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Effects of Second Order Dispersion in Free Space Optical Communication

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Abstract: Free Space Optic (FSO) can be considered as an attractive option to fiber optic. FSO has the capability to go beyond the limit of fiber optics. Unfortunately, due to the effects of dispersion in the atmosphere, FSO, as a point-to-point communication system that requires line-of-sight transmission; suffers from attenuation and signal loss. Thus, practical and detailed research is needed to improve this wireless system. In this study, simulation on FSO propagation using measured parameter values was carried out in order to gain better understanding on the pulse behavior in free space with better level of accuracy. Using MATLAB and experimental parameter values, a more precise model can be obtained and analyzed. This will allow some level of prediction on the behavior of the propagating light pulse in the atmosphere and subsequently the FSO system performance can be further improved.

Key words: Free space optics, second order dispersion, bit error rate, Gaussian pulse

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 (Agrawal, 2001; Arnon, 2003). Other advantages of adopting the optical wireless communication systems, also termed as Free Space Optics (FSO) or lasercom (laser communications), includes (Potasek and Kim, 2001):

- No licensing or tariffs fees required for its utilization (Potasek, 1999)
- Small, lightweight and compact
- Ease of installation and deployment (digging up of road is unnecessary)
- It offers very high data rates due to its large bandwidth
- High security fears (the extremely directional, narrow beam optical link makes eavesdropping and jamming nearly impossible)
- It operates at low power consumption
- 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 (Ricklin and Davidson, 2003; Bouchet *et al*., 2006).

Research related to pulse propagation in both fiber optic and FSO showed the propagating pulse is affected by both linear and nonlinear elements. The linear effects include the Group Velocity Dispersion (GVD) or Second Order Dispersion (SOD) 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 (Agrawal, 2002). Based on the severity of these effects, data reliability can be compromised and may lead to the increase in BER (Garlington *et al*., 2005). 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 study, the simulation on FSO is carried out without the nonlinear effects. The nonlinear Schrödinger equation is briefly discussed while two types of pulse are used in the second order dispersion simulation.

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NONLINEAR SCHRÖDINGER EQUATION MODEL

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 Method (BPM) (Bogomolov and Yunakosky, 2006; Wang *et al*., 2006).

Equation 1 represents the generalized form of NLSE for complex envelope A(z, t). The β_2 and β_3 are the quadratic and cubic dispersion coefficient respectively, α is the attenuation factor and γ is the nonlinear coefficient (Agrawal, 2002).

$$\frac{\partial A}{\partial z} = -\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} - \frac{\alpha}{2}A - i\gamma|A^2|A \qquad (1)$$

Under the assumption that the electric field of the light in free space has a slowly varying envelope A(z,t) and that the free space medium has an instantaneous nonlinear response, Eq. 1 can be rewritten as:

$$\frac{\partial U}{\partial z} = -\frac{i\beta_2}{2}\frac{\partial^2 U}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 U}{\partial t^3} - \frac{\alpha}{2}U - i\gamma|U^2|U \qquad (2)$$

where, Z is propagation length in free space, $U(z,t) = A(z,t)/\sqrt{P_0}$ is the complex electric field envelope A(z,t) normalized to the absolute amplitude of the field $\sqrt{P_0}$, P_0 is the peak power, t is time normalized to a convenient time scale T_0 measured in a reference frame moving with the group velocity of the pulse [$\tau = (t-z/v_g)/T_0$].

The NLSE is composed of linear and nonlinear terms and can be written in operator form as:

$$\frac{\partial U}{\partial z} = (\hat{D} + \hat{N})U$$
$$\hat{D} = -\frac{i\beta_2}{2}\frac{\partial^2}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3}{\partial t^3} - \frac{\alpha}{2} \qquad (3)$$
$$\hat{N} = -i\gamma|U^2|$$

where, $\hat{D}$ and $\hat{N}$ are linear (consist of SOD, TOD and attenuation) and nonlinear (SPM) operators respectively. Thus, taking the nonlinear part into calculation and then the dispersion term, the solution below is obtained:

$$U_1(z,t) = U(0,t)\exp[i\gamma|U(0,t)|^2 z] \qquad (4)$$

$$U(z,t) = F^{-1}\left\{\left[\left(\frac{i}{2}\beta_2\omega^2 - \frac{\beta_3\omega^3}{6} - \frac{\alpha}{2}\right)z\right]F[U_1(z,t)]\right\} \qquad (5)$$

where, F is the Fourier transform and ω is the Fourier frequency.

TYPE OF PULSE

Two types of pulse were used in the simulation. They are the chirped Gaussian pulse and the chirped hyperbolic secant pulse (Agrawal, 2002) as shown in Eq. 6 and 7 respectively as initial pulses:

$$U(0,t) = \sqrt{P_0}\exp\left[-\frac{1+iC}{2}\left(\frac{t}{T_0}\right)^2\right] \qquad (6)$$

$$U(0,t) = \sqrt{P_0}\,\mathrm{sech}\left(\frac{t}{T_o}\right)\exp\left(-\frac{iCt^2}{2T_0^{\,2}}\right) \qquad (7)$$

where, t is time period, T_0 is the half-width at 1/e intensity point and C is the frequency chirp. All of the simulations were carried out using the parameter values of, T_0 = 2 ps, P_0 = 1W and C = 0 (unchirped).

SECOND ORDER DISPERSION SIMULATION RESULTS

Second Order Dispersion (SOD) is a linear effect and the primary source of pulse broadening. From Eq. 2, SOD is governed by β_2, 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 (Agrawal, 2002). 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 (Bandelow *et al*., 2003). 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 β_2.

To observe the effect of SOD alone, β_3 and γ in Eq. 1 are set to zero while GVD, β_2 = 21 $ps^2\,km^{-1}$ (Potasek, 1999; Alexeev *et al*., 2004).

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

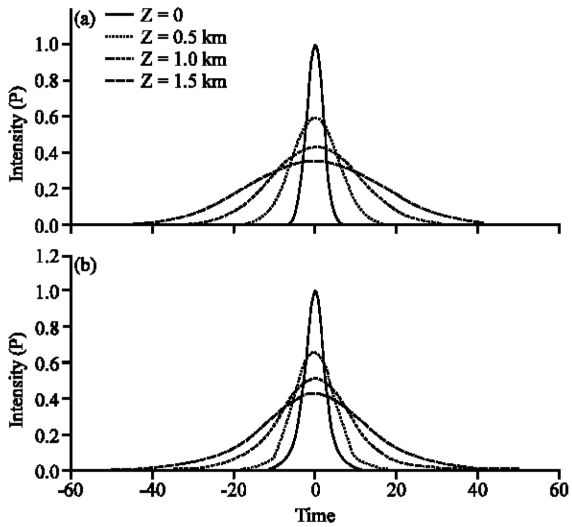

Fig. 1: Pulse propagation at z = 0, 0.5, 1, 1.5 km with $\beta_2 = 21\ ps^2\ km^{-1}$ for (a) unchipred Gaussian pulse and (b) unchipred hyperbolic secant pulse

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. 1a and b.

From Fig. 2a and b, the waterfall plot for both pulses showed 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 and 0.5 km but disappears as the pulse propagates; as can be observed in Fig. 2b.

Broadening rate for both Gaussian and hyperbolic secant pulse can be observed in Fig. 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

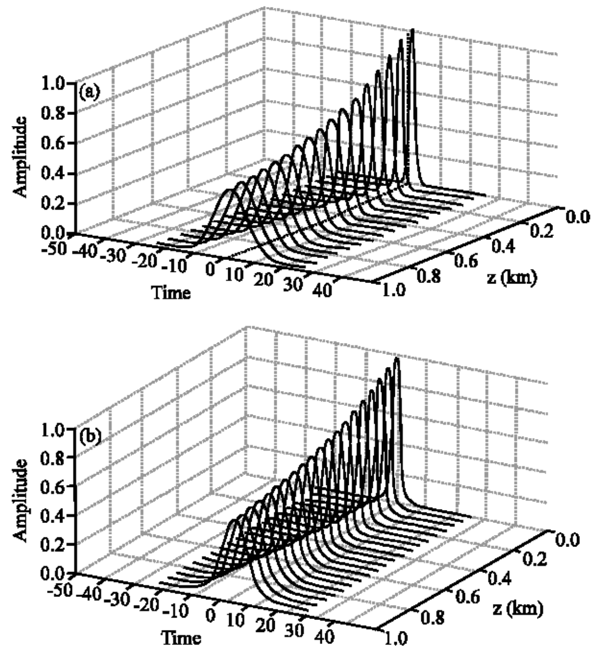

Fig. 2: Pulse propagation at z = 1 km and with $\beta_2 = 21\ ps^2\ km^{-1}$ for (a) unchirped Gaussian pulse and (b) unchirped hyperbolic secant pulse

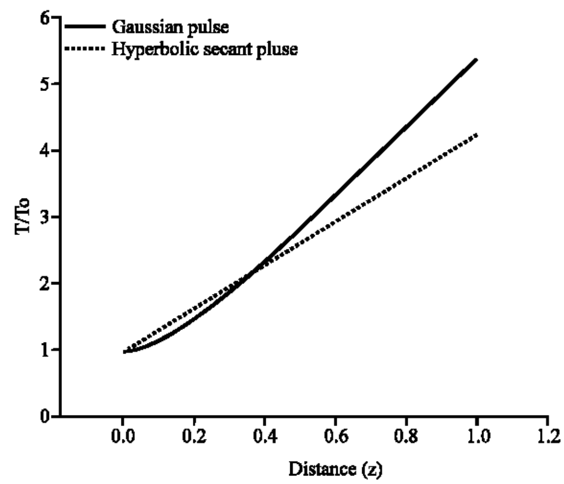

Fig. 3: Broadening factor for unchirped Gaussian and unchirped Hyperbolic Secant pulse over the distance, z = 1 km, with $\beta_2 = 21\ ps^2\ km^{-1}$

presented by Eq. 4 and hyperbolic secant pulse as in Eq. 5. These differences create variations and rare anomalies

CONCLUSION

In this study, the dispersion effects were simulated and shown individually in 1D and 2D graphical representation. Simulations were done in order to observe pulse behavior and response to linear parameters. The SOD effects on the pulse propagation in free space was observed and the pulse behavior was discussed. 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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