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Dispersion Compensation and Nonlinearity Mitigation Using Optical Phase Conjugation and Other Techniques- A Review

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***Abstract*— In today's world when there is a need of more and more data transmission, dispersion and nonlinearities in the fiber are two major problems faced by optical communication systems installed worldwide. For the long haul communication it becomes necessary to overcome these two problems. Dispersion compensation fiber(DCF) and dispersion-compensating grating(DCG) are the two amongst the other various techniques which provide satisfactory compensation of dispersion and nonlinearities in the fiber. DCF and DCG suffer from limitations like heavy insertion loss, presence of residual dispersion in DCF, etc., therefore, it is necessary to explore other techniques also and one of them is known as optical phase conjugation(OPC). As observed from literature, results provided by OPC are more reliable when compared with DCF and DCG. By using OPC with some other techniques mitigation of dispersion and nonlinearities can be done more precisely. Various techniques have been discussed in this paper.**

***Index Terms*— Chromatic Dispersion, Dispersion Compensating Fiber(DCF), Fiber Bragg Grating(FBG), Optical Phase Conjugation(OPC).**

I. Introduction

The major cause of dispersion in optical fiber is chromatic dispersion(CD). Chromatic Dispersion mainly occurs in the optical fiber when different light pulses with different wavelengths are transmitted. Pulses travel at different speed because of the refractive index variation with wavelength. After travelling some distance these light waves spread out in the optical fiber and leads to Inter Symbol Interference(ISI). Dispersion reduces the information carrying capacity of the fiber. Chromatic dispersion occurs due to material dispersion and waveguide dispersion. Material dispersion mainly depends on the refractive index of the silica material used to made fiber and because of this pulse spreading occurs. The amount of the pulse spreading in material dispersion, Δt_{mat} is given by:

$$\Delta t_{mat}/L(ps/km)=D_{mat}(\lambda)\Delta\lambda$$

Where,
$D_{mat}(\lambda)$ = material-dispersion parameter
$\Delta\lambda$ = spectral width of the light source
L = length of fiber in km

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Waveguide dispersion occurs when some amount of information carrying light pulse travelling in the core enters into cladding. So the portion of the light pulse in the cladding will travel faster as compared to light pulse in core because the refractive index of the cladding(n_2) is less than that of the core(n_1). The amount of the pulse spreading in waveguide, Δt_{wg} is given by:

$$\Delta t_{wg}/L=D_{wg}(\lambda)\Delta\lambda$$

Where,
$D_{wg}(\lambda)$ = waveguide-dispersion parameter
$\Delta\lambda$ = spectral width of the light source
L = length of fiber in km

Nonlinearity effects arise when data rates, transmission lengths, number of wavelength, and optical power levels of fiber are increased. Fiber nonlinearities limit the amount of data that can be transmitted on optical fiber. There are various techniques by which dispersion and nonlinearities can be compensated namely dispersion compensating fiber(DCF), fiber bragg grating(FBG), optical filter, electrical dispersion compensation, optical phase conjugation(OPC), etc.

<u>DISPERSION COMPENSATING FIBER (DCF)</u>

It is known to be the good technology for the compensation of dispersion. It reduces the dispersion by providing the large negative dispersion coefficient against the positive dispersion of the conventional fiber. It requires a proper length of the DCF which can compensate the dispersion.
Depending on the position of the DCF, Compensation is done by three different methods:

A) Pre-Compensation
B) Post-Compensation
C) Symmetrical-Compensation

PRE-COMPENSATION: In this, negative dispersion compensating fiber is placed before the standard fiber to compensate its positive dispersion.
POST-COMPENSATION: In this, negative dispersion compensating fiber is placed after the standard fiber to compensate its positive dispersion.
SYMMETRICAL-COMPENSATION: In this, negative dispersion compensating fiber is placed before and after the standard fiber to compensate its positive dispersion.
Pre-compensation, Post-compensation and symmetrical-

compensation is shown by Figure 1, Figure 2, Figure 3 respectively.

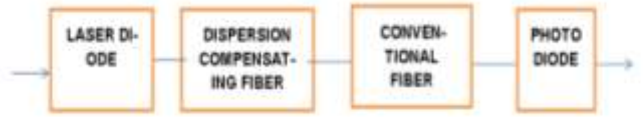

Figure 1: Pre-compensation technique

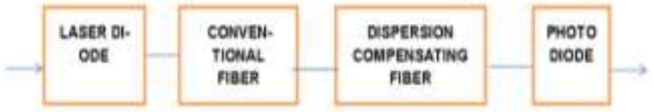

Figure 2: Post-compensation technique

Figure 3: Symmetrical-compensation technique

Limitation of Dispersion Compensation fiber(DCF)

DCF has high insertion loss and it is bulky also. Optical input power is also limited to a certain value for avoiding nonlinear impairments. Using DCF, the dispersion is not perfectly compensated as there is always present some residual dispersion, high order derivatives, high attenuation, low negative dispersion, etc. As the signal bandwidth increased, residual dispersion also increases. So to best compensate the dispersion, Fiber Bragg Grating (FBG) and Optical Phase Conjugation(OPC) are used. But on comparison of FBG and OPC for various results at transmitting and receiving end, it is found that the OPC is more suitable and reliable. Since OPC gives accurate results as compared to FBG, it is a suitable technique to replace FBG.

FIBER BRAGG GRATING (FBG)

When there is periodic change in the refractive index of the core it is known as grating. A very small amount of light is reflected from every change in refractive index and all the reflected light is combined into one reflected beam and the fiber bragg condition is met. Fiber bragg condition is given by:

$$2\Lambda n_{eff} = \lambda_B$$

Where,
Λ = grating period
n_{eff} = effective core refractive index
λ_B = bragg central wavelength

II. OPTICAL PHASE CONJUGATION(OPC)

A device called optical phase conjugator is used in the middle of the link for the inversion of the spectrum. Transmission distance of the installed fiber can be extended and also reduce the nonlinearities that limit the transmission.

Concept used in OPC:
It basically uses the four wave mixing(FWM) technique where two or three wavelengths produce two or one new wavelengths. By using OPC, the phase variation and the propagation direction of a light beam is completely reversed as. It uses phase conjugated wave to compensate dispersion at the receiver. The concept of the phase conjugation can be understood from Figure 4[1]. As the image is transmitted through conventional mirror, the received image at the receiver is doubly distorted but when it is passed through the phase conjugating mirror it is noticed that the original and the final image are same.

III. LITERATURE REVIEW

Some of the papers which have used OPC for compensation of dispersion and nonlinearity are reviewed below.

OPC is used in the mid-link of the fiber and the dispersion in the first fiber is compensated by OPC in second fiber. When compared with the DCF, it is found that by using OPC transmission distance can be increased by 44%. It is also noticed that by using odd number of OPC's in any given length of fiber, dispersion is compensated effectively but for even number of OPC's there is always some dispersion[2].
For the transmission of higher bit rates and for increased signal-to-noise ratio there are various ways in which OPC can be used with some other techniques to reduce the dispersion and nonlinearities in the fiber and help in the transmission of data.
Fiber nonlinearities can be reduced by using Distributed Raman Amplification(DRA) and also enhances OSNR(optical signal-to-noise ratio)[3],[4].OSNR can also be increased by providing high optical power per wavelength[5]. Impact of nonlinear inter-channel interactions are reduced by using polarization insensitive optical phase conjugation that is based on second order ultra long Raman fiber laser(URFL)[3].If in a transmission link there is a symmetry in dispersion and power distribution with respect to OPC position, nonlinearities by lumped Mid-span Spectral Inversion(MSSI)can be easily achieved. Two different configuration of links have been observed for the OPC device: first one is Dispersion Compensated Transmission with lumped amplification using Erbium-doped fiber amplifiers(EDFAs) and the second one is Dispersion-uncompensated transmission utilizing Distributed Raman Amplification(DRA). For both configurations, increase in Q-factor and transmission reach has been compared[5].
When the Distributed Raman Amplifier(DRA) is used with spectral inversion technique(OPC), the performance of the system is enhanced to a great extent. DRA is the most effective method to decrease the transmission loss in the transmission path as it slowly degrades the OSNR as compared to EDFA. By using OPC with DRA, the transmission rate is Tb/s and this is of great advantage to us in today's era[4]. Nonlinear compensation is perfectly achieved when in the middle of the link, OPC in combination with Distributed Raman Amplification(DRA) is set for the adjustment of the power excursion to a specific need. If phase conjugation is applied more than once in the transmission link, the benefits are enhanced to a good extent[6].
Mitigation of the nonlinear distortion for the multi-carrier systems like orthogonal frequency division multiplexing

(OFDM) by the use of optical phase conjugation(OPC) can also be done. With back-propagating Raman pump, the conversion efficiency is enhanced to a good

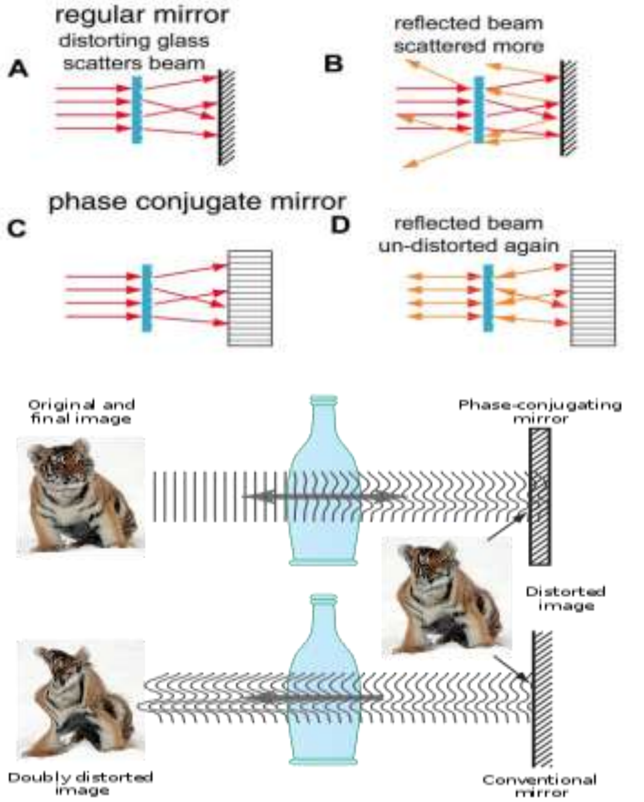

Figure 4: Phase conjugation using phase conjugation mirror.

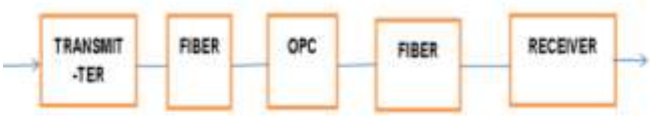

Figure 5: Block diagram of optical communication system using OPC.

value and hence, it maintains the output signal power. Since multi-carrier signals are more prone to nonlinearity in optical fiber, OPC has played a great role by providing high flexibility. Performance of the fiber-based OPC is improved when it is applied to coherent optical OFDM(CO-OFDM) system. Nonlinear distortions are completely suppressed and it is best proved in removing crosstalk among multichannel signals[7].Multiple phase conjugation can also be used in a wavelength division multiplexed(WDM) system to reduce the nonlinearities effectively. The impact of multiple phase conjugation in distributed Raman amplified(DRA) link is analyzed. Without considering the modulation formats of the wavelength division multiplexing(WDM) channels, optical phase conjugation(OPC) provides simultaneous compensation. As the nonlinearities are perfectly cancelled, the input power is available in large amount. It is necessary to look towards various requirements of the optical phase conjugation(OPC) like power excursion symmetry, mid-link location for the better and attractive result[6].

IV. INFERENCES DRAWN FROM LITERATURE REVIEW

Figure 6 shows the increase in transmission distance achieved using the techniques mentioned. Table 1 shows the parameters and conclusion arrived at in the papers reviewed.

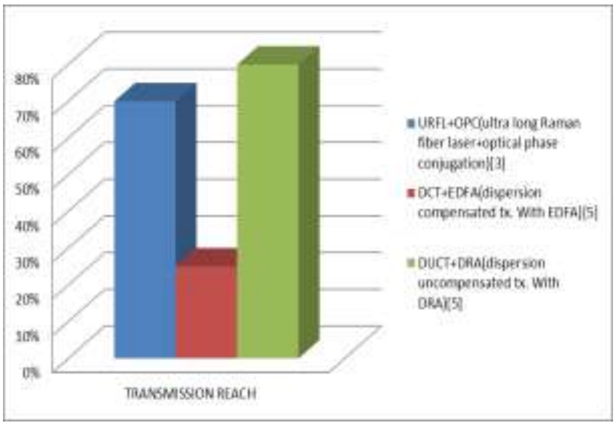

Figure 6: Transmission Reach using various techniques.

Table 1: Findings of the papers reviewed.

Ref. No.	Technique	Parameter	Findings
[3]	➢ EDFA+OPC ➢ URFL+OPC	• DFB lasers spacing-100GHz • Wavelength- 1551.72nm to 1557.36nm	• 40% compensation of the nonlinearities when compared with EDFA without OPC. The transmission reach is still less because of the insertion loss provided by the OPC. • In URFL+OPC technique, power symmetry is enhanced and because of this the nonlinearity compensation is increased by 70% when compared with the phase conjugated EDFA system. Transmission distance for 7*114 Gb/s DP-QPSK signal is increased to 10400 km which is only 5200 km for EDFA system.
[5]	➢ Dispersion compensated tx. Using EDFA	• Modulation Index- 1.44 radians • Signal Power- 2dBm • Pump Power- 29.2dBm	• Transmission reach using DCT using EDFA is only 25% whereas DUCT

	➢ Dispersion un-compensated tx. Using DRA ➢ Dispersion un-compensated without OPC ➢ Dispersion un-compensated with OPC ➢ WDM without OPC ➢ WDM with OPC	• On-Off gain- 5dB • No. of channels- 5 • OSNR penalty< 1dB	using DRA its 80%. So we prefer DRA over EDFA. • Transmission power and Q-factor received are increased with improvements of around 0.9 dB when the transmission link is 800 km and 1.1 dB when it is 400 km. • Fiber length for dispersion un-compensated without OPC is 1300km whereas with OPC it is 2400km. • Launched power for the WDM system without OPC is -2dBm and with OPC it is 0dBm.
[4]	OPC+DRA	• Bit rate- 112Gbps • No. of channels- 8 • Transmission power- 10dBm • Fiber length- 800km	• High spectral efficiency • Gain- 1.9 dB • Minimum Eye Opening penalty (EOP) achieved in the case when we use optical phase conjugation with Distributed Raman Amplifier is 0.4 whereas for DCF and OPC its 0.9 and 0.55 respectively.
[7]	OFDM system with back-propagating Raman pump + OPC	• 256 frequency comb lines • Optical bandwidth- 10GHz • Bit rate- 16.6Gbps	• Dynamic range of the signal input power has been extended to 7dB. • Conjugated output power is increased by 10dB. • Q-factor is improved by 1.2dB. • Removes crosstalk from multichannel signals.
[6]	WDM transmission with multiple phase conjugation	• Wavelength- 1530.022 to 1530.608 nm • Output powers of lasers- 25GHz	• Input power is large through each span and no phase distortions in all phase conjugation stage.

V. CONCLUSION

Though DCF and FBG are good techniques for dispersion compensation and nonlinearities mitigation, still because of disadvantages mentioned in the paper provides OPC for the compensation. When OPC in combination with some other techniques like DRA, URFL, etc, results in terms of transmission reach, Q-factor, eye opening penalty, conjugated output power, gain, etc are improved to a greater extent.

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