ANALYSIS OF SECOND ORDER DISPERSION ON FREE SPACE OPTICAL PROPAGATION

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Abstract

Free space optic (FSO) can be regarded as a potential and attractive option to fiber optic. FSO has the ability to go beyond the limit of fiber optics. Unfortunately, due to the dispersion effect in the atmosphere, FSO suffers from signal loss and attenuation. Thus, practical and detailed research is needed to improve the system. Simulation on FSO propagation using measured parameter values is important to gain better understanding and level of accuracy on the pulse behavior in free space. Using MATLAB as the simulation platform and with the help of experimental parameter values, an accurate model can be obtained and studied. This will allow some level of prediction on the behavior of the propagating light pulse in the atmosphere and subsequently the FSO performance can be further improved.

Keywords: *Atmospheric turbulence, Binary Pulse Position Modulation, Bit Error Rate, Simulation System.*

I. INTRODUCTION

Laser communication in free space offers an attractive alternative for transferring high-bandwidth data when optical fiber cable is either impractical or not viable. Here, wireless optical connectivity can be used as the last mile to connect fiber backbone to end users, such as from building to building, due to the cost and time-consumption on top of the impossibility and impracticality in laying down optic fibers [1]. Other advantages of adopting the optical wireless communication systems, also termed as free space optics (FSO) or lasercom (laser communications), includes [2]:-

a) no licensing or tariffs fees required for its utilization [3];
b) small, lightweight and compact;
c) ease of installation and deployment (digging up of road is unnecessary);
d) it offers very high data rates due to its large bandwidth;
e) high security fears (the extremely directional, narrow beam optical link makes eavesdropping and jamming nearly impossible);
f) it operates at low power consumption;
g) there are no rf radiation hazards (eye-safe power levels are maintained).

However, random fluctuations in the atmosphere's refractive index can severely degrade the wave front of a signal-carrying laser beam, causing the receiver to suffer from intensity fading.

This results in increased system bit error rates (BERs) particularly along horizontal propagation paths [4].

Research related to pulse propagation in both fiber optic and FSO show the propagating pulse is affected by both linear and nonlinear elements. The linear effects include the group velocity dispersion (GVD) and third order dispersion (TOD), while the nonlinear effects comprise of self phase modulation (SPM). Both the linear and nonlinear effects are responsible for pulse broadening as well as distortion [5]. Based on the severity of these effects, data reliability can be compromised and may lead to the increase in BER. In fiber optic the extent of these effects can be estimated and anticipated through numerous literatures and research. Unfortunately for FSO the extent of these effects cannot be estimated easily due to the random nature of the atmosphere. Thus, it is important to have an accurate prediction model to estimate pulse behavior in the atmosphere.

In this paper, the simulation on FSO is carried out without the nonlinear effects. The nonlinear Schrödinger equation is briefly discussed in Section II while the type of pulses used in the simulation is shown in Section III. Simulation results on the second order dispersion are presented in Section IV. The conclusion is given in Section V.

II. NONLINEAR SCHRÖDINGER EQUATION

The Nonlinear Schrödinger Equation (NLSE) is used to mathematically explain varying pulse envelope propagating in a medium with linear and nonlinear elements. Thus, NLSE is suitable for describing pulse propagation in free space. Numerical solution for NLSE can be obtained by applying split step Fourier (SSF) or beam propagation (BPM) method.

Equation (1) represents the generalized form of NLSE for complex envelope A(z,t). Equation (2) is the linear part of NLSE. It consists of second order dispersion (SOD), TOD and attenuation. Equation (3) is the nonlinear part of NLSE that denotes the SPM. The $\beta 2$ and $\beta 3$ are the quadratic and cubic dispersion coefficient respectively, α is the attenuation factor and γ is the nonlinear coefficient [5].

$$\frac{dA}{dz} = -\frac{i\beta_2}{2}\frac{d^2A}{dt^2} + \frac{\beta_3}{6}\frac{d^3A}{dt^2} - \frac{\alpha}{2}A - i\gamma|A|^2 A \quad (1)$$

$$\frac{\partial A_L}{\partial z} = -\frac{i}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial T^3} - \frac{\alpha}{2}A \quad (2)$$

$$\frac{\partial A_{NL}}{\partial z} = -i\gamma|A|^2 A \quad (3)$$

III. PULSE TYPE

Two types of pulses were used in the simulation. They are the chirped Gaussian pulse and the chirped hyperbolic secant pulse [5] as shown in (4) and (5) respectively.

$$A(z,t) = A_0 \exp\left[-\frac{1+iC}{2}\left(\frac{t}{T_0}\right)^2\right] \quad (4)$$

$$A(z,t) = A_0 \sec h\left(\frac{t}{T_o}\right)\exp\left(-\frac{iCt^2}{2T_0^2}\right) \quad (5)$$

$$A_0 = \sqrt{P_0} \quad (6)$$

Equation 6 is the pulse initial amplitude, while t is time period, T0 is the half-width at 1/e intensity point, P0 is the initial peak power and C is the frequency chirp. All of the simulations were carried out using the parameter values of, T0 = 2 ps, P0 = 1W and C = 0 (unchirped).

IV. SIMULATION RESULTS DUE TO SECOND ORDER DISPERSION

Second order dispersion (SOD) is a linear effect and the primary source of pulse broadening. From Eq. 2, SOD is governed by β2, known as the group velocity dispersion (GVD). GVD represents dispersion of group velocity that determines the broadening characteristic of the pulse. The frequency dependence of the group velocity leads to pulse broadening simply because different component of the pulse disperse during propagation and do not arrive simultaneously [5]. Pulse broadening occurs due to frequency chirps generated by the GVD induced phase shift. GVD changes the phase of each spectral component of the pulse by an amount that depends on the frequency and the propagated distance [6]. The generated frequency chirps changes the velocity of each spectral components causing them to travel in different velocity. Spectral components at the leading edge travel faster compare to the trailing edges. This causes a delay on the pulse arrival. Pulse broadening is dependent on the delay and linearly correlated with distance. The pulse broadening does not rely on the sign of β2.

To observe the effect of SOD alone, β3 and γ in Eq. 1 are set to zero while GVD, β2 = 21 ps2/km [3].

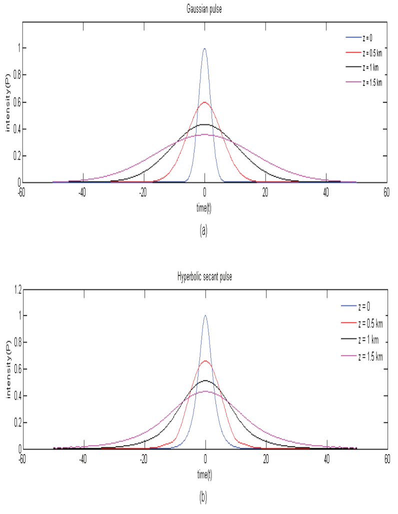

Fig. 1. Pulse propagation at z = 0;0.5;1;1.5 km with β2 = 21 ps^2/km for (a) unchipred Gaussian pulse and (b) unchipred hyperbolic secant pulse

The broadening experienced by both pulses can be observed in Fig. 1, where both pulses show a significant amount of broadening. Pulse broadening is linearly correlated with the propagated distance. As the pulse propagates, constant phase shift cause a constant increase in chirp. The increase in chirp affects the velocity and the arrival of the pulse spectral components. The change of velocity consequentially increases delay and cause further broadening. The magnitude of delay increases with the distance. These effects can be observed in Fig. 1(a) and Fig. 1(b).

From Figure 2(a) and 2(b), the waterfall plot for both pulses show similar characteristics in pulse broadening. It is obvious SOD induced broadening increase linearly with propagating distance. Nevertheless, both pulses have displayed different broadening rates. Hyperbolic secant pulse reveals a lower broadening rate compare to Gaussian. This can be observed as Gaussian pulse exhibits wider broadening and lower pulse amplitude as it propagates, in comparison to hyperbolic secant pulse. This implies that both pulses have different effect to GVD. There is one important attribute; hyperbolic secant pulse shows a faint distortion at both edges of its pulse. Distortion can be seen between distances 0.3 km and 0.5 km but disappears as the pulse propagates; as can be observed in Fig. 2(b).

Broadening rate for both Gaussian and hyperbolic secant pulse can be observed in Figure 3. Hyperbolic secant pulse shows lower broadening rate at about 34.5% compare to Gaussian pulse. The difference in broadening rate can be traced back to the difference in the pulse shape. The pulse shape is defined by the pulse equation and both pulses manifest differently over the same parameters as can be seen in the Gaussian pulse which is presented by Eq. 4 and hyperbolic secant pulse as in Eq. 5. These differences create variations and rare anomalies

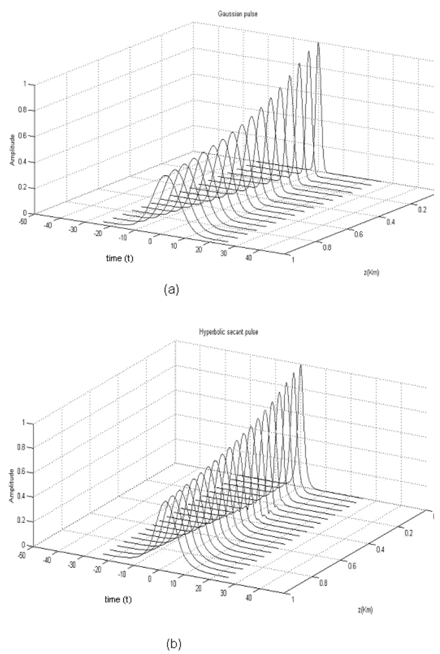

Fig. 2. Pulse propagation at z = 1 km and with β2 = 21 ps2/km for (a)unchirped Gaussian pulse and (b)unchirped hyperbolic secant pulse.

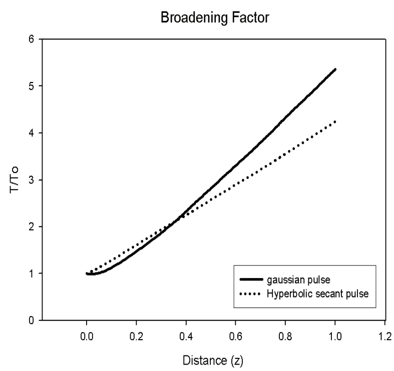

Fig. 3. Broadening factor for unchirped Gaussian and unchirped Hyperbolic Secant pulse over the distance, z = 1 km, with β2 = 21 ps2/km,

V. CONCLUSION

In this paper the dispersion effects were simulated individually in 1D and 2D graphical representation. Simulations were done in order to observe pulse behavior and response to linear parameters. Pulse propagation in free space was simulated with the SOD in order to observe the pulse behavior in free space. Simulation result may serve as a prediction model that can be used to estimate or predict to an extent the actual pulse behavior in free space.

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