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Effects of Polarization Mode Dispersion on Soliton Pulse and Compare with Linear Pulse

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Abstract: There are number of problems associated with the propagation of information through optical fibers. A pulse propagation model is essential to investigate the effects in nonlinear optical fiber communication. In this paper we used Symmetric Split-step Fourier method to solve the nonlinear Schrödinger equation (NLSE) which describes the pulse propagation model in optical fiber. We reported some simulation results such as variation in the soliton amplitude and pulse broadening of linear and nonlinear hyperbolic secant pulse due to dispersion. We also reported how the nonlinearity of soliton pulse compensates for these effects due to the dispersion. Finally the dispersion managed solitons are considered which are proved to be more robust to pulse broadening than conventional solitons.

Keywords: Optical Fiber communication, Soliton, Group velocity Dispersion, Nonlinearity, Nonlinear Schrödinger equation, dispersion management.

1. Introduction

Optical fibers provide the best way for high-speed long-haul digital communication. This is because the short wavelength of light, making it possible to pack the data densely and the attenuation has been lowered close to the physical limits which allow the fibers to be designed in single-mode [1].

Two major factors that degrade the propagation of signal through optical fibers are the attenuation and the Dispersion. The signal attenuation or fiber loss is defined as the ratio of the optical output power P_{out} from a fiber of length L to the optical input power P_{in}. The two powers are related by the relation [2]

$$P_{out} = P_{in} e^{-\alpha L} \quad (1)$$

here the α is called the attenuation constant to account for fiber loss.

The optical signal not only loses its power due to attenuation, but the pulse gets broadened as it travels along the fiber due to the phenomenon known as dispersion. Dispersion in optical fibers arises because of the wavelength dependence of refractive index. Fiber dispersion mainly depends on group velocity dispersion (GVD) parameter.

The nonlinear effect in optical fiber originates from the nonlinear refractions, which are intensity dependent, thus by increasing the intensity of light in optical fiber nonlinear effects can be induced. The intensity dependence refractive index causes an intensity dependence phase shift in the fiber; this effect is called self phase modulation (SPM). An interesting consequence of fiber nonlinearities is optical solitons, which can be supported when there is anomalous dispersion $\beta_2 < 0$. Solitons in optical fiber can be defined as nonlinear pulses that propagate nearly dispersion-free for long distances and undergo elastic collisions [3]. Thus, soliton propagation in nonlinear single-mode dispersive fiber experiences a balancing act between the dispersive and nonlinear effects. Solitons appear in various fields of physics, yet the most promising application of solitons is in the filed of optical fiber communication.

This paper is organized as follows: numerical model of the pulse propagation using NLSE is covered in Section 2. In Section 3, we described the symmetric split-step algorithm used to solve the nonlinear Schrödinger equation. In Section 4, we provided performance comparison and numerical results; Section 5 concludes the paper.

2. Numerical Model of Pulse propagation

The numerical model of the pulse propagation through single mode fiber with dispersion and nonlinearity is represented by the nonlinear Schrödinger equation (NLSE) and is given by [1]

$$\frac{\partial A}{\partial z}+\frac{\alpha}{2}A+\frac{i}{2}\beta_2\frac{\partial^2 A}{\partial t^2}=i\gamma\left|A^2\right|A \quad (2)$$

here A is the slowly varying amplitude of the pulse envelop, α is the attenuation parameter accounts for the fiber loss and is neglected in our simulations, β_2 is accounts for dispersion and γ is the nonlinear parameter of the fiber, t represents a frame of reference moving with the pulse at group velocity and z is the distance along which the soliton propagates through the fiber. In order to maintain the soliton conditions the input pulse through the NLSE will be should be the hyperbolic secant pulse of the form:

$$A(0,t)=N\sec h(t/T_0) \quad (3)$$

where N is the soliton order, and T_0 is the initial pulse width of the soliton. In this paper we considered the hyperbolic secant pulse as input pulse and simulation results are obtained for pulse broadening and the soliton amplitude as they propagate along the length of the fiber over a long distance.

2.1. Dispersion management

Dispersion-managed (DM) solitons offer significant advantages with respect to conventional solitons in high capacity transmission systems. The main idea was to combine high local group-velocity dispersion with low path-average dispersion. The former feature results in the reduction of the four-wave mixing while the latter one reduces the Gordon-Haus timing jitter effect. Due to their characteristics, dispersion-managed solitons offer tremendous advantages that make them a preferred option for upgrading the embedded fiber plant and for use in new ultrahigh-speed multiplexed systems operating at 40 Gbit/s per channel. One of the most remarkable features of dispersion-managed solitons is that they can exist even where the average dispersion is zero or normal. This result opens the prospect of wavelength-division multiplexed soliton systems with wavelengths near zero dispersion.

The DM soliton systems investigated in this paper consist of fibers with alternating anomalous and normal dispersion fibers of equal length 40 m, ($L_1=L_2=40m$) as show in Fig(1), and we change both S value (map strength) and average GVD, D_{av} by changing the local GVD. The map strength and average dispersion are defined as [4] $S=\lambda^2\left|D_1L_1-D_2L_2\right|/(2c\pi T_{FWHM}^2)$ and

$$D_{av}=(D_1L_1+D_2L_2)/(L_1+L_2) \quad (4)$$

respectively, where D_1 and D_2 are the GVD coefficient of the anomalous and normal fibers in ps/km nm, L_1 and L_2 are the lengths of the two segments, λ is the wavelength, and c is the vacuum light speed.

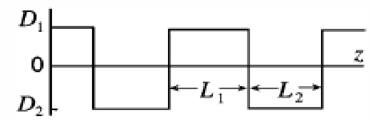


Fig. 1. Schematic illustration of the dispersion map.

3. Symmetric Split-Step Fourier Method

Symmetric split-step Fourier method (SSSFM) is used to solve the NLSE numerically. Before discussing the Symmetric Split-step Fourier method let us briefly discuss the Split-Step Fourier method (SSFM) which was used to solve NLSE [5]. This SSFM is based on splitting the NLSE into two separate operators, the difference operator *D* that accounts for dispersion and absorption in optical fiber i.e. the linear part of the NLSE and the *N* operator that accounts for the nonlinear effects induced during pulse propagation [5]. So we can rewrite equation (2) in the form:

$$\frac{\partial A}{\partial z}=(D+N)A \quad (5)$$

These operators D and N are given by

$$D=-\frac{i}{2}\beta_2\frac{\partial^2}{\partial T^2} \text{ and } N=i\gamma|A|^2-\frac{\alpha}{2} \quad (6)$$

The SSFM assumes that dispersion and nonlinearity act separately over a short fiber distances *h* and results in errors. In this method as the pulse propagates from *z* to *z*+*h* two steps are performed, in the first step nonlinearity acts alone and *D*=0, in the second step the dispersion acts alone and *N*=0 [2]. Mathematically

$$A(z+h,t)=\exp(hD)\exp(hN)A(z,t) \quad (7)$$

The split step Fourier method computes the nonlinear operator *N* in the time domain and the dispersion operator *D* in the frequency domain, under the assumption that both act independently, thus ignoring the noncommuting nature of the operators *N* and *D*. The accuracy of the SSFM can be improved by adopting a slightly different procedure to solve the pulse propagation model described in [2], where equation (7) becomes:

$$A(z+h,t)\approx\exp(h\frac{D}{2})\exp\left(\int_z^{z+h}N(z^1)dz^1\right)\exp(h\frac{D}{2})A(z,t) \quad (8)$$

Where $\int N(z^1)dz^1 \approx \frac{h}{2}\left[N(z)+N(z+h)\right]$

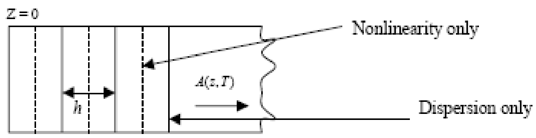


Fig. 2. Schematic illustration of the Symmetric SSFM

Here to improve the accuracy of the model, each segment is further divided into two halves each of length h/2, where h is the step size for one segment. During the implementation, it is assumed that the non linearity is lumped at the mid-plane of each segment rather than at the boundary. As a procedure, the optical field A(z, t) , is first propagated for a distance h/2 considering only dispersion. Then the output field at the middle of plane z+h/2 is multiplied by the nonlinear term to include the effect of nonlinearity over the whole segment of the length h. Finally, the field is propagated through the remaining distance h/2 with dispersion only to obtain the resultant field A(z+h, t). This is illustrated in figure (2). We used a step size of 40 m which was within very safe limit to ensure that the nonlinear phase $Ø_{NL}= \gamma Ph << 0.1$ [6], where P is the peak power at the input of the step. The results obtained through our developed model are in well accordance with the results presented in the literature.

3.1. Symmetric Split-Step algorithm:

Compute B1= FFT of (A) : Fast Fourier transform of A.

Compute B2=exp (Dh/2) ×B : Dispersion term for half segment in frequency domain.

Compute D1=IFFT of (B2) : Dispersion term for half segment in time domain.

Compute NonL=exp (hN) : Nonlinear term.

Compute C1=FFT of (Nonl) : Fourier transform of nonlinear part.

Compute C2= exp (Dh/2)×C1 : Dispersion term for the second part of the segment.

Compute A=IFFT of (C2) : Pulse after the length 'h'

The above algorithm is to be repeated required number of times to get the output pulse at the end of given length of the fiber.

4. Numerical Simulation and Results

For our simulation results we considered real single mode fiber (SMF) operating at wavelength of 1550 nm. The nonlinear Schrödinger equation (2) is solved by using the Symmetric Split-step Fourier method by taking the initial hyperbolic secant pulse of the first order i.e. with N=1. First the effect of dispersion on this pulse is quantified by simulating the NLSE without the nonlinearity i.e. by taking the γ=0 (Linear pulse). The initial T_{FWHM} pulse width is taken as 60 ps. The full width half maximum width is related to the initial pulse width T_0 by the relation $T_{FWHM} \approx 1.763\ T_0$. In our simulations the fiber loss is assumed to be zero. The fast Fourier transform is considered by taking 512 time samples.

Figure 3 shows the pulse amplitude $R = |A|^2$ of linear (γ=0) hyperbolic secant pulse at distances z = L_d, z = $2L_d$, z = $4L_d$, where L_d is the dispersion length and is given by $L_d = T_0^2/\beta_2$. The parameter β_2 is called the GVD coefficient and is related to the GVD parameter D as $\beta_2 = (-D\lambda^2)/(2\pi c)$; where λ is the operating wavelength=1550nm and c is the velocity of light in free space.

In case of dispersion only, the pulse broadens more and more as it propagates in the fiber. Here for the GVD parameter value of D=16 ps/km.nm, the dispersion length comes around 64km. The curve of $z/L_d=0$ in figure 3 represents the input pulse A(0,t) at z=0. When the nonlinearity coefficient γ is included then the pulse broadening gets reduced due to the balancing action of dispersion and nonlinearity.

Fig.3. Amplitude R of sech pulse at different lengths.

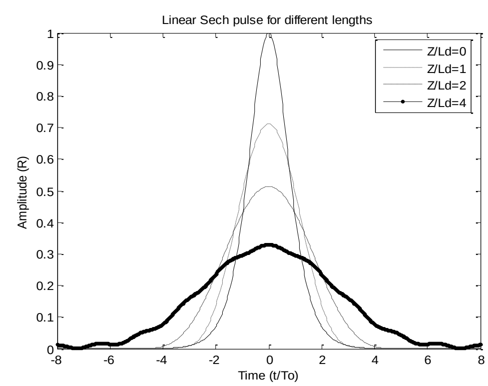
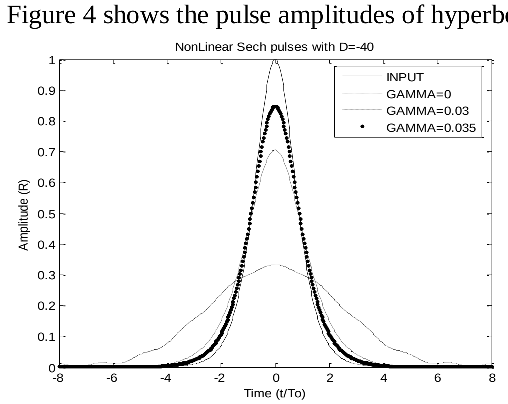


Fig. 4. Amplitude of hyperbolic secant pulse for different values of γ after travelling a distance of 100km

Figure 4 shows the pulse amplitudes of hyperbolic



secant for different values of nonlinear coefficient γ. Here the GVD parameter is taken in the anomalous dispersion regime as D = -40 ps/mk.nm.

As can be seen from the above results as the soliton propagates along the fiber the amplitude reduces which results in pulse broadening. The average pulse broadening of the linear pulse with γ=0 and soliton pulse for different γ after propagating a distance of 100km are shown in figure 5. As the nonlinear coefficient γ increases the average pulse broadening of the soliton pulse gets reduced.

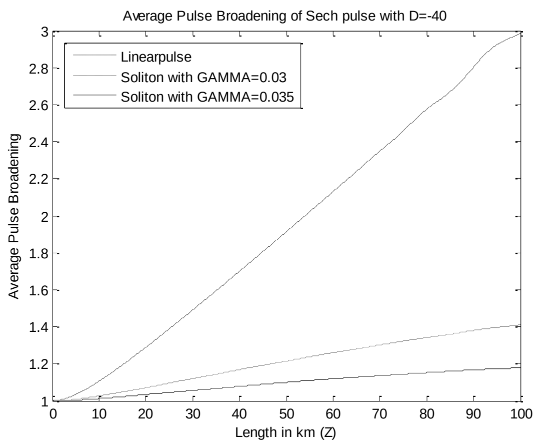


Fig. 5. Average pulse broadening of Linear and Soliton pulses with hyperbolic secant input profile.

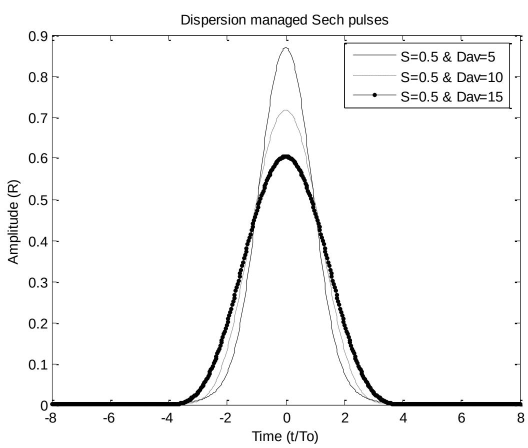


Fig. 6. Amplitude of Dispersion managed Soliton pulse with hyperbolic secant input profile.

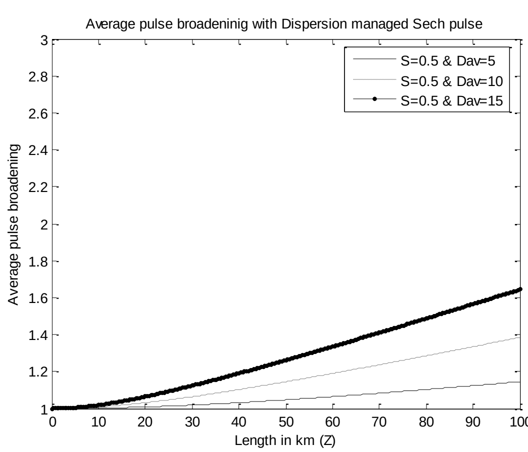


Fig. 7. Average pulse broadening of Dispersion managed Soliton pulse with hyperbolic secant input profile

In this paper we investigated the dispersion managed solitons with map strength S=0.5 and different values of average dispersion D_{av}= 5, 10, 15ps/km.nm. As the value of average dispersion increases the robustness of soliton to pulse broadening also increases. The value of the map strength S accounts for the nonlinearity of the fiber; hence the pulse broadening gets reduced in DM solitons even with γ=0. Figures 6 & 7 respectively shows the amplitude and average pulse broadening of the dispersion managed soliton for different values of average dispersion.

5. Conclusions

In this paper the Symmetric Split-step algorithm has been implemented to solve the nonlinear Schrödinger equation numerically. The results obtained with this algorithm are in well accordance with the standard results existing in the literature. Here we investigated the effects of group velocity dispersion on pulse broadening and the soliton amplitude by considering the initial hyperbolic secant input pulse profile. We also observed that the nonlinearity (Self phase modulation) of the soliton counter balances the effects of group velocity dispersion. As the nonlinear coefficient of the soliton increases the pulse broadening due to dispersion gets reduced. But when we consider the dispersion managed soliton with alternate normal and anomalous group velocity dispersion parameters with a period of 40m the dispersion gets reduced even for less values of nonlinear coefficient. Thus we conclude that dispersion managed solitons, with alternate normal and anomalous group velocity dispersion, are more robust to pulse broadening than the conventional solitons, with constant group velocity dispersion, for the same distance travelled.

6. References

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