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Research Article

Analytical Approach of High Peak Power Optical Pulse Propagation in Nonlinear Dispersive Fibers

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Abstract

The advent of fiber optics has revolutionized telecommunication systems around the world, enabling an unprecedented amount of information exchange, all at the speed of light. One of the keys to the success of the ensuing photonics revolution will be the use of optical solitons in fiber optic communication systems. Solitons are a special breed of optical pulses that can propagate through an optical fiber undistorted for tens of thousands of kilometers. A rapid progress during the 1990s has converted optical solitons into a practical candidate for modern light wave system. In this paper a brief overview of the development of non linear optics and optical solitons is provided. The nonlinear schrodinger equation has been solved under soliton condition, so that soliton propagation can be simulated.The numerical analysis of the nonlinear effect is done by NLSE. The equation is solved using split step algorithm,which is coded in Matlab. The results are displayed in the form of 3D pulse at regular intervals, phase charge and pulse broadening ratios are

Keywords: *Optical pulse, Fiber, Nonlinearities, Chirped, Dispersion*

1. Introduction

Very narrow optical pulses with high peak powers that retain their shapes as they propagate along the fiber are referred to as soliton. Such pulses takes advantages of nonlinear effects in silica, particularly self-phase modulation (SPM) resulting from the Kerr nonlinearity to overcome the pulse broadening effects of GVD. SPM causes the pulse to narrow, thereby partly compensating the chromatic dispersion. If the relative effects of SPM and GVD for an appropriate pulse shape are controlled properly, the compression of the pulse resulting from SPM can exactly balance the broadening of the pulse due GVD. Therefore, the pulse shape either does not change or changes periodically as the pulse propagate down the fiber (Hasegawa *et al*,1973) (Kumar,1990), (Kumar *et al*,2011), (Haus, 1993),. In the case of silica optical fibers, one of the manifestations of the nonlinearity is the intensity dependent refractive index according to the following equation

$n=n_o+ n_L I$

where n_0 is the linear refractive index of silica, (for the intensity levels),n_L is the nonlinear refractive index of silica (Agrawal,2002), (Thyagarajan *et al*,1996).Thus, when an optical pulse travels through the fiber, the higher intensity portions of the pulse encounter a higher refractive index of the fiber compared with the lower intensity regions. This intensity dependent refractive index leads to the phenomenon known as self-phase modulation(SPM).The emergence of EDFAS that optically compensate any fiber attenuation and optical solitons that are dispersion and nonlinearity against each other simultaneously compensation both effects are truly revolutionising the field of optical fiber telecommunications. These developments are expected to make terabit communication systems over hundreds of thousands of kilometres a reality.

2. Dispersion Compensation

The group velocity associated with the fundamental mode is frequency dependent because of chromatic dispersion. As a result different spectral components of the pulse travel at slightly different group velocities, a phenomenon referred to as group velocity dispersion (GVD) (Senior, 2004), (Keiser, 2000). Let us consider a pulse (of spectral width $\Delta\lambda_0$) propagating through a fiber characterized by the propagation constant β . The spectral width $\Delta\lambda_0$ could be due to either the finite spectral width of the source itself or finite duration of a Fourier Transform limited pulse. The group velocity of the pulse is given by

$$1/V_g = d\beta/d\acute{\omega} \qquad (1.1)$$

For conventional single mode fibre with zero dispersion

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around 1300mm atypical variation of V_g with wavelength is shown by the solid curved in figure.

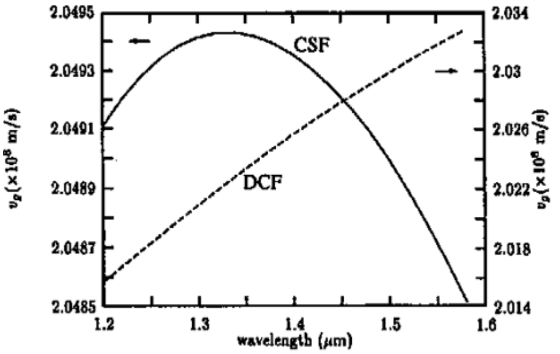

Fig1: Typical variation of v_g with λ_0 for a CSF(conventional single mode fiber) and a DCF.at the operating wavelength, the CSF has (small) positive dispersion and the DCF has (large) negative dispersion.

After propagating through a fiber for a certain length L1, we allow the pulse to propagate through another fiber where the group velocity varies , as shown by the dashed curve in the figure. The red component will now travel faster than the blue components and the pulse will tend to reshape itself into its original form. This is the basic principle behind dispersion compensation. Now the total dispersion of a single mode fiber is given by

$$D_t=D_M+D_{\acute{\omega}}=-2\Pi c/\lambda^2(d^2\beta/d\acute{\omega}^2) \quad (1.2)$$

where D_M and $D_{\acute{\omega}}$ are material dispersion and waveguide dispersion respectively.

Thus $d^2\beta/d\acute{\omega}^2 < 0$ implies operation at $\lambda_0 > \lambda_z$ and conversely . Let $(D_t)_1$ and $(D_t)_2$ be the dispersion coefficient of the first and second fiber, respectively.Thus, if the lengths of the two fibers (l1 and l2) are such that

$$(D_t)_1L_1 + (D_t)_2L_2 = 0 \quad (1.3)$$

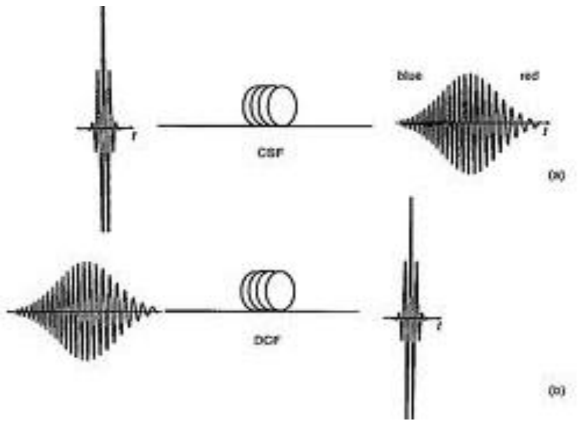

Fig 2: The basic principle of dispersion compensation

Then the pulse emanating from the second fibre will be identical to the pulse entering the first fibre.

In Fig (2) we show the broadening of an unchirped pulse as it propagates through a fibre is characterized by

$(D_e) > 0$, $(\lambda_0>\lambda_z)$

Thus, because of the physics discussed above the pulse gets broadened and chirps, the front end of the pulse gets blue shifted , and the trailing edge of the pulse gets red shifted . The pulse is said to be negatively chirped pulse is now propagated through another fibre of length L_2 characterised by $(D_t)_2< 0$ .Then the chirped pulse will get compressed , (fig2) and if the length satisfies equation (1.3), then pulse dispersion will be exactly compensated.

3. Self-Phase Modulation

There exist many different types of fiber nonlinearities, but the one of most concern to soliton theory is self-phase modulation (Keiser, 2000), (Ghatak *et al*, 1999). With self-phase modulation, the optical pulse exhibits a phase shift induced by the intensity-dependent refractive index. The most intense regions of the pulse are slowed down the most, so they exhibit the greatest phase shift. Since a phase shift changes the distances between the peaks of an oscillating function, it also changes the oscillation frequency along the horizontal axis. The concepts of phase shift and chirp may be applied to an optical pulse. Fig 3(a) shows an unchirped Gaussian pulse, and Fig 3(b) shows the same pulse after being chirped by a phase shift. This simplification is known as a pulse envelope, and it is a common way of representing the shape of an optical pulse. The chirped pulse in Fig 3(b) has the same envelope as the unchirped pulse in Fig 3(a). This is because self-phase modulation only broadens the pulse in the frequency domain, not the time domain.)

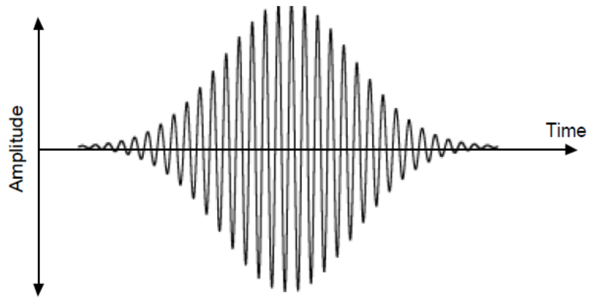

Fig 3(a): An unchirped Gaussian pulse

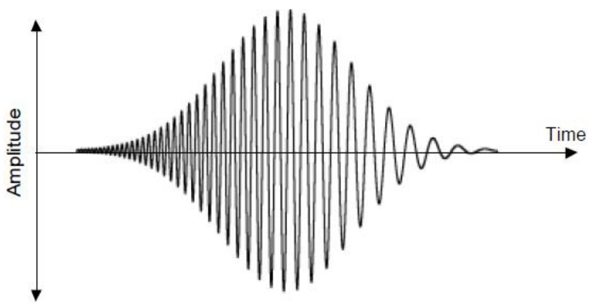

Fig 3(b): A chirped Gaussian pulse

As in Fig 3(b), self-phase modulation leads to a chirping with lower frequencies on the leading (right-hand) side and higher frequencies on the trailing (left-hand) side of the pulse. Like dispersion, self-phase modulation may lead to errors at the receiving end of a fiber optic communication system. This is particularly true for wavelength-division multiplexed systems, where the frequencies of individual signals need to stay within strict upper and lower bounds to avoid encroaching on the other signals.

4. Optical Fibre Soliton Transmission

The optical solitons propagate without changing their shape in optical medium due to a balance between two effects, viz, group velocity dispersion of the medium and Kerr effect (Agrawal,2002), (Thyagarajan *et al*,1996), (Senior, 2004), (Keiser, 2000), (Ghatak *et al*, 1999),(Deb *et.al*,1993).

Basic Propagation Equation: The mathematical description of solitons employs Non Linear Schrodinger Equation (NLSE) and satisfied by the pulse envelop A (z,t) in presence of GVD and SPM. This equation can be written as,

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

Where the fibre losses are included through the α-parameter while β_2 and β_3 account for the second and third order dispersion (TOD) effects. The nonlinear parameters $\gamma = 2\pi n_2/\lambda A_{eff}$ is defined in terms of the nonlinear index coefficient n_2, the optical wavelength λ, and effective core area A_{eff} .To discuss the soliton solution as simply as possible , we neglect third order dispersive effect setting β_3=0. It is useful to write this equation in a normalized form by introducing,

$\tau=\frac{t}{T_o},\xi=\frac{z}{L_D},U=\frac{A}{\sqrt{P_o}}$, Where T_o is a measure of the pulse width, P_o is the peak power of the pulse and L_D $=\frac{T_0^{\ 2}}{|\beta_2|}$

is the dispersion length. Equation (a) then takes the form:

$$i\frac{\partial U}{\partial \xi}-\frac{s}{2}\frac{\partial^2 U}{\partial \tau^2}+N^2|U|^2U-i\frac{\alpha}{2}U=0$$

Where s= sign(β_2)= +1 or – 1 depending on whether β_2 is positive(normal GVD) or negative (anomalous GVD)

The parameter N is defined as $N^2= \gamma.P_0$. $L_D = \gamma P_0 T_0^2/|\beta_2|$. It represent a dimension less combination of the pulse and fiber parameters. The NLSE belongs to a special class of nonlinear partial differential equations that can be solved exactly with a mathematical technique known as the inverse scattering method. Although the NLSE supports solitons for both normal and anomalous GVD, pulse like solitons are found only in the case of anamolous dispersion.

Bright Solitons: Consider the case of anamolous GVD by setting s = -1. It is common to introduce u= NU as a renormalized amplitude (Opticwave, 2008), (Abowitz *et al*, 2000). NLSE can be written in the following form:

$$i\frac{\partial u}{\partial \xi}+\frac{1}{2}\frac{\partial^2 u}{\partial \tau^2}+|u|^2u-i\frac{\alpha}{2}u=0$$

This equation can be solved by the inverse scattering method. When an input pulse having an initial amplitude

$$u=N\,\mathrm{sec}h\left(\frac{\tau}{t_0}\right)$$

is launched into the fibre, its shape remains unchanged during propagation when N=1, but follows a periodic pattern for integer values of N>1.

An optical pulse where parameters satisfy the condition N=1 is called the fundamental soliton. The parameter N represents the order of the soliton.

The numerical analysis of the nonlinear effects is done by NLSE. The equation is solved using an algorithm called Split-Step Algorithm, which is coded in Matlab. NLSE has been solved under soliton condition, so that soliton propagation can be simulated. The MATLAB files solves NLSE under soliton condition and display the results in 3D graphics along with the pulse broadening ratio and phase shift has also been calculated and displaced. We used the soliton pulse and studied the effects of attenuation, dispersion and non-linear through the fiber optic length by numerical simulation.

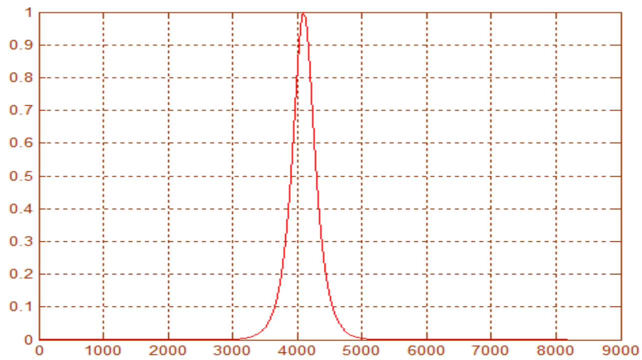

Fig 4: Input fundamental soliton pulse

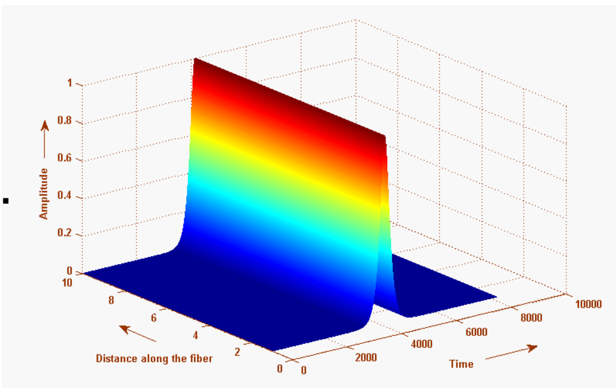

Fig 5: Output spectrum of input pulse

We have consider the following parameters for soliton propagation simulation:S = -1(Anomalous GVD) Fiber loss value (α) = 0.2dB/km, Fiber non-linearity in ω/M (ϒ) = 0.002, soliton order (N)=1, Initial pulse width(in sec) = 150×10^{-12}, input power in watts, P_o=0.01,fundamental soliton pulse, u=N sech(τ/t_0).

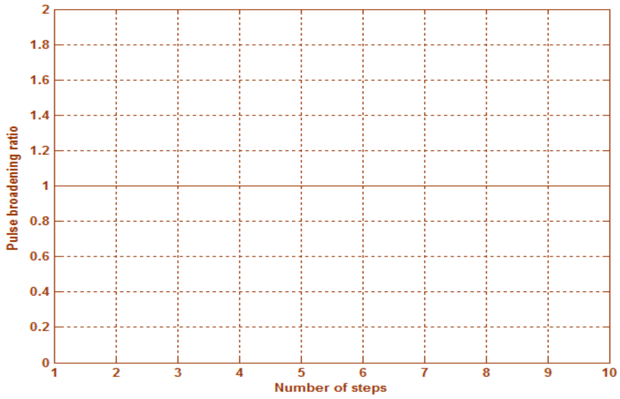

Fig 6: Pulse broadening ratio plot

Fig 7: Phase change of the soliton with distance

The input soliton pulse is shown in fig(4) where we have plotted absolute value of u vs t. Soliton pulse has taken as an input signal and studies all effects that change its shape due to attenuation, dispersion and non-linearity. The spectral output pulse waveform as shown in fig (5), indicate that the pulse broadening is zero for soliton propagation. Received signal will be the replicate of input signal. Output spectrum is a three dimensional plot, which has X, Y and Z axis. In the plots shown X-axis represents "time", Y-axis represents "distance", and Z-axis represents "amplitude". Fig (6) indicates the pulse broadening ratio plot. It is found that input pulse is not broadened with respect to the distance travelled. Fig (7) indicates the phase change with distance travelled. We have done the analysis of self phase non linear effects in optical system. It is observed that self phase non-linear effect and GVD balances each other and hence we get the output pulse without any kind of pulse broadening.

Conclusion

In this paper we deal with the analysis of selfphase nonlinear effect and GVD effect in optical system. Numerical analysis of the nonlinear shrodinger equation is done in matlab to analyze the effects of nonlinearity in fiber. The single pulse and pulse train was used as inputs. The MATLAB file solves NLSE under soliton condition. So that soliton propagation can be simulated. The results are displayed in the form of 3D pulse at regular intervals, phase change and pulse broadening ratios are calculated.The results indicate that soliton propagates in an optical fiber without changing their shape even when travelling over long distances. The group velocity dispersion of the medium and Kerr effect balance each other while soliton is propagating in the optical fiber. Solitons promise to play a decisive role in the next generation.

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