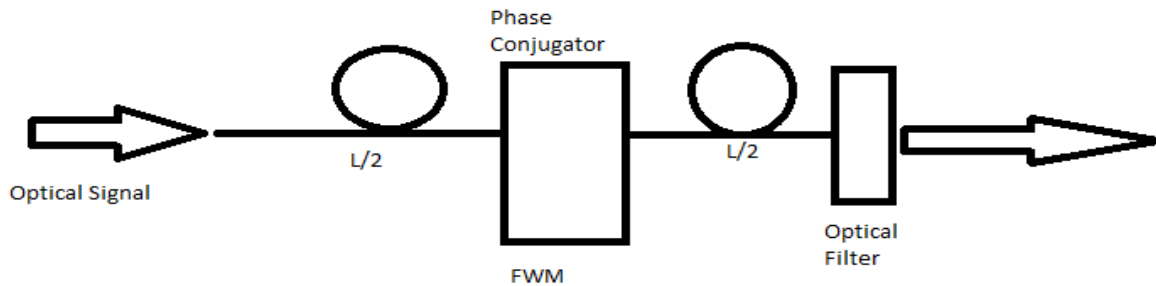
Figure b).

It uses four-wave mixing to generate phase conjugated idle field in the middle of the fiber link. This is shown in above figure b).

The pulse propagation equation is given by-

$$\frac{\partial A}{\partial Z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} = 0 \, ; \longrightarrow (4)$$

where A is the pulse-envelope amplitude.

Take the complex conjugate of above equation (4) we get

$$\frac{\partial A^*}{\partial Z} - \frac{i\beta_2}{2}\frac{\partial^2 A^*}{\partial t^2} - \frac{\beta_3}{6}\frac{\partial^3 A^*}{\partial t^3} = 0$$

Comparison of above two equation shows that β_2 is reversed for the phase-conjugated field. Therefore pulse shape is restored at the fiber end. The β_3 term does not change sign on phase conjugation therefore OPC cannot compensate for the third-order dispersion. OPC compensates the even order dispersion terms and leaves the odd order dispersion term. Pulse spectrum just before the phase conjugator is given by

$$\tilde{A}(L/2,\omega) = \tilde{A}(0,\omega)\exp(i\omega^2\beta_2 L/4)$$

And pulse spectrum after the phase conjugation is

$$\tilde{A}^*(L/2,\omega) = \tilde{A}^*(0,\omega)\exp(i\omega^2\beta_2 L/4)$$

Spectrum inversion takes place because $\omega_C = 2\omega_P - \omega$.

Optical field at the end of the fiber link is given by

$$A^*(L,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{A}^*\left(\frac{L}{2},\omega\right)\exp\left[\frac{i}{4}\omega^2\beta_2 L - i\omega t\right]d\omega \longrightarrow (5)$$

Where $\tilde{A}^*\left(\frac{L}{2},\omega\right)$ is the Fourier transform of $\tilde{A}^*\left(\frac{L}{2},t\right)$ and is given by

$$\tilde{A}^*\left(\frac{L}{2},\omega\right) = \tilde{A}^*(0,-\omega)\exp\left(-\frac{i}{4}\omega^2\beta_2 L\right)d\omega$$

Put this value in equation (5), we get

$$A(L,t) = A^*(0,t).$$

Thus pulse shape is restored to its input form irrespective of how much pulse broadened in the first section. This technique is also known as ***midspan spectral inversion***.

a) Self-Phase Modulation (SPM) Compensation:- The OPC technique is different from all other dispersion compensation techniques. It can compensate both GVD and SPM simultaneously. This feature was noted in 1980s [36].
Pulse propagation in a lossy fiber is given by-

$$\frac{\partial A}{\partial Z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = i\lambda|A|^2 A - \frac{\alpha}{2}A \longrightarrow (6)$$

Where β_3 term is neglected, α is related to the fiber losses. When $\alpha = 0$, A^* satisfies the same equation when we take the complex conjugate of equation (6) and change z to –z. Therefore midspan OPC can compensate for SPM and GVD simultaneously. Fiber losses destroy this important property of midspan OPC. The main reason for this is: SPM –induced phase shift is power dependent. Due to this much larger phase shifts are induced in the first-half of the link than the second half and OPC cannot compensate for the nonlinear effects.

$$\text{Using, } A(z,t) = B(z,t)\exp(-\alpha z/2) \longrightarrow (7)$$

The pulse propagation is given by-

$$\frac{\partial B}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 B}{\partial t^2} = i\gamma(z)|B|^2 B \longrightarrow (8)$$

where $\gamma(z) = B\gamma\exp(-\alpha z)$.

By taking the complex conjugate of equation (4) then perfect SPM compensation accurs only if $\gamma(z) = \gamma(L-z)$. This condition is not satisfied for $\alpha \neq 0$.

Perfect compensation of both GVD and SPM is obtained by using Dispersion-decreasing fibers. In such fibers $|\beta_2|$ decreases along fiber length. Assuming that $|\beta_2|$ in equation (8) is a function of z. With transformation

$$\xi = \int_0^z \gamma(z)dz \longrightarrow (9)$$

where $b(\xi) = \beta_2(z)/\gamma(\xi)$. Both GVD and SPM are compensated if $b(\xi) = b(\xi_L - \xi)$, where ξ_L is the value of ξ at z=L. This condition is satisfied when the dispersion decreases in the same way as $\gamma(z)$ therefore $\beta_2(\xi) = \gamma(\xi)$ and $b(\xi) = 1$.

$\gamma(Z)$ decrease exponentially as exp(- α z) due to fiber losses, both GVD and SPM can be compensated exactly in dispersion-decreasing fiber whose GVD decreases as exp(- α z).

If FBG dispersion compensation technique is compared with Optical Phase Conjugation dispersion compensation technique then Optical Phase Conjugation is best technique to reduce the dispersion in optical fiber communication [54].

7) Dispersion Compensation For High-Capacity System:- WDM light wave system uses a large number of channels to handle the capacity of more than 1 Tb/s. Therefore it becomes necessary to compensate the dispersion of each channel for better transmission.

a) Broadband Dispersion compensation:- A WDM signals occupy bandwidth of 30nm. Because of wavelength dependence of β_2 or the dispersion parameter D, the dispersion will be different for each channel. Various types of method are used for dispersion compensation in WDM systems.**1)** by using single broadband fiber grating or multiple fiber grating with their stop bands tuned to individual channels. **2)** use an optical filter with periodic transmission peaks.

Dispersion compensation by fiber grating [29]- A chirp fiber grating can have a stop band of 10nm. These gratings are used in WDM system if the number of channels are small (<10). A 6-nm-bandwidth chirped grating was used for four- channel WDM systems (each channel operating at 40Gb/s) [37]. If the WDM–signal bandwidth is much larger then a cascaded chirped grating is used in series for dispersion compensation. Each channel reflects one channel and compensates its dispersion [38]-[42].

Advantage of this technique is that the grating is tailored to match the GVD of each channel. Cascaded grating scheme for four-channel WDM system is shown in figure below.
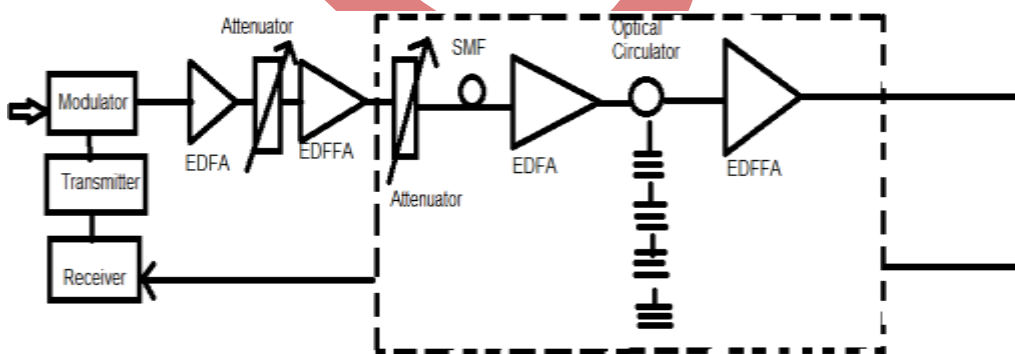

Figure: Cascaded Grating used for dispersion compensation in WDM system [41].

Four grating compensates the GVD of all the channels and two optical amplifiers handles the losses. The use of multiple grating becomes difficult when number of channel increases and signal bandwidth becomes more than 30nm.
This problem is solved by using **FP filter**. This filter compensates the GVD of all the channels if all the channels are spaced apart equally and free spectral range of the filter is matched to the channel spacing. But FP filters are not be designed with large amount of dispersion. This problem is solved by using **Sampled Fiber Grating** [43]-[45]. This grating has multiple stop band and is easy to fabricate. These fibers are used for simultaneous compensation of fiber dispersion

over 240 km for two 10-Gb/s channels [43]. But if the number of channels increase then it becomes more difficult to compensate the GVD of all channel simultaneously. This problem is solved by using **negative-slope dispersion compensating fibers.** These fibers are used for dispersion management in highly capacity WDM system with large number of channels. A broadband DCFs was used to transmit a 1-Tb/s WDM signal (total 101 channels and and each operating at 10Gb/s) over 9000 km [46]. The highest capacity of 11-Tb/s WDM signal (total 273 channels and and each operating at 40Gb/s) is transmitted by using reverse-dispersion fibers [47].

b) Tunable Dispersion Compensation:- It is very difficult to achieve the full GVD compensation for all channels in a WDM system. A small amount of residual dispersion always remains there. Postcompensation technique is used to avoid the residual dispersion of each channel. But this technique cannot be used for commercial WDM system because of following reasons-**1)** Precise amount of residual dispersion is not known in practice (dispersion variations takes place along the fiber length).

2) Dyanamic variations can accur because of temperature fluctuations.

Therefore tunable dispersion compensation technique is used.

Tunable Dispersion Compensation By Stretched Fiber Grating:- In it dispersion is tuned by stretching a nonlinearly chirped grating. Grating is placed on a mechanical stretcher and a piezoelectric transducer is used to stretch it [48]. In a chirped grating group delay is given by

$$\tau_g = \frac{2}{c} \int_0^{L_g} \bar{n}(z)dz$$

Stress-induced changes in the mode index $\bar{n}$ change the local Bragg wavelength as

$$\lambda_B(z) = \bar{n}(z)\Lambda(z)$$
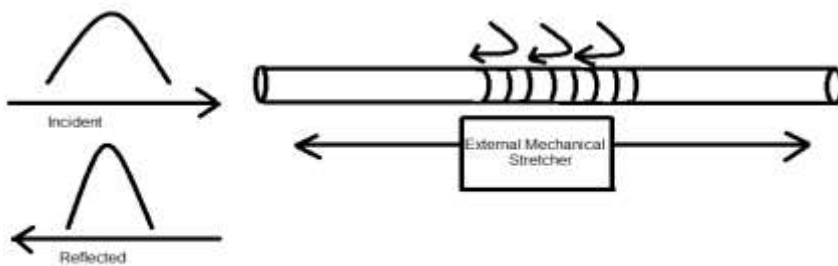
Slope of group delay at a given wavelength does not change when $\bar{n}$ is a linear function of z. Grating dispersion is given by

$$D_g(\lambda) = \frac{d\tau_g}{d\lambda} = \frac{2}{c} \frac{d}{d\lambda}\left(\int_0^{L_g} \bar{n}(z)dz \right)$$

where τ_g is the group delay and L_g is the grating length.

Value of D_g at any wavelength can be changed by changing the mode index $\bar{n}$ by stretching.

Temperature Tuning :- In it grating is made with a linear chirp and a temperature gradient is used to produce the tunable dispersion. Distributed heating of the Bragg grating requires a thin film heater deposited on the outer surface of the fiber grating.
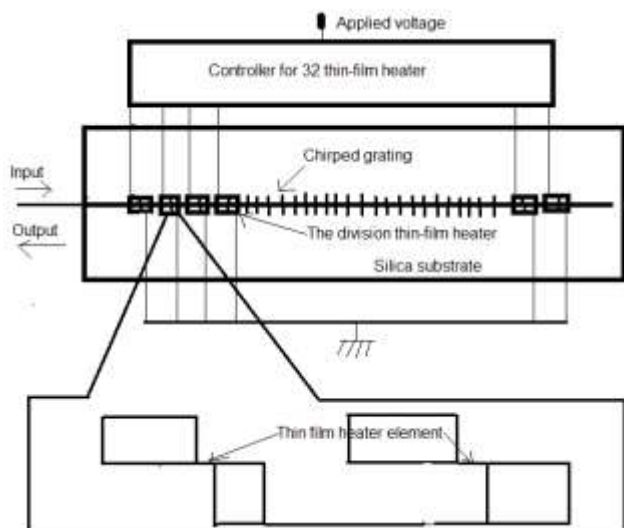
A segment thin-film heater provides better temperature control. It contains 32 chromium heating elements formed on a silica substrate. It needs a few volts to change the dispersion slope from +100 to -300 ps/n m^2 .

c) Higher-Order Dispersion Management :- When bit rate of single channel increases from 40 Gb/s then third and higher- order dispersive effects increase and effects the optical signal. The third order dispersion is compensated by using DCFs. DCFs fibers have negative dispersion slope therefore β_2 and β_3 are of opposite signs in comparison with standard fibers. Consider a fiber link containing two different fibers of length L_1 and L_2 . The condition for third- order dispersion compensation becomes

$$\beta_{31}L_1 + \beta_{32}L_2 = 0$$

Cascaded MZ ferometric filters is used for higher order dispersion management because of programmable nature of such filter. These filters have dispersion slope -15.8 ps/n m^2 over 170-GHz bandwidth [49] and they are used to compensate third- order dispersion over 300 km of a dispersion shifted fiber with $\beta_3 \approx 0.05$ps/(km-n m^2) at operating wavelength.

Figure below compares the pulse at the fiber output with and without β_3 compensation when a 2.1-ps pulse is transmitted over 100 km.

 The equalizing filter eliminates the oscillatory tail and reduces pulse width to 2.8 ps. Residual increase in the pulse width takes place due to PMD.

Cascaded Chirped Fiber Gratings – A nonlinearly chirped fiber grating is used to compensate the third –order dispersion [50]. Cascading of two chirped grating compensates β_3 without affecting β_2 .
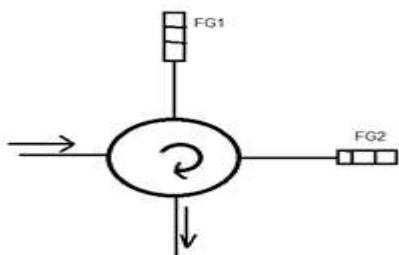
One of the chirped grating is flipped so that the combination provides no net dispersion.

d) PMD Compensation:- The use of dispersion management technique can eliminate the GVD –induced broadening but does not affect the PMD- induced broadening. Therefore it is necessary to compensate the PMD dispersion for better transmission.

Need for PMD Compensation-

Average pulse broadening for a link of length L is given by-

$$\sigma_T = D_P \sqrt{L}$$

where D_P is the PMD parameter.

If $B\sigma_T = 0.1$, then the system length and bit rate should satisfy the condition $B^2 L < (10D_P)^{-2}$.

In case of old fiber links, $B^2 L < 10^4 (Gb/s)^2 - km$ if $D_P = 1 ps/\sqrt{km}$ is used as representative value. Such fibers require PMD compensation at B= 10 Gb/s when links length exceeds even 100km. For modern fibers $D_P = 0.1 ps/\sqrt{km}$. As a result, $B^2 L$ exceeds $10^6 (Gb/s)^2 - km$.

PMD compensation is not necessary at 10 Gb/s but it becomes necessary at 40 Gb/s if link length exceeds 600 km.

PMD Compensation Technique-

a) Optical PMD compensator:- In it PMD–distorted signal is separated into two components along PSPs, which are delayed by different amounts being combined.
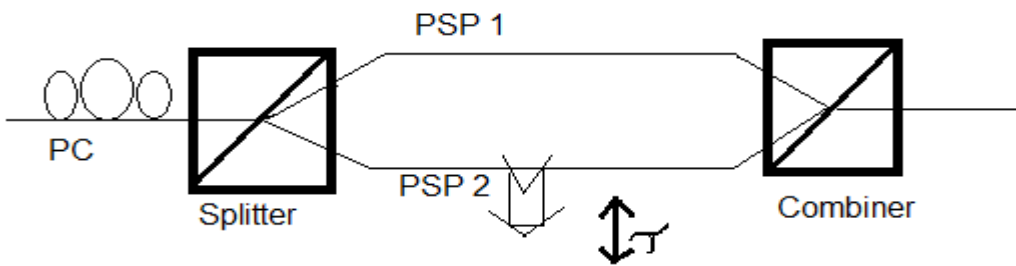

Delay is adjustable in one branch through a variable delay line. A feedback loop is used to adjust polarization controller in response to change in the fiber PSPs. The success of this technique is depend upon L/L_{PMD} .

$$L_{PMD} = \left(\frac{T_0}{D_P}\right)^2$$ is the PMD length for pulses of width T_0 [51].

b) Electrical PMD compensators- Electrical PMD equalizer corrects for the PMD effects within the receiver using a transversal filter.
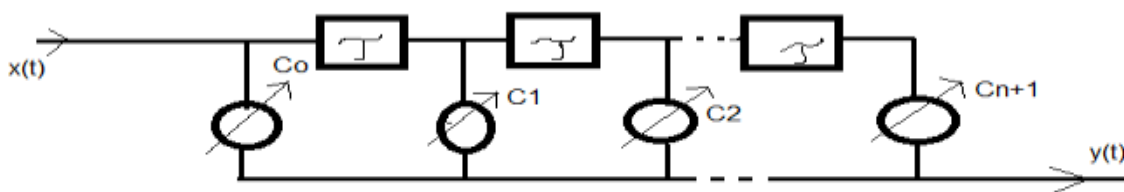
This filter splits the electrical signal x(t) into a number of branches using multiple delay lines to form output as

y(t)= $\sum_{m=0}^{N-1} c_m x(t - m\tau)$ where N is the total number of taps, τ is the delay time,

C_m is the tap weight for mth tap. Tap weight is adjusted in a dynamic fashion to improve the system performance [52].

Conclusion:-
In this paper we have reviewed the various dispersion compensation techniques (schemes). The dispersion compensating fiber (DCF) removes the limitations of precompensation and postcompensation schemes. The limitations of DCF is removed by optical filter. Fiber Bragg Grating works as an optical filter. Fiber Bragg Grating has also certain limitations. And when FBG technique is compared with Optical Phase Conjugation technique then Optical Phase Conjugation techniques becomes the best technique to reduce the dispersion in optical communication system[54]. Therefore overall Optical Phase Conjugation technique is the best technique to reduce the dispersion in optical

communication system. In this paper case we also reviewed the dispersion management for high-capacity system. Various techniques are used to avoid the dispersion of high-capacity system according to requirement.

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