

Analysis of PMD and PDL effect on Chirped Gaussian and SuperGaussian pulse shapes by controlling SOP in SMF

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Abstract— In this paper, a numerical analysis of impairments due to PMD and PDL on system performance is investigated in High Speed Optical Communication System. Optical Polarization has pronounced effect on signal quality. Thus there is a need to control the State of Polarization (SOP). Pulse Broadening can be controlled by launching the light signal in particular State of Polarization such as Linear and Circular. Two types of Pulses such as Chirped Gaussian and Supergaussian pulses are launched at different SOP into the optical fiber and it is found that maximum pulse width reduction is achieved when the pulse is at Circular SOP than that of Linear SOP. Also results clearly show that with PMD and PDL, pulse width ratio of Chirped Gaussian pulse is much reduced than that of Chirped Supergaussian Pulse.

Keywords- States of Polarization (SOP), Polarization Mode Dispersion (PMD), Polarization Dependent Loss(PDL), Split Step Fourier Transform(SSFM)

I. INTRODUCTION

The Polarization related impairments have become a major barrier for Long Haul Optical Communication System. Impairments include Polarization Mode Dispersion (PMD) in optical fibre due to Manufacturing defect and Environmental changes, Polarization Dependent Loss (PDL) in Passive Optical Components such as Isolator, Circulator and Polarization Dependent Gain (PDG) in Optical Amplifiers. Presence of Polarization Mode Dispersion (PMD) and Polarization Dependent Loss (PDL) in optical fibres reduces the network performance particularly those network operating at high data rates. In a perfect fibre, the State of Polarization (SOP) inside the fibre remains constant and the effect of PMD, PDL and PDG could be easily destroyed.

Polarization Control is necessary to enhance the Optical Signal to Noise Ratio (OSNR) at the receiver in Coherent Detection Systems and to mitigate PMD in Optical Communication System. Although Free Space Optical Communication are needed for certain applications and have been studied extensively, most terrestrial applications make use of Fibre Optic Communication Systems. Fibre Optic Communication Systems have been developed for telecommunication applications. The telecommunication applications can be broadly classified into two categories, Long Haul and Short Haul, depending on whether the optical signal is transmitted over relatively long or short distances [1].

Interaction of the second order PMD component with the Chromatic Dispersion and Chirp will cause a broadening/narrowing and shape distortion. However the problem is very small for $C=0$, while the variation of pulse shape will be large for $C \neq 0$ [2]. To estimate the extent of pulse broadening in SMF, an analytical expression for the pulse broadening is obtained and they found that the pulse broadening induced by dispersion fluctuation can be large at high bit rates and the effect of third order dispersion is also significant at high bit rate.[3]

A combination of PMD and PDL in optical fiber may lead to anomalous pulse broadening. A mathematical description is put forward, where PMD is evaluated in the presence of XPM, PDL and chirp. Simulation shows that the delay of a chirped Gaussian pulse depends not only on PDL, but also on the chirp of the pulse itself [4]. The nature of how Chirped Gaussian Pulse is affected in the system with PMD and PDL is analyzed [5]. They showed that the delay of chirped Gaussian pulse depends not only on the group delay characteristics of the transmission system but also on the chirp of the pulse itself. The combined effect of PMD and PDL on pulse broadening in optical transmission links for both PMD uncompensated and compensated system are investigate by Numerical Simulation [6]. A multivariable search algorithm capable of finding optimum values of angle describing the input linear polarization, input frequency and PDL that influence pulse narrowing is presented and compared with single variable search algorithm [7].

In this paper, pulse width ratio for Gaussian and Supergaussian pulses are determined for different values of chirp parameter and it is found that the maximum pulse compression is obtained for chirped Gaussian pulse. Also system performance with PMD and PDL for different States of Polarization is analyzed at the end of

fiber and it is observed that linear SOP is more broadened as compared to Circular SOP.

II. SYSTEM MODEL

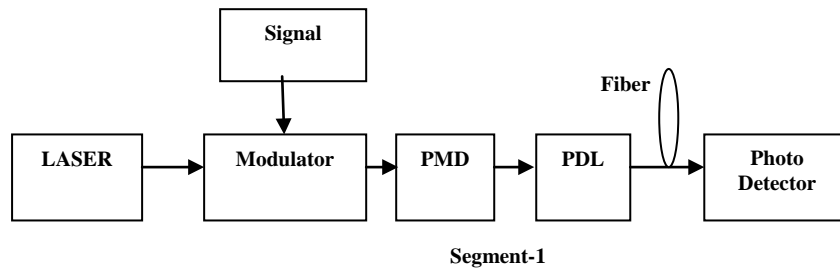


Fig.1 General model of an optical communication system

The analytical treatment of PMD is quite complex because of its statistical nature. Hence a numerical simulation is carried out on optical communication system and such a system must first be modelled by dividing the fibre into a large number of segments. The system consists of an optical transmitter, optical fibre and a photo detector. Fig .1 shows a model of general optical communication system. The pulses from the transmitter are assumed to be chirped Gaussian or Super Gaussian with a pulse width of 50ps and wavelength of 1550nm, input power of 2mW were propagated through a 500km long fibre.

A. POLARIZATION MODE DISPERSION (PMD)

Polarization Mode Dispersion is a dispersion effect occurring inside optical fibres, which can cause the optical receiver to be unable to interpret the signal correctly and can decrease the fibre optic networks performance, particularly those networks operating at high data rates. Single-mode optical fibre support one fundamental mode, which consists of two orthogonal polarization modes and they move toward the receiver at right angles to each other.

Due to the manufacturing defect, asymmetry in the fibre core introduces small refractive index differences for the two polarization states. This difference in refractive index is known as birefringence. The birefringence causes one polarization mode to travel faster than the other, resulting in a difference in the propagation time, which is called the Differential Group Delay (DGD) [8]. DGD is usually measured in picoseconds and is denoted as $\Delta\tau$. The mean value of DGD is PMD. The difference can also change the state of polarization (SOP) of the light as it travels along the fibre.

$$PMD = \frac{\Delta\tau}{\sqrt{L}} \text{ ps} / \sqrt{\text{km}} \quad (1)$$

where L is the length of the fiber.

B. POLARIZATION DEPENDENT LOSS (PDL)

Signal Loss in the fiber depends upon polarization state of signal. Hence, any changes in polarization states will change the signal power along the fiber and optical power goes on decreasing due to fiber loss. PDL is defined as the ratio of the maximum and the minimum transmission or Intensity of an optical device with respect to all polarization states [9].

$$PDL = 10 \log \left(\frac{T_{\max}}{T_{\min}} \right) (\text{dB}) \quad (2)$$

where T is the optical transmittance or power taken over the entire polarization-state space.

Fibre bending, Fibre Coupling are some of the causes of PDL. The impact of PDL on system performance is random fluctuation in the signal and consequently, bit-error-rate is increased.

C. CHIRPED GAUSSIAN PULSE

Output power emitted from light source for each wavelength is approximately Gaussian distribution in form. The term Gaussian refers to envelope of the launched pulse. Assumption of Gaussian envelope is mostly for mathematical convenience. The Gaussian pulse after propagating a distance, its frequency is not constant but is chirped. A pulse is said to be chirped if its carrier frequency changes with time. Fig.2 shows the chirped Gaussian pulse.

Consider the propagation of chirped Gaussian pulse inside an optical fiber at $Z = 0$ and its electric field is given as

$$A(0,t) = \sqrt{P_0} \exp\left[\frac{-1 + iC\left(\frac{t}{t_0}\right)^2}{2}\right] \quad (3)$$

where C represents the chirping parameter, P₀ is the peak power of the incident pulse and t₀ is the pulse width.

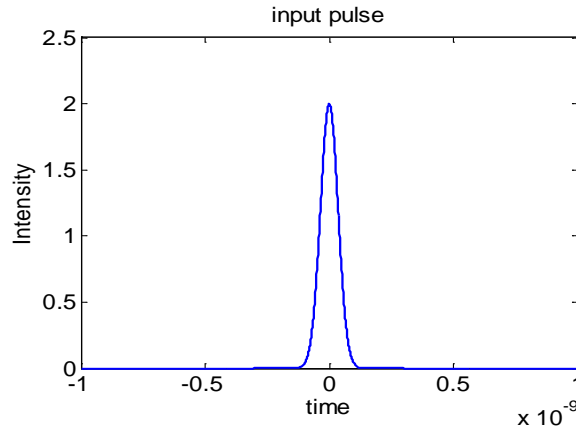


Fig.2 Chirped Gaussian Pulse

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 1x2 Jones vectors which describe the SOP, and 2x2 Jones matrices which describe the transmission media. Jones vector and matrix are smaller in size, and they describe the field directly. [10]

Each section is randomly rotated and random phase shift is added between two polarized component of the signal. Angle of rotation and phase shift are chosen in (0,2π).

The resultant Jones or transfer matrix T(w) is

$$T(w) = \prod_{n=1}^N \begin{bmatrix} e^{j(\sqrt{3\pi/8} D_{PMD} w \sqrt{h_n} / 2 + \phi_n)} & 0 \\ 0 & e^{-j(\sqrt{3\pi/8} D_{PMD} w \sqrt{h_n} / 2 + \phi_n)} \end{bmatrix} \begin{bmatrix} \cos \theta_n & \sin \theta_n \\ -\sin \theta_n & \cos \theta_n \end{bmatrix} \quad (4)$$

where

N – no of sections

h_n – length of the nth section

φ_n – random phase shift in the nth section

θ_n – random orientation of the birefringent axes of the nth section

System performance at the end of the fiber can be analyzed by launching the chirped Gaussian input pulse at different States of Polarization.

If a Linearly polarized signal is launched into an optical fiber the output electric field is given as

$$A_{out}(w) = T(w) \begin{pmatrix} \cos \theta_{in} \\ \sin \theta_{in} \end{pmatrix} A_{in}(w) \quad (5)$$

where A_{in}(w) is the Fourier transform of A(z,t), θ_{in} is the input polarization angle.

If a Circularly Polarized signal is launched into an optical fibre, the output electric field can be written as

$$A_{out}(w) = T(w) \begin{pmatrix} 1 \\ 1e^{j\frac{\pi}{2}} \end{pmatrix} A_{in}(w) \quad (6)$$

Here $A_{out}(w)$ is the output pulse obtained at the end of the fiber.

D. CHIRPED SUPERGAUSSIAN PULSE

In practice, optical pulses are often non-Gaussian. A Super Gaussian pulse with steep leading and trailing edges has been used to study the system performance. The sharpness of the edges plays an important part in the broadening ratio.

For an incident Chirped Supergaussian pulse the Electric field can be written as

$$E(0,t) = \sqrt{P_o} \exp\left[\frac{-1 + iC}{2} \left(\frac{t}{t_o}\right)^{2m}\right] \quad (7)$$

where the parameter m controls the pulse shape. Chirped Gaussian pulse correspond to $m=1$. For higher values of m i.e. $m>1$ the pulse become Supergaussian(rectangular) with sharper leading and trailing edges.[11]

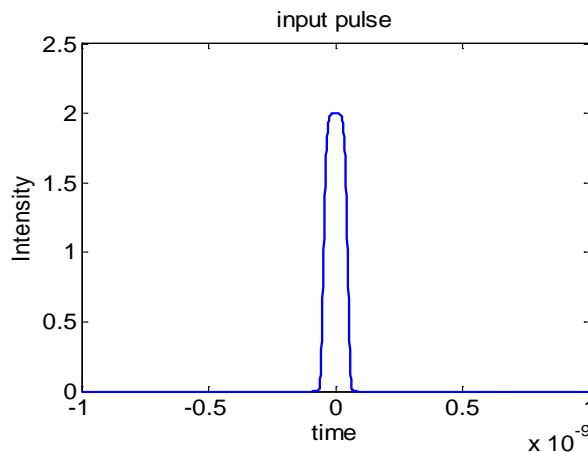


Fig.3 shows the Supergaussian pulse for $m=2$

Here m is related with rise time T_r .

$$T_r = \frac{t_0}{m} \quad (8)$$

Chirp C may be positive or negative. Frequency increases (positive or up chirp) or decreases (negative or down chirp) with time.

Here Chirped Supergaussian pulse is propagated at different states of polarization.

First Linearly Polarized signal is incident and the output at the end of the fibre is obtained as

$$E_{out}(w) = T(w) \begin{pmatrix} \cos \theta_{in} \\ \sin \theta_{in} \end{pmatrix} E_{in}(w) \quad (9)$$

Next the output at the fibre end is obtained by launching Circularly Polarized signal and is given as

$$E_{out}(w) = T(w) \begin{pmatrix} 1 \\ 1e^{j\frac{\pi}{2}} \end{pmatrix} E_{in}(w) \quad (10)$$

III.RESULTS AND DISCUSSION

Here we have considered two types of pulses which are Gaussian Pulse and Super Gaussian Pulse. Optical pulse propagation in single mode fibre is described by Coupled Nonlinear Schrödinger Equation [12] and is given as

$$\left[\frac{\partial}{\partial z} + \frac{\alpha_{x,y}}{2} + \beta_{1,x,y} \frac{\partial}{\partial t} - i \frac{\beta_2}{2} \frac{\partial^2}{\partial t^2} \right] A_{x,y}(t, z) = -i\gamma \frac{8}{9} [|A_{x,y}(z, t)|^2 + |A_{y,x}(z, t)|^2] A_{x,y}(t, z) \quad (11)$$

The different terms in the equation describe the different effects like PMD, GVD, PDL and Nonlinearity .Nonlinear effect depend on the transmission length. Longer the fibre more the light interacts with the fibre material and greater the nonlinear effect. In the above equation A represents the slowly varying amplitude of the pulse envelope and is split into linear and nonlinear equations.

The Coupled Nonlinear Schrödinger Equation cannot be solved analytically in general. They have been numerically simulated using Split Step FFT Algorithm. This algorithm divides the optical fiber into many small sections of equal size in which the dispersion and nonlinearity can be considered separately in the frequency domain and time domain. Fig.4 shows the simulation model for one section.

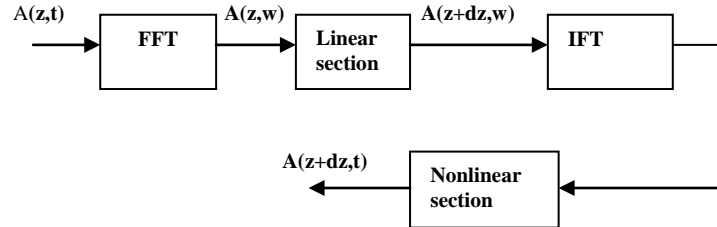


Fig.4 fibre section from z to dz.

To find the pulse amplitude at the end of single section from z to dz, first the fibre is modelled as a concatenation of Linear and Non linear sections where Fast Fourier Transform (FFT) and Inverse Fourier Transform (IFT) are taken. This is repeated for the entire fiber length and the system performance can be analysed.

Chirped Gaussian and Supergaussian pulses are propagated inside optical fiber. Fig.5 illustrates the pulse width ratio for different states of polarization. Whether the pulse shall spread or not depends on how one launches the input pulse i.e. the input SOP.

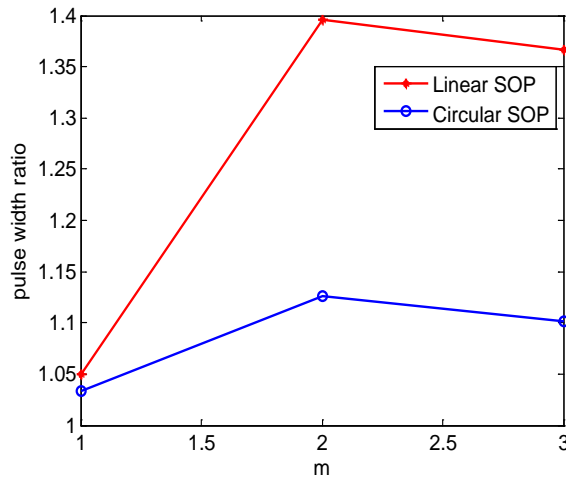


Fig.5 pulse width ratio for different SOP

Pulse width ratio is obtained for different values of m. Here m=1 represents Chirped Gaussian pulse and m > 1 represents supergaussian pulse. A comparison of pulse width ratio is done by launching the input at different states of polarization such as Linear and circular. Pulse width reduction is achieved for a PMD of 1ps, a PDL of 0.2dB, Nonlinear coefficient $\gamma=1.32W^{-1}/km$, and an input pulse width of 50ps in circular state of polarization. Numerical simulations show that the pulse width ratio is minimum for different values of m in Circular state of polarization and increases for Linear SOP.

From the Table-I, for a PMD of 1ps, a PDL of 0.2dB, C=2 and an input pulse width of 50ps, pulse width ratio is obtained for different values of m at linear and circular states of polarization.

TABLE-I

Comparison of pulse width ratio for Linear and Circular SOP

| SOP | PMD ps/km ^{0.5} | PDL (dB) | Chirp (C) | m | Pulse Width Ratio |
|----------|-----------------------------|-------------|--------------|---|-------------------------|
| Linear | 1 | 0.2 | 2 | 1 | 1.0496 |
| | | | | 2 | 1.3964 |
| | | | | 3 | 1.3670 |
| Circular | 1 | 0.2 | 2 | 1 | 1.0331 |
| | | | | 2 | 1.1261 |
| | | | | 3 | 1.1009 |

Fig.6 illustrates the pulse width ratio of Gaussian and Supergaussian pulses. Results clearly show that for both the pulses, if the chirp factor increases pulse width increases whereas when chirp factor decreases, pulse width is compressed. For C = -2 i.e. negative chirped pulse, there is no considerable difference in pulse width ratio is observed for various input pulses whereas the pulse width ratio increases for positive chirped pulse.

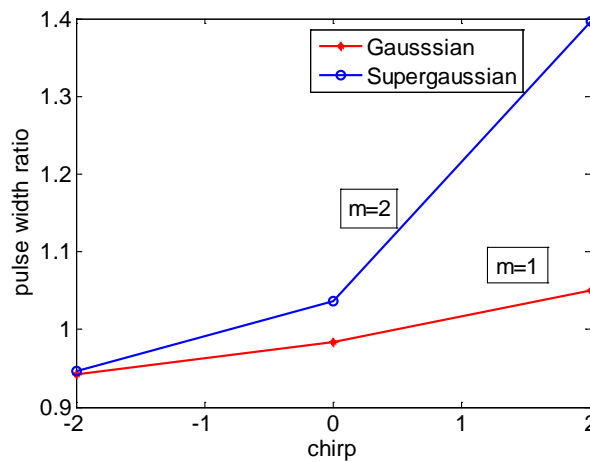


Fig.6 pulse width ratio of Gaussian and Supergaussian pulse with different Chirp

Table-II illustrates the pulse width ratio with various chirps. Here a maximum pulse width reduction of around 5.8 % is achieved for C= -2 i.e. output pulse width is only about 94.2 % of the input pulse at C = -2. Chirped Supergaussian pulse with C = 2 have most broadened pulse width ratio (1.3964). Pulse width ratio of 1.000 is not broadened at all. Chirped Gaussian pulse with C = -2 have pulse width ratio (.9421) slightly narrower than the input pulse.

TABLE-II

Comparison of the Gaussian and Supergaussian pulse widths after propagation through a fiber with PMD and PDL for various values of Chirp

| Pulse Type | m | PMD ps/km ^{0.5} | PDL (dB) | Chirp (C) | Pulse Width Ratio |
|----------------------|---|-----------------------------|-------------|----------------|-------------------------|
| Gaussian pulse | 1 | 1 | 0.2 | -2 | 0.9421 |
| | | | | 0 | 0.9835 |
| | | | | 2 | 1.0496 |
| Super gaussian pulse | 2 | 1 | 0.2 | -2 | 0.9459 |
| | | | | 0 | 1.0360 |
| | | | | 2 | 1.3964 |

IV.CONCLUSION

Pulse Width plays an important role on the pulse broadening/narrowing in a system distorted by PMD and PDL. In an earlier work, the behavior of Chirped Gaussian pulse with PMD and PDL is analyzed. Here comparison of the Chirped Gaussian and Supergaussian pulses with PMD, PDL and Nonlinearity is done and it is found that by adjusting the States of Polarization, output pulse width can be controlled. Also pulse width is small for negative chirped pulse, while it is larger for positive chirped pulse. However it is clear that negative chirped Gaussian pulse with Circular State of Polarization is narrower at the output than they were at the input of the system and hence the best results are noted for Chirped Gaussian Pulse with Circular SOP.

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