OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 10, No. 5-6, May-June 2016, p. 447 - 452

Mitigation of PMD and PDL induced signal degradation using Levenberg-Marquardt algorithm

S. VINAYAGAPRIYA*, A. SIVASUBRAMANIAN[a]
Research Scholar, Sathyabama University, St. Joseph's College of Engineering, Chennai, TN, India
[a]*Professor, VIT University, Chennai, TN, India*

Polarization Mode Dispersion and Polarization Dependent Loss are among the most important fiber impairments that induce errors and limit the overall system performance. In this paper, Levenberg-Marquardt Training Algorithm is proposed to mitigate the pulse deformation induced by Polarization Mode Dispersion and Polarization Dependent Loss. Reduction in output waveform distortion can be achieved by choosing appropriate states of polarization. Results show circularly polarized positive chirped super-gaussian input signal giving higher compression factor compared to linearly polarized signal. However, an improvement in compression ratio is achieved using Levenberg-Marquardt Algorithm. Since it is the fastest technique and gives accurate solution, it is used for PMD, PDL related problems.

(Received February 25, 2016; accepted June 9, 2016)

Keywords: States of Polarization, Levenberg-Marquardt Algorithm, Single Mode Optical Fiber

1. Introduction

Polarization Mode Dispersion(PMD) plays an important role in High Speed Single Mode Optical Communication System. PMD can be described in terms of Birefringence. A material which produces difference in refractive indexes for the orthogonally polarized mode is said to be Birefringent. Birefringence in a fiber can change the polarization state of the optical signal guided by the fiber. In the absence of all the birefringence, the injected polarization state will be maintained along the optical fiber. Each birefringence mechanism introduces a phase delay between the two polarization eigen modes. This causes a change in the state of polarization of the guided light when both modes are excited.

The effective PMD for a pulse in the case of zero Polarization Dependent Loss(PDL) is defined as the difference between maximum and minimum time delay through the fiber. The corresponding input state of polarization is defined as the two orthogonal input principal states of polarization [1]. PDL in optical communication system has the potential of considerably degrading system performance by reducing the signal to noise ratio. It has become important in long terrestrial systems where components are required to be cheaper than in undersea cable system resulting in much higher PDL values [2].

The presence of PMD, PDL, Chromatic Dispersion and initial chirp has effects on the propagated pulses in Single Mode Fiber. Impairments were found to be dependent on Chirp and to be highly dependent on launch states of polarization [3]. RMS pulse width of a signal transmitted through an optical fiber with PMD is minimized by varying the input and the output states of polarization. This results in reduction of the optical power in the output pulse [4]. A new algorithm has been developed for optimization of PMD pulse-width compression problem which is more efficient, better for real time implementation and is guaranteed to be globally convergent [5].

An Artificial Neural Network(ANN) Model has been constructed for simultaneous identification of three separate impairments namely PMD, Optical Signal-to-Noise Ratio, and Chromatic Dispersion that can degrade optical channels. ANN were trained with parameters derived from eye diagrams and can be used to determine the levels of Optical Signal to Noise Ratio, Chromatic Dispersion and Differential Group Delay for 10 Gb/s non-return-to-zero On-Off Keying and 40 Gb/s return to zero Differential Phase Shift Keying signals. This method provides a powerful new technique for monitoring the performance of optical channels [6].

Performance improvement is achieved by Polarization Scrambling involving Bit Synchronous Sinusoidal Polarization Modulation and Phase Modulation in the presence of PMD, Fiber Nonlinearity and may strongly mitigate nonlinear SPM Impairments in dispersion managed Single channel or Wavelength Division Multiplexed NRZ 10 Gb/s Fiber Optic Transmission System [7]. Inter-polarization crosstalk caused by second order PMD and its impact on the polarization multiplexed transmission of ultra short optical pulses is presented. Optimum pulse width, pulse waveform and modulation format must be chosen for achievement of an ultra high bit rate and to realize an ultrahigh-speed transmission over long distance [8].

The impact of PMD and PDL on a Gaussian pulse is investigated and the pulse broadening, pulse arrival time and transmission coefficient have been noted. With PDL, pulses with some special input state of polarization are narrower at the output than they were at the input of the system. [9]. Proper selection of ANN Structure and training method is essential. A Multilayer Perceptron Network model using Levenberg-Marquardt Algorithm is important for improvement of the system performance. A Gauss Newton Algorithm proposed in [10] is a Quasi Newton Optimization method and does not guarantee convergence. A well known modification of the Gauss Newton Algorithm is Levenberg-Marquardt Training Algorithm which increases the convergence speed of the ANN. Levenberg-Marquardt algorithm is an iterative technique that locates the minimum of a function.

Levenberg-Marquardt Algorithm outperforms Back Propagation algorithm. Back Propagation Neural Network suffers from the problem of slow convergence and convergence to local minima. An improved version of Back Propagation Algorithm is the Levenberg-Marquardt Algorithm. In this paper, Chirped Super-gaussian input pulse is launched at various states of polarization such as Linear and Circular. Pulse deformation due to PMD and PDL is observed at the output and is mitigated using Levenberg-Marquardt Training Algorithm.

The rest of the paper is organized as follows. The basic PMD and PDL theory are studied in section 2. Optical System Transmission setup and ANN model is reported in section 3. Results and Conclusion are given in section 4 and 5.

2. Theory

Single Mode optical fiber supports two polarization modes. As an optical pulse propagates through the single mode fiber potentially, there exist two physical effects, namely PMD and PDL and these two result from either intrinsic non cylindrical symmetric core shape or from the environment perturbations such as bending and twisting. With high bit rates in high speed optical system, both PMD and PDL are recognized as the more important limiting factor .Also output pulse broadening or narrowing depends on the input polarization and for certain values of PDL, the output pulse can be narrower than the input pulse[11].

PMD may be usually described by means of the fiber Jones matrix. The analysis of the PMD impact on the system performance is easily worked out by means of the Jones matrix or transfer matrix. In the presence of frequency chirp, the Jones vector of a Gaussian pulse at the fiber input can be written as [12]

$$E_{in}(w) = A_o \exp\left[\frac{-w^2\tau_{in}^2}{1-iC}\right]\varepsilon \tag{1}$$

where A_0 is constant, τ_{in} is the rms pulse width, C is the linear frequency chirp parameter and ε represent the states of polarization of the input pulse.

An optical device can change the polarization state of light beams. The polarization state of the field can be represented by a Jones calculus (Jones vector and Jones matrix). Jones calculus includes 1×2 Jones vectors which describe the State of Polarization and 2×2 Jones matrices which describe the transmission media. Jones vector and matrix are smaller in size, and they describe the field directly.

$E_{out}(w)$ can be obtained from the following relationship between the Jones vector and Jones matrix of the fiber which is

$$E_{out}(w) = T(w)\,E_{in}(w) \tag{2}$$

where T(w) is the Jones matrix or Transfer matrix.

Sometime PDL [13] is defined as

$$PDL = \Gamma = \frac{T_{\max} - T_{\min}}{T_{\max} + T_{\min}} \tag{3}$$

Also PDL in dB is $PDL_{dB} = 10\log\left[\frac{T_{\max}}{T_{\min}}\right]$ (4)

where T_{max} and T_{min} are the maximum and minimum transmission coeffecients.

The effective pulse broadening is a measure to describe the effect of PMD on the basis of a single pulse. Using root mean square values, the effective pulse broadening τ_{eff} [14] is given by

$$\tau_{eff}^2 = \tau_{out}^2 - \tau_{in}^2 \tag{5}$$

Here τ_{in} is the input pulse width and τ_{out} is the output pulse width.

The input and output power is defined as

$$P_{in}(t) = |E_{in}(t)|^2 \tag{6}$$

$$P_{out}(t) = |E_{out}(t)|^2 \tag{7}$$

Now, the input and output pulse width is given as

$$\tau_{in}^2 = \frac{\int_{-\infty}^{\infty} t^2 P_{in}(t)dt}{\int_{-\infty}^{\infty} P_{in}(t)dt} - \left[\frac{\int_{-\infty}^{\infty} tP_{in}(t)dt}{\int_{-\infty}^{\infty} P_{in}(t)dt}\right] \tag{8}$$

$$\tau_{out}^2 = \frac{\int_{-\infty}^{\infty} t^2 P_{out}(t)dt}{\int_{-\infty}^{\infty} P_{out}(t)dt} - \left[\frac{\int_{-\infty}^{\infty} tP_{out}(t)dt}{\int_{-\infty}^{\infty} P_{out}(t)dt}\right] \tag{9}$$

In order to estimate the changes in pulse width, the ratio of the full width half maximum of the Input pulse to the compressed pulse is defined as the Compression Factor [15] and is given by

$$F_c = \frac{T_{FWHM}}{T_{comp}} \tag{10}$$

and

$$PWR = \frac{output\ pulsewidth}{input\ pulsewidth} \tag{11}$$

Here PWR represent the Pulse Width Ratio and Effective Compression Ratio which measures the pulse degradation is defined as

$$Compression\quad Ratio = \frac{input\quad pulsewidth - output\quad pulsewidth}{input\quad pulsewidth} \tag{12}$$

3. System model

3.1. General system setup

Laser drive was turned on to produce a train of linearly chirped super-gaussian pulse with peak power 2mw, 50ps pulse width at a wavelength of 1550nm is propagated through a single mode fiber of length 100km. A fiber link is considered as a concatenation of N birefringent fiber segment. Segment length depends on the fiber length. Here in each segment we consider concatenation of a uniform PMD element with a PDL element. Fig. 1 represent an optical transmission system trained using Levenberg-Marquardt Algorithm.

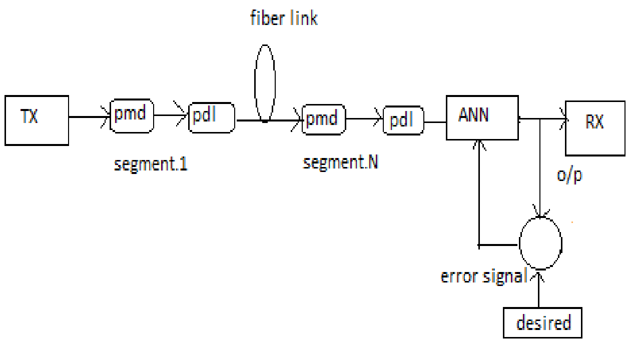

Fig. 1. System model of an optical fiber link with ANN

Optical pulse propagation within the fiber is simulated by numerically solving the Nonlinear Schrondinger Equation using Split Step Fourier Method(SSFM) [16]. SSFM computes the evolution of pulse in the frequency domain. Then Fourier transforms the result in time domain. Broadened pulse width at the fiber end can be controlled by varying the launch angle of an input signal. PMD, PDL and nonlinear effects are considered in the simulation. In SSFM fiber is divided into small portions and then nonlinearity is considered at the center of the segment while linear term such as PMD and PDL at two halves.

Resulting output pulse is found by the convolution of super-gaussian pulse shape with linear term. This is performed in the frequency domain. Then again by transforming back into time domain and multiplying this by nonlinear term, the output pulse at the end of first segment is found. This is repeated for N segment. Here Pulse compression and broadening at the fiber output mainly depend on Chirp, PMD and PDL and also on the launch state of polarization. The 50ps input pulse was broadened with a nearly linear chirp across the entire pulse. Pulse broadening reduces the peak power substantially. This leads to fading in the coherent and direct detection system.

The states of polarization of the input pulse are varied. Initially the input linearly polarization of the chirped supergussian pulse can be written as

$$A_{in}(t) = \sqrt{P_O}\,\exp\left[\frac{-1+iC}{2}\left(\frac{t}{\tau_{in}}\right)^{2m}\right]\begin{bmatrix}\cos\theta_{in}\\ \sin\theta_{in}\end{bmatrix} \tag{13}$$

where P_o is peak optical power, C is chirp parameter, τ_{in} is the input pulse width, m is the super-gaussian parameter, θ_{in} is the input launch angle($\pi/4$).

As the signal propagates, in each segment of a fiber, the polarized component has a random rotation and a random phase shift. This can be represented mathematically by a frequency dependent transfer matrix T(w) which transforms the two orthogonally polarized components of the input signal into the corresponding output ones [17].

$$A_{out}(w) = T(w)A_{in}(w) \tag{14}$$

$$T(w) = \prod_{n=1}^{N} B_n(w)R(\alpha_n) \tag{15}$$

$$T(w) = \prod_{n=1}^{N}\begin{bmatrix} e^{j(\sqrt{3\pi/8}\,bw\sqrt{h_n}/2+\phi_n)} & 0 \\ 0 & e^{-j(\sqrt{3\pi/8}\,b\,w\sqrt{h_n}/2+\phi_n)}\end{bmatrix}\begin{bmatrix}\cos\alpha_n & \sin\alpha_n\\ -\sin\alpha_n & \cos\alpha_n\end{bmatrix} \tag{16}$$

where N is the number of segments

$B_n(w)$ represents the birefringence matrix of the n^{th} segment with h_n length.

$R(\alpha_n)$ is the matrix of a rotator that represent the random coupling angle between the segment axes.

b is the PMD coefficient of the fiber in ps/$\sqrt{km}$

w is the optical frequency.

ϕ_n is the random phase shift in the n[th] section.
The angle of random rotation and phase shift are chosen in [0,2π].

The input circular polarization of the chirped super-gaussian pulse can be written as

$$S_{in}(t) = \sqrt{P_O}\,\exp\left[\frac{-1+iC}{2}\left(\frac{t}{t_o}\right)^{2m}\right]\begin{bmatrix}1\\ 1e^{j\frac{\pi}{2}}\end{bmatrix} \qquad (17)$$

Similarly the output in frequency domain for circular SOP is obtained as

$$S_{out}(w) = T(w)H_{in}(w) \qquad (18)$$

At the end of the link, it is clear that the linear state of polarization is more distorted and broadened as compared to circular state of polarization. Fluctuated output signal is given at the input end of the ANN and is trained using Levenberg-Marquardt Algorithm. This results in a better quality compressed pulse and larger compression factors.

A significant improvement in pulse narrowing is achieved using ANN. This control of pulse shape has become important in numerous optical fields such as coherent control, ultrafast spectroscopy and high field physics.

3.2 Artificial Neural Network

The basic architecture is Multilayer Perceptron type consisting of an input layer, one output layer and one or more hidden layers. The neurons of every layer are joined to the next layer neurons by some weight. An efficient training algorithm is required after designing the network with a suitable architecture and different hidden neurons.

The purpose of training a network is to minimize errors among the output and the target. Through training, weights and some stable values called bias are modified continuously in order to ensure minimum error. Further, transfer function is used to transfer, output of every layer to the next layer. Tansig and Sigmoid was selected as the transfer function that yielded best results. For fast and efficient training, Levenberg Marquart Training Algorithm is used to train the network.

Due to Levenberg and Marquardt, Levenberg-Marquart method is a compromise between the Newtons method and Gradient descent method. Newton method converges rapidly near a global minimum, but may also diverge. The Gradient descent method, is assured of convergence through a proper selection of the step size parameter but convergence is a slow process [18].

Levenberg-Marquardt algorithm is designed specifically for keeping the sum of squared errors to the minimum. Here the problem is addressed by seeking to minimize the error function while at the same time trying to keep the step size small so as to ensure validity of the linear approximation [19].

4. Results and discussion

Super-Gaussian pulses with positive and negative chirping are transmitted at two different input states of polarization with frequency of 193THz for initial pulse width of 50ps and input power of 2mW. Since PMD and PDL limits the bit rate and induces random fluctuations in the signal, computer solutions are often necessary to mitigate this limitation in order to improve the system performance. Pulse width analysis is carried out for linear and circular states of input polarization.

Positive chirped super-gaussian pulse with C=1,2 and m= 3 is propagated through the fiber and the presence of PMD and PDL is seen leading to pulsewidth broadening and reduction in signal amplitude. When negative chirped super-gaussian pulse with C= -1, -2 and m=3 is transmitted through the optical link, pulse get affected and two peaks are observed at the output end. Then the deformed output pulse is given as input to ANN and is trained using Levenberg-Marquardt algorithm where pulsewidth broadening and distortion can be minimized. Various values of PMD, PDL and Chirp are shown in Table 1.

Table 1. Shows the various impairments and the corresponding range

Impairements	Value range
PMD	[0.2 : 1.2] ps/ $\sqrt{km}$
PDL	[0.2 : 0.8]dB
Chirp	[-2 : 2]

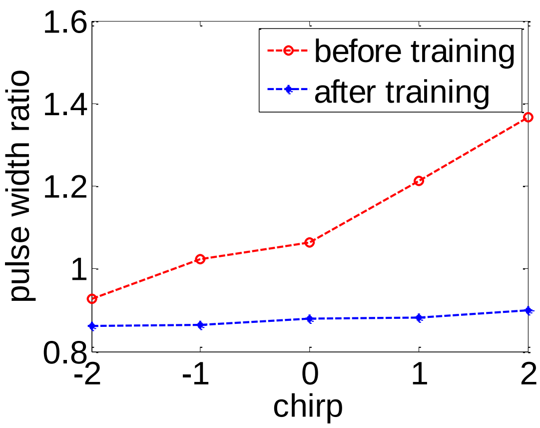

Fig. 2. Pulse width ratio for linear state of polarization

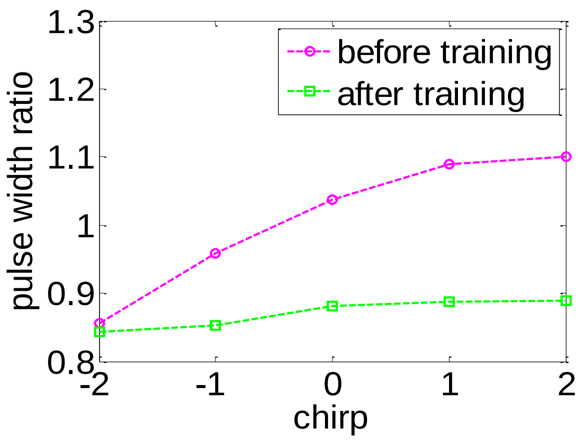

Fig. 3. Pulse width ratio for circular state of polarization

Fig. 2 corresponds to Linear state of polarization and Fig. 3 corresponds to a circular state of polarization. The Pulse width ratios for various chirp values are presented here. The figures show the curve going up before training when the chirp is positive and this amount of pulse broadening is high for linear as compared to circular state of polarization. It is observed that through Levenberg Marquardt training algorithm, pulse width ratio reaches a minimum and the pulse width or broadening ratio less than one indicates no broadening at all.

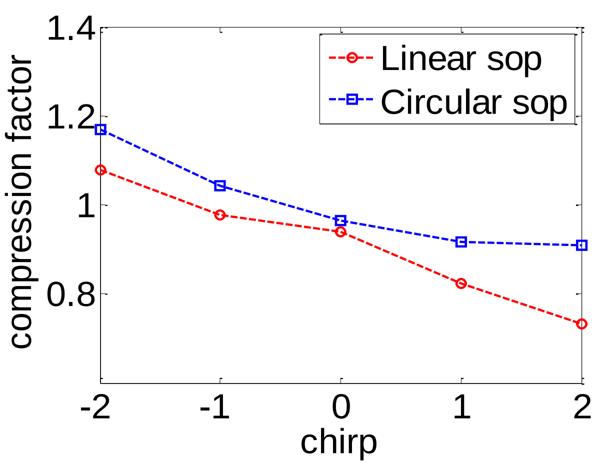

Fig 4. Compression factor for different state of polarization

Fig. 4 shows the compression factor for various values of chirp parameter. As expected, positive chirp leads to decrease in compression factor. Also maximum compression factor is obtained for circular state of polarization instead of a linear state of polarization through LM training. This indicates a significant improvement in compression factor can be achieved using Levenberg-Marquardt algorithm.

Table 2. Shows the pulse width ratio for different values of chirp parameter

Training Method	SOP	Super-Gaussian parameter (m)	chirp (C)	Pulse Width Ratio	
				Before Training	After Training
Levenberg Marquardt	Linear	3	-2	0.9266	0.8624
		3	-1	1.0239	0.8631
		3	0	1.0642	0.8807
		3	1	1.2128	0.8825
		3	2	1.3670	0.8991
	Circular	3	-2	0.8557	0.8440
		3	-1	0.9585	0.8522
		3	0	1.0367	0.8807
		3	1	1.0902	0.8870
		3	2	1.1009	0.8899

Table 2 illustrates the pulse width ratio before and after training. Before training , the pulse is most broadened i.e., maximum Pulse Width Ratio(1.3670) is obtained for Linear SOP whereas PWR(1.1009) with Circular state of polarization and by using Levenberg Marquardt method, maximum pulse width reduction of 15.6% is achieved through training and the output pulse width is only 84.4% of the input pulse.

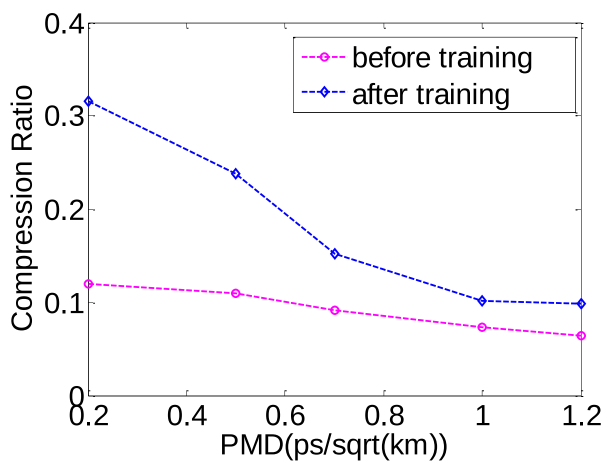

Fig. 5. Compression ratio for various values of PMD

PMD coefficients are varied up to 1.2 ps/ $\sqrt{km}$ and compression ratio for various values of PMD are generated. Fig. 5 shows the compression ratio decreasing as PMD value increases. The result shows that ANN with Levenberg Marquardt training can increase the compression ratio.

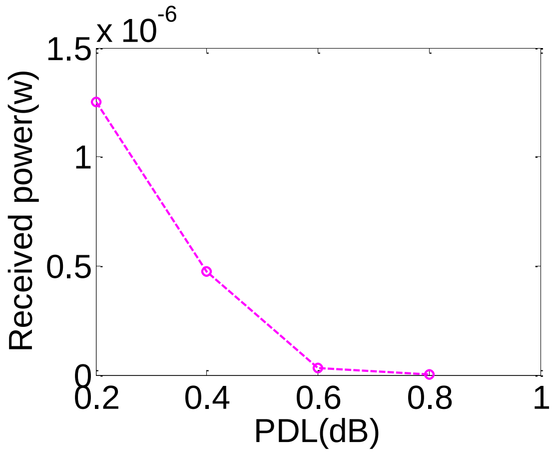

Fig. 6. Received power for various PDL values

Fig. 6 shows received peak power decreasing with increase in PDL. Several components of optical systems such as isolators, couplers possess more than 0.2 dB PDL. However with training, the amount of received power is high for lower PDL values.

5. Conclusion

The Impact of Polarization Mode Dispersion and Polarization Dependent Loss on positive and negative chirped super-gaussian optical pulse can be viewed in the form of pulse splitting, peak power reduction and pulse stretching. Simulation results show compression factor, pulse broadening ratio and compression ratio being found in order to determine the changes in the pulse width. Maximum pulse compression was observed for a light launched with circular states of polarization through Levenberg-Marquardt training which improves the system performance.

References

[1] Ping Lu, Liang Chen, Journal of Light Wave Technology, **19**(6), (2001).
[2] Mark Shatif, Antonio Mecozzi, IEEE Photonic Technology Letters, **16**(2), (2004).
[3] Hessan Abid Yasser, Nizar Salim, International Journal of Optics, volume 2013.
[4] Liang Chen, Maurino Yanez, Journal of Light Wave Technology, **19**(6), (2001).
[5] Yaguang Yang, Erin Sahinci, International Journal for Light and Electron Optics, **114**(8), 365 (2003).
[6] Jeffrey A. Jargon, Xiaoxia Wu, IEEE Photonic Technology Letters, **21**(1), 54 (2009).
[7] Wabnitz, Turitsyn, Journal of Light Wave Technology, **30**(15), 2494 (2012).
[8] Toshihiko Hirooka, Koudai Harako, Journal of Light Wave Technology, **31**(5), 809 (2013).
[9] A. Steinkamp, S. Vorbeck, Proceedings of SPIE-Ihe International Society for Optical Engineering, **5596**, 10 (2004).
[10] Tiago Mota, Jorgean Leal, International Journal of Communication, Network and System Sciences, 71 (2014).
[11] Liang Chen, Xiaoyi Bao, Journal of Lightwave Technology, **18**(5), (2000).
[12] Ping Lu, Liang Chen, Optic communication-2003 (243-248).
[13] N. Gisin, Optics Communication **114**, 399 (1995).[14] Tobias Graveman, Jens, Edger Voges, IEEE Photonics Technology Letters, **16**(3), (2004).
[15] Govind P. Agrawal, “Applications of Nonlinear Fiber Optics”, 2006.
[16] A. O. Dalforno, A. Paradisi, IEEE Photonic Technology Letters, **12**(3), (2000).
[17] Govind P. Agrawal. “Fiber -Optic Communication Systems”, John Wiley and Sons(Asia) Pvt Ltd., third edition, 2002.
[18] Simon Hayhin, Third Edition , Pearson Publication 2009.
[19] Christopher M. Bishop, “Neural Networks for Pattern Recognition”, Oxford University press, 2006.

*Corresponding author: vinpriyabala@gmail.com