A Review on Optical Fiber Non-Linearities and their Mitigation Using Optical Phase Conjugation

Parminder Singh[1], Dr. Divya Dhawan[2]
[1]*P.G. Scholar, ECE Dept., Punjab Engineering College (Deemed to be University), Chandigarh, India.*
[2]*Asisstant Professor, ECE Dept., Punjab Engineering College (Deemed to be University), Chandigarh, India.*
[1]*parminderdutt71@gmail.com*, [2]*divyadhawan@pec.ac.in*

***Abstract**:* Optical communication systems represent backbone of modern communication systems**.** Optical fiber is considered as a perfect transmission medium with nearly limitless bandwidth, but in practical scenario transmission is affected by many limitations, mainly dispersion and fiber nonlinearities, as the transmission distance increases. Fiber nonlinearities impose the biggest threat in implementation of next generation Long-Haul optical systems. It is necessary to mitigate fiber nonlinearities to improve the transmission distance and performance of the next generation optical systems. In this paper different types of optical fiber nonlinearities, the need of mitigation of optical fiber nonlinearities, and the mitigation of optical fiber nonlinearities in optical domain by using optical phase conjugation has been discussed.

I. INTRODUCTION

As per the number of users are increasing day by day, the demand of higher data rates and more capacity is increasing parallelly. To meet the requirement of high capacity and to increase the data rates in future Long-Haul systems, higher order and advanced modulation schemes i.e. Quadrature amplitude modulation(QAM), are perfect candidates in contrast to less complex modulation schemes such as Quadrature Phase Shift Keying(QPSK) and Binary Phase Shift Keying(BPSK). While using higher order modulation schemes, due to the requirements of higher OSNR at the receiver end, higher input power is launched for the same length of transmission[1]. But, at higher input powers, Kerr induced nonlinearities become dominant, resulting in lower values of the OSNR at the receiver end and limiting transmission distance as well. Coherent detection DSP based algorithms i.e. Digital back propagation(DBP)[2], Volterra nonlinear equalizer(VNLE)[3], Perturbation based techniques[4], can be used to mitigate fiber nonlinearities. Apart from these techniques, nonlinearities can be mitigated in optical domain by using Phase conjugation(PC)[5].

In this paper mitigation of optical fiber nonlinearities using optical phase conjugation, scheme of using OPC at the mid-span (Single OPC)[6] and use of more than one OPC (Multiple OPC)[7] is discussed.

This paper is organized as follows: in section-2, a brief introduction to fiber nonlinearities is given, in section-3, technique of optical phase conjugation to mitigate fiber nonlinearities is described (both in single OPC and multiple OPC Configurations), in section-4 various research works involving the use of OPC for nonlinearity mitigation is discussed.

II. FIBER NON-LINEARITIES

Optical communication over single mode fiber gets affected by several restrictions, apart from the linear distortions which are: chromatic dispersion (CD), polarization mode dispersion(PMD), polarization dependent loss(PDL) and fiber attenuation, nonlinear impairments are serious problem at higher input powers to achieve higher data rates. Refractive index of optical fiber depends upon intensity of signal travelling inside the optical fiber, known as Kerr-effect, which makes optical fiber a nonlinear medium. Depending upon the power of the input signal and spacing between different channels (in multi-channel transmission), Kerr effect induces different type of nonlinearities i.e. Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), Four Wave Mixing (FWM), Cross Polarization Modulation (XpolM)[8]. At high input powers fiber nonlinearities become dominant, so their mitigation for error free long-haul transmission is must.

In [9], Self-Phase modulation was identified as a dominant source of pulse broadening as a result of gain saturation in semiconductor laser amplifiers, that is responsible for time-dependent variations in the carrier density, and hence the refractive index. It was found that due to SPM there is a frequency shift in the signal, which results in pulse broadening when it interacts with dispersion.

In XPM there is a frequency shift, due to interaction of signals with each other (in multi-channel systems) and with optical fiber [10], which leads to frequency shift. Interaction between this frequency shift with the dispersion results in broadening of the optical pulse.

Four-wave mixing is similar to third-order inter-modulation distortion in which two or more optical waves at different wavelengths mix to generate new optical waves at other wavelengths, which results in power depletion as well as receiver complexity[11]. FWM depends on spacing between channels and the dispersion of fiber. Dispersion in optical fiber changes with the wavelength of signal, the FWM-generated new signal has a different speed from the original signal. By increasing fiber dispersion interaction between these signals can be avoided. In spite of being nonlinear distortion, FWM is a promising method which can be used for wavelength conversion, dispersion compensation and all optical switching operations[12].

In WDM transmission system, Cross polarization modulation takes place when state of polarization of a signal depends on the state of polarization of other co-propagating signals inside the optical fiber[13]. Cross polarization modulation results in depolarization of the original transmitted signal, which results in channel crosstalk for dual-polarization systems. Cross polarization modulation can dominate the cross- phase modulation effect and XpolM can be treated as additive gaussian noise. Table-1 summarizes the dependence of the Kerr-induced fiber nonlinearity on the bit rate and channel spacing.

Table 1: Fiber Nonlinearity versus Bitrate and Channel Spacing[8]

Type	SPM	XPM	FWM	XpolM
On Increasing Bit- Rate	Increases	Increases	Increases	No effect
On decreasing channel Spacing	No effect	Increases	Increases	Increases

A.Mitigation of fiber Nonlinearities: Propagation of optical signal inside the fiber can be characterized by Nonlinear Schrӧdinger equation(NSE)[8]. In case of single polarization transmission NSE can be written as:

$$\frac{\partial B}{\partial Z} + j\frac{\beta_2}{2}\frac{\partial^2 B}{\partial t^2} + \frac{\alpha}{2}\mathrm{B} = j\gamma'|B|^2\mathrm{B} \qquad (1)$$

Where, B is the electric field envelope of the optical signal. α is the fiber attenuation coefficient, β_2 is the second-order dispersion parameter, γ is the nonlinear coefficient of the fiber, and $\gamma'=\frac{8}{9}\gamma$ is the adapted nonlinear coefficient for dual-polarization systems.

The term on the right side describes the influence of the nonlinearity on the pulse, whereas the second term on the left-hand side, can be addressed to the linear effect of dispersion in the waveguide.

Fiber nonlinearities can be mitigated either in digital domain using Digital back propagation(DBP), volterra based nonlinear equalizer(VLNE), perturbation-based technique or in optical domain using Phase conjugation (PC).

The main concept of using digital algorithms is to solve inverse nonlinear Schrӧdinger equation and create inverse channel with inverse parameters and by propagating received signal at the receiver end through this channel, fiber impairments can be removed. Since, in digital techniques an inverse replica of channel is created and signal is passed through it, which requires a lot of computational time, their real time implementation for long-haul communication system is tough[8].

DBP technique can be implemented both at the transmitter and receiver side[8]. The DBP concept consists of transmitting the received signal through a fictitious fiber with inverse parameter, total fiber span is divided in small steps, and each step is a cascading of linear and nonlinear sections, due to which it requires high computational time.

In VNLE, inverse volterra series transfer functions are used to model fiber with inverse parameters, similar to DBP in VNLE linear and nonlinear distortions are treated separately, but in VNLE instead of cascading these sections parallel approach is used, which reduces computational time and makes it faster than DBP[8].

Perturbation techniques are largely investigated to model optical fiber, main idea of this technique is the use of nonlinear distortions as a perturbation correction to unperturbed solution. Perturbation technique requires large number of perturbation terms, making it difficult to implement in real-time systems. DBP based techniques require computational time which makes them slow. Fiber nonlinearities can be mitigated in optical domain using phase conjugation. There are two ways to implement phase conjugation, either at mid-span optical phase conjugation(OPC)[14] or transmitting Phase conjugated twin waves(PCTW)[15]. In mid-span OPC original signal propagates for half of the length of the transmission distance and rest of the distance is covered by conjugate of the original signal, which effectively cancels out fiber impairments (both linear and non-linear). In PCTW conjugated signal is transmitted with the original signal, and at the receiver end, original signal is recovered by superimposing both of the signals. PCTW is not a spectrally efficient method as two signals are transmitted inside the fiber carrying same information. In next section an introduction of optical phase conjugation is given followed by its implementation in single OPC configuration and multiple OPC configuration is discussed.

III. OPTICAL PHASE CONJUGATION

Optical phase conjugation is a well-known technique to compensate linear as well as nonlinear impairments in optical fibers. Optical phase conjugation is a physical transformation of a signal, in which phase of the signal is shifted by an angle of π, keeping amplitude and propagation direction of the signal same. This phase shifted signal is conjugate of the original signal, to get conjugate of the original signal, FWM phenomenon is used, original signal interacts with pump signals in highly nonlinear medium to generate conjugate signal, various techniques to get conjugate signal is discussed in section-4.

To overcome optical fiber impairments OPC can be used in two ways either at mid-span using single OPC or using multiple OPC at prespecified distances.

A. Mid-Span OPC: The concept of using optical phase conjugator at the exact mid-point is that the conjugate of optical signal is affected by fiber nonlinearities in the similar fashion as of optical Signal itself, but in reverse direction[6].

Rewriting equation 1,

$$\frac{\partial B}{\partial Z} + j\frac{\beta_2}{2}\frac{\partial^2 B}{\partial t^2} + \frac{\alpha}{2}\mathrm{B} = j\gamma'|B|^2\mathrm{B}$$

Taking conjugate of above equation,

$$-\frac{\partial B^*}{\partial Z} + j\frac{\beta_2}{2}\frac{\partial^2 B^*}{\partial t^2} - \frac{\alpha}{2}B^* = j\gamma'|B^*|^2 B^* \qquad (2)$$

Where * denotes complex conjugate of the signal, Equation (2) describes the behavior of signal when it is back propagated through the fiber, which is complex conjugate of the signal propagating in forward direction of fiber. Using this mutual-conjugate relation, in[16], it was concluded that conjugate signal gets affected by the nonlinear distortions in similar manner, but in reverse direction than that of the original signal.

So, the idea behind using optical phase conjugator at exact middle point of transmission length is to cancel out the nonlinearities introduced in first half of the transmission link by nonlinearities introduced in second half of the transmission link[6].

The block diagram of using OPC at the mid-point of the optical link is shown in figure-1.

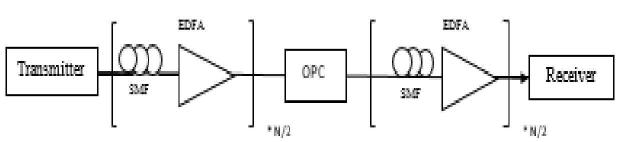

Figure-1: Mid-Span Configuration of OPC

Where N is the total number of spans.

B. Multiple OPC Configuration: By using Mid-Span Single OPC configuration, one might be able to mitigate fiber nonlinearities in an efficient manner, but at the cost of flexibility of the transmission link and significant portion of the bandwidth also, because there is a need of vacant bandwidth for conjugated signal. To improve the flexibility of the optical system multiple OPC can be used, signal can be dynamically routed after using OPC at some specified distance, also original wavelength of the signal can be retained by using even number of optical phase conjugators in transmission link[7], which reduces complexity at the receiver end. Block diagram of multiple OPC configuration is shown as below:

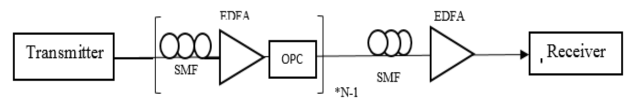

Figure-3: Multiple OPC Configuration

To get the conjugate signal at the mid-span, there are three important design parameters: pump powers, length of highly non-linear fiber (HNLF) and signal bandwidth [17].

For CO-OFDM systems, relation between power distorted in OPC and pump power is given by following equation:

$$P_{opc} = 3N_{sc}^2(\gamma L)^4 P_{pump}^2 P_{sc}^3 \qquad (3)$$

Where P_{opc} is OPC distorted power, N_{sc} is the number of sub-carriers, γ is the non-linear coefficient, L is the span length, P_{pump} is the pump power and P_{sc} is the power of subcarrier.

As the OPC distorted power is directly proportional to the square of the pump power, this causes both the OPC signal and OPC distortion to increase with the square of P_{pump} , thus the performance in the nonlinear medium cannot be improved by increasing pump power. Theoretically optimal signal quality is directly proportional to length of HNLF. However, if length of HNLF is more than 1-km, the optimal signal quality begins to reduce, it was shown in simulations. In[17], dependence of maximum Q-factor upon signal bandwidth was discussed, it was shown that OPC can accommodate S, L and C bands, provided the HNLF is dispersion less across the span.

IV. RESEARCH WORK RELATED TO MITIGATE FIBER DISTORTIONS USING OPC

Optical phase conjugation has been a promising method to overcome fiber distortions. Various research work involving optical phase conjugation to mitigate fiber nonlinear impairments is listed in table-2, different techniques used to get the conjugate signal at the mid-span are also listed in table-2 and discussed after that.

Table-2: Research work involving OPC to mitigate fiber nonlinearities

Reference Number	Year of Publication	System Specifications	Technique used for Phase Conjugation.	Results
[6]	2004	Wavelength division multiplexed system over 800 km of standard single mode fiber(SSMF) at 640 Gb/s (16*40 Gb/s) data rate.	Magnesium-oxide-doped periodically poled lithium niobite (MgO: PPLN)-based polarization-diverse subsystem as optical phase conjugator.	Successful transmission of 16 40-Gb/s channels over 800-km was achieved, need of in-line dispersion compensation was eliminated.
[18]	2005	Return-to-zero differential phase-shift-keyed (RZ-DPSK) system at data rate of 40-Gb/s over 3200-km transmission distance.	Single lithium niobite ($LiNbO_3$) based optical phase conjugator.	The compensation of intra-channel nonlinearities in a 40-Gb/s RZ-DPSK system using optical-phase conjugation at transmission distances of 3200 and 6400 km was demonstrated. Also, it was shown that single OPC is enough to mitigate nonlinearities throughout the link.
[19]	2012	16-QAM (604.7-Gb/s) single-polarization CO-OFDM super-channel over SSMF of 800-km (10 × 80-km) link.	Phase insensitive fiber optical parametric amplifier (PI-FOPA) with 1008-m long highly nonlinear fiber(HNLF).	Mid span spectral inversion improved the nonlinear threshold of a 604.7- Gb/s 16-QAM single-polarization CO-OFDM super-channel by 4.8 dB over the tested 10 × 80-km link.
[20]	2012	252 Gb/s (9*28 Gb/s) polarization multiplexed-16QAM, signal was propagated over SSMF link over 1600-km,3200-km,4800-km spans.	Optical phase conjugation along with the digital back propagation algorithm was used to mitigate nonlinear distortions.	Using OPC with DBP improves the flexibility of the system, also transmission reach was improved by a factor of ~2.
[14]	2014	4-QAM 224 Gb/s CO-OFDM system over 800-km (10*80-km) span of SSMF.	Phase shifting filters, which splits nonlinear element into two sections, suppressing XPM in first section and inserting pump in the second section.	Design proposed was able to improve transmission performance at optimum power by 1.2 dB and back-to-back performance by 3.6 dB.
[1]	2015	Experimental set up of 16-QAM wavelength division multiplexed field installed system over SSMF of 400-km length.	Polarization insensitive OPC based on two orthogonal pumps, Optical band-pass filters were used to suppress amplified spontaneous emission (ASE).	Q-factor improvement of more than 0.4 dB was achieved and transmission capacity of OPC system was almost doubled.

[7]	2016	32-Gbaud PDM 16-QAM (2.048 Tbit/s) wavelength division multiplexed signals over 900-km (4*250-km) span of SSMF.	Broad-band polarization insensitive fiber optical parametric amplifier (PI-FOPA).	Repeated optical phase conjugation was demonstrated for the first time, over a distance of 900-km and at data rate of 2.048 Tb/s system performance was improved by using repeated OPC, also receiver complexity was reduced.
[21]	2017	8 × 32-Gbaud PDM QPSK Channels over 3600-km fiber span and 8 × 32-Gbaud PDM 16-QAM over 912-km fiber span, WDM transmission systems.	Multiple phase conjugators based on Polarization insensitive fiber optic parametric amplifier (PI-FOPA)	Nonlinear threshold was increased ~5dB by deploying repeated OPC, in comparison to no OPC case, and ~2dB in comparison to single mid-span OPC.
[22]	2018	The 300-GHz wide superchannel consisted of eight 200 Gb/s PDM-16 QAM sub-channels on a 37.5-GHz grid, also 1.6-Tb/s superchannel without shifting the occupied wavelength band using phase insensitive OPC was experimentally demonstrated	Polarization insensitive, and wavelength-shift-free optical phase conjugator (OPC).	The OPC subsystem was characterized in single-channel (200 Gb/s) and eight-subchannel (1.6 Tb/s) superchannel scenarios. More than 26 dB of original signal suppression was achieved at the OPC output in all scenarios resulting in low coherent crosstalk over a broad operation bandwidth of the OPC of up to 300 GHz

From the above table it can be observed that OPC is an efficient technique to mitigate both linear and nonlinear fiber distortions.

The most important thing, while deploying OPC to overcome fiber impairments, is to generate conjugate copy of transmitted signal at the mid-span of transmission distance. It can be done by using any of the above-mentioned techniques, here is a brief explanation of these techniques is given. Generally, conjugate signal is generated by the process of four-wave mixing in highly nonlinear medium. Polarization insensitive fiber optic parametric amplifier(PI-FOPA) is used for the conjugation purposes, in this technique there are two pumps, whose frequencies are symmetrically situated on the either side of the original signal, and a highly nonlinear fiber(HNLF) of length of ~200-400 meter. These signals interact with each other in HNLF and through the process of FWM conjugate copy of the signal is generated, original signal is filtered out by using a proper band-pass filter and the conjugate signal is made to propagate rest of the transmission distance, which cancels out the chromatic dispersion and nonlinear distortions efficiently [1],[19]. While using PI-FOPA spectral efficiency is less, because there is a need of vacant band for the conjugate signal and receiver complexity is high due to wavelength conversion, to reduce the receiver complexity repeated OPC configuration can be used, by using even number of OPC's original transmitted signal wavelength can be recovered [7],[21]. In [22] discussed a novel OPC, which was polarization-insensitive, and spectrally efficient i.e. no need of vacant band for conjugate signal, the original input signal is inherently suppressed in a polarization-diversity loop setup. This allows for spectrally efficient, wavelength-(band)-shift-free generation of phase-conjugated idlers over a continuous operating band.

In [7], Phase conjugation was achieved by using highly non-linear fiber(HNLF), a polarization controller was used to align the pump signal polarizations with the principle state of polarization of the HNLF to minimize polarization-mode-dispersion, and to remove random polarization signals wavelength-selective-switch (WSS) followed by a controllable optical switch was used, which would select either original signal or idler. Pump powers used were 25.1 dBm and 24.2 dBm respectively, HNLF of length 500 meter was used, with zero dispersion wavelength of 1578.5 nm and with nonlinear coefficient of 20/W/km. using these parameters PI-FOPA was used to conjugate the signal, and pumps were removed using fiber Bragg gratings (FBGs).

In[6],[18], PPLN based optical phase convertor was used, firstly pump is combined with the signal and then launched into the PPLN waveguide to get conjugate signal. After the waveguide, the remaining pump is rejected with a fiber Bragg grating and the converted signal is further filtered and amplified in another amplifier.

In[22], architecture of Optical phase conjugation was reviewed, to conjugate the signal without the requirement of extra band-width for conjugate signal, polarization diversity loop was used to reject the original signal in a wavelength-transparent manner by its polarization beam splitter, eliminating the need of band-pass filter to filter out the original signal, moreover the need of extra band-width was eliminated.

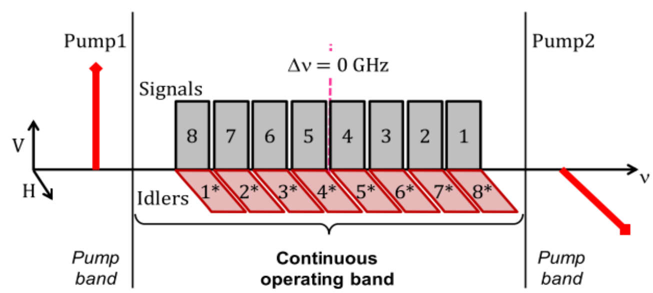

Figure-3: Signal and idler channel allocation in wavelength shift-free Optical Phase Conjugation (V: Vertical polarization, H: Horizontal polarization)[22]

V. CONCLUSION

Optical Phase conjugation is an efficient technique to mitigate fiber nonlinearities in contrast to other nonlinear mitigation techniques i.e. Digital Back Propagation, Volterra Nonlinear Equalizer, Perturbation based Technique. As being an optical domain method, it does not require any computational time. Drawback for using OPC is that it reduces flexibility of system and increases complexity of receiver, also it requires extra bandwidth for conjugated signal, these drawbacks can be significantly reduced by using multiple OPC configuration or the new OPC architecture discussed in [22], but flexibility of the system still remains a major concern.

To improve the flexibility of the system and to mitigate fiber nonlinearities efficiently, Optical phase conjugation can be used with digital nonlinearity mitigation techniques i.e. DBP, VLNE etc. as in[20].

REFRENCES

[1] S. Yoshima, Y. Sun, K. R. H. Bottrill, F. Parmigiani, P. Petropoulos, and D. J. Richardson, "Nonlinearity mitigation through optical phase conjugation in a deployed fibre link with full bandwidth utilization," *Eur. Conf. Opt. Commun. ECOC*, vol. 2015–Novem, no. 1, pp. 3–5, 2015.

[2] E. Ip and J. M. Kahn, "Compensation of dispersion and nonlinear impairments using digital backpropagation," *J. Light. Technol.*, vol. 26, no. 20, pp. 3416–3425, 2008.

[3] H. Chin, J. Mårtensson, M. Forzati, and A. Netlab, "Volterra Based Nonlinear Compensation on 224 Gb / s PolMux-16QAM Optical Fibre Link," *Proc. Opt. Fiber Conf.*, no. 1, p. JW2A.61, 2012.

[4] X. Liang, S. Kumar, J. Shao, M. Malekiha, and D. V. Plant, "Digital compensation of cross-phase modulation distortions using perturbation technique for dispersion-managed fiber-optic systems," *Opt. Express*, vol. 22, no. 17, p. 20634, 2014.

[5] G. S. He, "Optical phase conjugation: principles, techniques, and applications," *Prog. Quantum Electron.*, vol. 26, pp. 131–191, 2002.

[6] S. L. Jansen *et al.*, "Spectral Inversion," vol. 16, no. 7, pp. 1763–1765, 2004.

[7] H. Hu, R. M. Jopson, A. H. Gnauck, D. Pilori, and S. Randel, "Fiber Nonlinearity Compensation by Repeated Phase Conjugation in 2 . 048-Tbit / s WDM transmission of PDM 16-QAM Channels," pp. 7–9, 2016.

[8] A. Amari, O. A. Dobre, R. Venkatesan, O. S. S. Kumar, P. Ciblat, and Y. Jaouen, "A survey on fiber nonlinearity compensation for 400 Gbps and beyond optical communication systems," *IEEE Commun. Surv. Tutorials*, pp. 1–40, 2017.

[9] G. P. Agrawal and N. A. Olsson, "Self-phase modulation and spectral broadening of optical pulses in semiconductor laser amplifiers," *Quantum Electron. IEEE J.*, vol. 25, no. 11, pp. 2297–2306, 1989.

[10] R. R. Alfano, P. L. Baldeck, P. P. Ho, and G. P. Agrawal, "Cross-phase modulation and induced focusing due to optical nonlinearities in optical fibers and bulk materials," *J. Opt. Soc. Am. B*, vol. 6,

no. 4, pp. 824–829, 1989.

[11] K. Inoue, "Four-Wave Mixing in an Optical Fiber in the Zero-Dispersion Wavelength Region," *J. Light. Technol.*, vol. 10, no. 11, pp. 1553–1561, 1992.

[12] D. Nesset, D. D. Marcenac, P. L. Mason, A. E. Kelly, S. Bouchoule, and E. Lach, "Simultaneous wavelength conversion of two 40 Gbit/s channels using four-wave mixing in a semiconductor optical amplifier," *Electron. Lett.*, vol. 34, no. 1, pp. 107–108, 1998.

[13] M. Winter, D. Kroushkov, and K. Petermann, "Polarization-multiplexed transmission system outage due to nonlinearity-induced depolarization," *Eur. Conf. Opt. Commun. ECOC*, vol. 1–2, pp. 19–23, 2010.

[14] M. Morshed, A. J. Lowery, and L. B. Du, "Reducing Nonlinear Distortion in Optical Phase Conjugation using a Midway Phase-Shifting Filter," vol. 1, pp. 56–58, 2014.

[15] L. Xiang, S. Chandrasekhar, and P. J. Winzer, "Phase-conjugated twin waves and fiber nonlinearity compensation," *Optoelectron. Commun. Conf. Aust. Conf. Opt. Fibre Technol.*, no. July, pp. 938–940, 2014.

[16] C. Lorattanasane and K. Kikuchi, "Design Theory of Long-Distance Optical Transmission Systems using Midway Optical Phase Conjugation," *Lightwave*, vol. 15, no. 6, pp. 948–955, 1997.

[17] M. Morshed, L. B. Du, and A. J. Lowery, "Mid-span spectral inversion for coherent optical OFDM systems: Fundamental limits to performance," *J. Light. Technol.*, vol. 31, no. 1, pp. 58–66, 2013.

[18] A. Chowdhury *et al.*, "Compensation of intrachannel nonlinearities in 40-Gb/s pseudolinear systems using optical-phase conjugation," *J. Light. Technol.*, vol. 23, no. 1, pp. 172–177, 2005.

[19] L. B. Du, M. M. Morshed, and A. J. Lowery, "Fiber nonlinearity compensation for OFDM super-channels using optical phase conjugation," *Opt. Express*, vol. 20, no. 18, p. 19921, 2012.

[20] D. Rafique and A. D. Ellis, "Nonlinearity Compensation via Spectral Inversion and Digital Back-Propagation: A Practical Approach - OSA Technical Digest," *Opt. Fiber Commun. Conf.*, p. OM3A.1, 2012.

[21] H. Hu, R. M. Jopson, A. H. Gnauck, S. Randel, and S. Chandrasekhar, "Fiber nonlinearity mitigation of WDM-PDM QPSK/16-QAM signals using fiber-optic parametric amplifiers based multiple optical phase conjugations," *Opt. Express*, vol. 25, no. 3, p. 1618, 2017.

[22] I. Sackey *et al.*, "Waveband-Shift-Free Optical Phase Conjugator for Spectrally Efficient Fiber Nonlinearity Mitigation," *J. Light. Technol.*, vol. 36, no. 6, pp. 1309–1317, 2018.

AUTHORS

Parminder Singh pursuing M.Tech in Electronics and communication at Punjab Engineering College (Deemed to be university) Chandigarh, India.

Dr. Divya Dhawan is currently working as Assistant Professor

in ECE Department of Punjab Engineering College University of Technology Chandigarh, India. She has a teaching experience of nearly 18 years. She is a member of IEEE, ISTE, and IEI. Her research interests include Optical Communication, Photonics Systems and Digital system design.