Analysis of Chirp Induced Impairments in Fiber Optic Transmission Systems Using Various Types of Fiber

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Abstract—For the high bit rate, large capacity multi-channel fiber communications the group velocity dispersion (GVD), non-linearity and loss effect has a great impact on the performance of fiber optic communication. On the other hand chirping plays an important role on pulse broadening. This paper represents an analytical model of pulse broadening factor with chirping and first order group velocity dispersion. For different values of chirping parameter the pulse broadening factor is analyzed for different bit rates and fiber parameters. Results showed that chirping has a significant impact on pulse broadening. For negative chirping there is no pulse compression and when the bit rate of the system increases the pulse broadens more with the fiber length and limits the system performance. Results showed that large effective area fiber (LEAF) shows better performance than standard single mode fiber (SSMF) and non-zero dispersion shifted fiber (NZDSF).

Keywords—GVD, SSMF, LEAF, NZDSF

I. INTRODUCTION

Group velocity dispersion (GVD) is one of the main factors limiting transmission length in high bit rate optical transmission system. When the fiber length is such that L < LNL but L > L0 then the pulse evolution is governed by group velocity dispersion. In this case the nonlinear effect is less [1]. Most analytical expression showing the pulse broadening effect considering the Gaussian pulse envelope as input when considering first order GVD [2]. The first order GVD effects with various chirp parameter is shown mostly [2]. Analysis showed that a chirped Gaussian pulse broadens monotonically but at a rate faster than that of un-chirped pulse. In different dispersion regimes the un-chirped and chirped Gaussian pulse propagation comparison is shown [3]. Most of the methods do not show the chirped Gaussian pulse behavior for various data rates with the different fiber parameters [4]. One approach to evaluate the performance of optical fiber link is to analyze the pulse broadening caused by different factors and how to compensate this broadening effect [5]. In this research paper, investigation has been carried out to find pulse broadening factor by solving nonlinear Schrödinger equation (NLSE), considering the first order GVD with the chirped Gaussian pulse propagation at various data rates as a function of transmission distance using different fibers. Next, for different fiber parameters the pulse broadening effects are analyzed for various positive and negative chirping values at different data rates.

II. THEORETICAL BACKGROUND

If Gaussian input pulse is chirped prior to transmit it into the fiber then for the different chirp parameter they show interesting behavior when considering first and second order GVD. A chirped Gaussian pulse is mathematically represented by:

\[ A(0, T) = \exp \left( (1 + iC) \frac{\gamma}{\omega_0} \right) \]  

Where, C illustrates the chirp parameter which may be negative or otherwise. If \( \omega_0 = 0 \), this equation will reduce to un-chirped Gaussian pulse.

The fiber loss, GVD and nonlinearity effects occur simultaneously during the propagation of an optical pulse. The effects of these parameters can be modeled using the nonlinear Schrödinger equation [1],

\[ \frac{\partial A}{\partial z} + i \frac{\partial^2 A}{\partial T^2} \left( \frac{n_2 \alpha}{C A_{eff}} \right) + \frac{1}{2} \frac{\partial^3 A}{\partial T^3} + \frac{\alpha(z)}{2} A = i \gamma |A|^2 A \]  

Where \( A \) is the slowly varying amplitude of the pulse envelope; \( i \) is the imaginary vector; \( \alpha \) is the fiber loss, \( \frac{n_2 \alpha}{C A_{eff}} \) represents the nonlinear effect where \( n_2 \) represents the carrier frequency, \( c \) is the velocity of light, \( n_2 \) is the nonlinear refractive index and \( A_{eff} \) is the effective cross-sectional area of the fiber and \( \beta_2, \beta_3 \) represents the first and second order GVD effects respectively; \( T \) is measured in frame of reference moving with the pulse at the group velocity \( v_g(T) = \frac{dZ}{d\omega} \) and \( z \) is the propagated distance. In equation (1), the effect of GVD is included through dispersion parameter that is related to \( \beta_2 = (-\Delta \lambda^2)/(2\pi c) \) where \( \Delta \lambda \) is the operating wavelength, \( D \) is the dispersion parameter and \( c \) is the velocity of light in free space. If we use the normalized amplitude \( A(z, T) \) then we can write the linear partial differential equation in the form,

\[ \frac{\partial A}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 A}{\partial T^2} \]  

If \( \tilde{A}(z, \omega) \) is the Fourier transform of \( A(z, T) \), then,

\[ A(z, T) = \int_{-\infty}^{+\infty} \tilde{A}(z, \omega) \exp(-i\omega T) \, d\omega \]
The above equation satisfies an ordinary differential equation,
\[
\frac{d^2 A}{dz^2} = \frac{1}{2} \beta \omega^2 A
\]  
(5)
whose solution is :
\[
\tilde{A} (z, \omega)=\tilde{A} (0, \omega) \exp\left(\frac{i}{2} \beta \omega^2 z\right) 
\]  
(6)
This equation (6) shows that phase of each spectral component of the pulse changes due to GVD. Using equation (6) in (4) the general solution of (2) is,
\[
A(z,T)=\frac{1}{2\pi} \int_{-\infty}^{+\infty} \tilde{A}(0,\omega) \exp\left(\frac{i}{2} \beta \omega^2 z - i\omega T\right) d\omega
\]  
(7)
Where \( \tilde{A} (0, \omega) \) is the Fourier transform of the incident field at \( z=0 \) and is found by,
\[
\tilde{A} (0, \omega) = \frac{1}{\sqrt{1+iC}} \int_{-\infty}^{+\infty} A(0,T) \exp\left(-\frac{it^2}{2} \right) T_0 \exp\left(-\frac{t^2}{2} \right) dT
\]  
(8)
By substituting equation (1) in (8) \( \tilde{A} (0, \omega) \) is given by,
\[
\tilde{A} (0, \omega) = \tilde{A} (0, \omega) \exp\left(-\frac{im^2 \omega^2 t^2}{2(1+iC)} \right)
\]  
(9)
Here, \( a = \frac{1 + iC}{2T_0^2} = -i\omega \)  
As for a general quadratic exponent we know,
\[
\int_{-\infty}^{+\infty} \exp\left[-(ax^2 + bx + c)\right] dx = \sqrt{\frac{\pi^2}{a}} \exp\left(-\frac{b^2 A \pi}{4\alpha} \right)
\]  
(10)
To obtain the launched field ,put \( \tilde{A} (0, \omega) \) from (9) to (7). The integration can be performed analytically using (10),
\[
A(z,T) = \frac{T_0}{\sqrt{T_0^2 - \beta^2 T^2(1+iC)}} \exp\left(-\frac{(1+iC)T^2}{2|T_0^2 - \beta^2 T^2(1+iC)|} \right)
\]  
Here, \( a = \frac{T_0^2}{\beta^2 T^2} = -\frac{1}{2} \beta^2 T, b = iT, c = 0 \)
Considering the dispersion length \( L = \frac{\beta^2 T}{\beta^2} \)

The broadening equation considering the first order GVD with the chirped Gaussian pulse propagation is given by:

\[
\frac{T_1}{T_0} = \sqrt{(1 + C \beta^2 T)^2 + \left(\frac{\beta^2 T}{2\pi\sigma^2}\right)^2}
\]
\[
= \sqrt{(1 + LC)^2 + L^2}
\]
In our research work we use the following parameters to find our desired result.

### Table I. Simulation Parameters for Different Fibers

<table>
<thead>
<tr>
<th>Parameter(Unit)</th>
<th>Fiber types</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SSMF</td>
</tr>
<tr>
<td>Nonlinear Refractive Index, n₂(m²/W)</td>
<td>2.35×10⁻²⁰</td>
</tr>
<tr>
<td>Wavelength, λ(μm)</td>
<td>1550</td>
</tr>
<tr>
<td>Input Power, P(mW)</td>
<td>40-80</td>
</tr>
<tr>
<td>Bit Rate, B(Gb/s)</td>
<td>20-50</td>
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</tbody>
</table>

### III. RESULTS AND DISCUSSIONS

Fig.1 shows the analytical pulse broadening factor caused by first order GVD considering chirped Gaussian pulse in a standard single mode fiber (SSMF) optical transmission system, operating in 1550nm wavelength at the data rates of 20Gbps and 50Gbps considering input power is 40mW. At 20Gbps data rate the pulse broadening factor is almost constant up to fiber length 1.4km for positive chirping, while at 50Gbps data rate the length is 1.24km. But for un-chirped pulse at 20Gbps the pulse broadening factor remains constant up to length 4.65km and 1.07km for 50Gbps bit rate. At bit rate 20Gbps and 50Gbps the corresponding half width of the pulse is 21.3ps and 8.5ps respectively. At this pulse widths the dispersion length, at which the pulse width becomes \( \sqrt{2} \) times of the initial width defined by \( L_D = \frac{T_0}{\beta^2} \) is 20.9km and 3.33km respectively. At 20Gbps data rate, the pulse broadening factor becomes double at 36.54km while it is 4.86km at 50Gbps data rate for positive chirping. Again for un-chirped pulse it becomes double at 36.13km and 6.12km for 20 and 50 Gbps data rate respectively.
Fig. 2 shows for negative chirping at 20 Gbps bit rate the initial pulse broadening factor is 1.05 and at 50 Gbps it is 1.334. It is also seen that for negative chirping there is no pulse compression and with the fiber length the pulse broadening factor increases rapidly. The pulse broadening factor becomes double at 18.74 km when the system operates at 20 Gbps but it becomes 4.4 km when the system operates at 50 Gbps for negative chirping. Whereas for un-chirped pulse that is for \( c = 0 \) at 20 Gbps bit rate the pulse broadening factor is almost constant up to distance 4.72 km while at 50 Gbps it is 1.5 km. After this length the pulse broadening ratio increases rapidly.

Fig. 3 shows the pulse broadening factor with the distance for LEAF fiber. From figure it is observed that at bit rate 20 Gbps the pulse broadening rate is almost constant up to distance 3.72 km for positive chirping, while at 50 Gbps it is 1.14 km. At bit rate 20 Gbps and 50 Gbps the corresponding half width of the pulse is 21.3 ps and 8.5 ps. The corresponding dispersion length is 101.72 km and 16.2 km respectively. The pulse broadening factor becomes double at 183.5 km when the system operates at 20 Gbps but it becomes 28.13 km when the system operates at 50 Gbps for negative chirping. For un-chirped pulse, the pulse broadening factor is almost constant up to distance 21.63 km and 3.72 km for bit rate 20 Gbps and 50 Gbps respectively. At 20 Gbps bit rate the broadening factor becomes double at 175.8 km and 28.12 km at 50 Gbps.

In Fig. 4 for negative chirping at 20 Gbps bit rate the initial pulse broadening factor is 1.01 and at 50 Gbps it is 1.063. It is also seen that for negative chirping there is no pulse compression and with the fiber length the pulse broadening factor increases rapidly. It is observed that at bit rate 20 Gbps the pulse broadening rate is almost constant up to distance 2.34 km for negative chirping, while at 50 Gbps it is 1.2 km. The pulse broadening factor becomes double at 85.02 km when the system operates at 20 Gbps but it becomes 14.91 km when the system operates at 50 Gbps for negative chirping. Whereas for un-chirped pulse that is for \( c = 0 \) at 20 Gbps bit rate the pulse broadening factor is almost constant up to distance 22 km while at 50 Gbps it is 3.6 km. After this distance the pulse broadening ratio increases rapidly.

Fig. 5 shows the pulse broadening factor with the distance for NZDSF fiber. From figure it is observed that at bit rate 20 Gbps the pulse broadening rate is almost constant up to distance 2.56 km for positive chirping, while at 50 Gbps it is 1.07 km. At bit rate 20 Gbps and 50 Gbps the corresponding half
width of the pulse is 21.3ps and 8.5ps respectively. The corresponding dispersion length is 71.11km and 11.32 km respectively. The pulse broadening factor becomes double at 127.9km when the system operates at 20Gbps but it becomes 19.24km when the system operates at 50Gbps for negative chirping. For un-chirped pulse, the pulse broadening factor is almost constant up to distance 15.33 km and 3.5km for bit rate 20Gbps and 50Gbps respectively.

It is observed that at bit rate 20Gbps the pulse broadening rate is almost constant up to distance 1.71 km for negative chirping, while at 50Gbps it is 1.21 km. The pulse broadening factor becomes double at 59.87km when the system operates at 20Gbps but it becomes 11.25 km when the system operates at 50Gbps for negative chirping. Whereas for un-chirped pulse at 20 Gbps bit rate the pulse broadening factor is almost constant up to distance 15.58 km while at 50Gbps it is 3.79 km. After this distance the pulse broadening ratio increases rapidly. At 20Gbps the broadening factor becomes double at 125.2km and 21.7km at 50Gbps.

IV. CONCLUSION

The combined effects of chirping and GVD on the transmitting pulse in optical transmission system have been investigated. For this an analytical model is developed considering chirped Gaussian pulse. Then the output pulse behavior at different bit rates, power and GVD parameters are visualized graphically by MATLAB program. After analysis, the results showed that the impairments of chirping and GVD are more on SSMF than LEAF and NZDSF. It is also found that the negative chirping effect on pulses is more than positive chirping in all the 3 different types of fiber. It is also observed that input power has no effect on pulse broadening.

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