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SOLITONS IN PCF

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Abstract-Solitons are steady and firm nonlinear travelling waves that sustain their shape and speed in interactions .Optical solitons have shown tremendous potential globally in the various domains and because of this lots of research activities are going on and these have attracted much curiosity and interest in the research and industrial cosmos. In this paper, we give a brief overview of the basic idea of temporal solitons, simulate it and see its possible applications and the challenges in the field of Photonic Crystal fiber communications.

Keywords: PCF, Solitons

1. INTRODUCTION

The word soliton refers to steady and firm nonlinear travelling waves that sustain their shape and speed in interactions. Solitons have been discovered in many branches of Physics. In the context of Photnic Crystal Fibers, solitons are not only of fundamental interest but also have practical applications in the field of optical communications. James Scott Russel was the first scientist who discovered a soliton wave in 1834 when he unexpectedly detected in the narrow water canal a smoothly shaped water pile that to his surprise was able to propagate in the canal without an evident change in its shape a few kilometers along. The actual reason of propagation of this solitary wave was not interpreted for a many years until suitable mathematical model was formed in the 1960's together with a method of solving nonlinear equation with the help of inverse scattering method [5]-[8].

The activity of modulation disequilibrium tells that propagation of a continuous-wave (CW) beam inside optical fibers is intrinsic unstable because of the nonlinear phenomenon of SPM and leads to formation of a pulse train in the anomalous dispersion regime of optical fibers.

2. PULSE PROPAGATION IN OPTICAL FIBER

The propagation of light can be precisely described mathematically with Maxwell equations. When equations for magnetic and electric fields are combined together one get

$$\nabla^2\vec{E} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{E} = \frac{1}{\varepsilon_0 c^2}\frac{\partial^2}{dt^2}\vec{P} \qquad (1)$$

Where c is the speed of light in the vacuum and ε0 is the vacuum permittivity. The induced polarization P consists of two parts:

$$\vec{P}(\vec{r},t) = \overrightarrow{P_L}(\vec{r},t) + \overrightarrow{P_{NL}}(\vec{r},t) \qquad (2)$$

Where PL(r,t) and PNL(r, t) are related to electric field by relations:

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$$\overrightarrow{P_L}(\vec{r},t) = \varepsilon_0 \int_{-\infty}^{+\infty} \chi^{(1)}(t-t') \cdot \vec{E}(\vec{r},t')dt' \quad (3)$$

$$\overrightarrow{P_{NL}}(\vec{r},t) = \varepsilon_0 \iiint_{-\infty}^{+\infty} \chi^{(3)}(t-t_1,t-t_2,t-t_3) * \vec{E}(\vec{r},t_1)\vec{E}(\vec{r},t_2)\vec{E}(\vec{r},t_3)\, dt_1dt_2dt_3 \quad (4)$$

Where $\chi(1)$ and $\chi(3)$ are the first and third order susceptibility tensors.

For healthier interpreting a soliton pulse propagation in fibers it is essential to set up our modeling on the mathematical expression (1). We will suppose that a solution for electric filed E have a form:

$$E(r,t) = A(Z,t)\, F(X,Y) \exp(i \beta_0 Z) \quad (5)$$

where F(X, Y) is transverse field distribution which corresponds to the fundamental mode of single mode fiber.

The time dependence of A (Z,t)implies that all spectral components of the pulse may not propagate at the same speed inside the optical fiber because of chromatic dispersion . This effect is included by modifying the refractive index as

$$\tilde{n} = n(\omega) + n_2 |E|^2 \quad (6)$$

The frequency dependence of $n(\omega)$ plays an important role in the formation of temporal solitons. It leads to broadening of optical pulse in the absence of nonlinear effects. To obtain an equation satisfied by the pulse amplitude A (Z, t) ,it is useful to work in the Fourier domain for including the effects the effects of chromatic dispersion and to treat the nonlinear term as a small perturbation. The Fourier transform of $\tilde{A}$ (Z, ω) is found to satisfy

$$\frac{\partial \tilde{A}}{\partial z} - i[\beta(\omega) + \Delta\beta - \beta_0]\tilde{A} \quad (7)$$

Where $\beta(\omega)= k_0\, n(\omega)$ and $\Delta\beta$ is the nonlinear part defined as

$$\Delta\beta = k_0 n_2 |A|^2 \frac{\iint_{-\infty}^{\infty} |F(X,Y)|^4 dxdy}{\iint_{-\infty}^{\infty} |F(X,Y)|^2 dxdy} \quad (8)$$

Above equation implies that each spectral component within the pulse envelope acquires a phase shift whose magnitude is both frequency and intensity dependent as it propagates down the fiber. Taking the inverse transform of Eq.(7) and obtain the propagation for A(Z,t). Expanding β in Taylor series around the carrier frequency ω_0.

$$\beta(\omega) = \beta_0 + \beta_1(\omega-\omega_0) + \frac{1}{2}\beta_2(\omega-\omega_0)^2 + \ldots \quad (9)$$

Where of $\beta_m = (d^m\beta / d\omega^m)$, m=1, 2, 3... Substituting Eq.(9) in Eq.(7) and taking inverse transform we obtain the equation for A(Z, t) as

$$\frac{\partial A}{\partial Z} + \beta_1\frac{\partial A}{\partial Z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = i\gamma |A|^2 A \quad (10)$$

The parameters $\beta_1$and β_2 include the effect of dispersion to first and second orders, respectively. Physically, $\beta_1=1/v_g$, where v_g is group velocity accompanying with the pulse and takes into account the dispersion of group velocity. For this reason, β_2 is called the group velocity dispersion (GVD) parameter. Parameter γ is nonlinear parameter that takes into account the nonlinear properties of a fiber medium. Parameter β_1 is in true case always positive but on the other hand parameters λ_{ZD} and γ can be in some specific case either positive or negative. The parameter β_1 is closely associated in practice with better known parameter called dispersion parameter – D (ps/nm/km). The relation between them is in the form:

$$D = \frac{d}{d\lambda}\left(\frac{1}{vg}\right) = -\frac{2\pi c}{\lambda^2}\beta 2 \qquad (11)$$

As, the dispersion parameter D is a monotonically increasing function of wavelength, crossing a zero point at wavelength λZD, which is called a zero chromatic dispersion wavelength. If a system operates with wavelengths above λZD, where D is positive, β2must be negative and a fiber is said to work in anomalous dispersion mode. If the fiber is run below λZD, the D is negative and β2 must be positive. In this case a fiber is said to operate in normal dispersion mode. As far as the nonlinear parameter γ is concerned, it can be generally either positive or negative, depending on the material of the wave guide. For silica fiber is parameter γ positive but for some other materials it can be negative. More specifically, equation (10) has only two solutions, in the form of either dark or bright soliton. Corresponding to the light pulse there is the bright soliton but a pulse shaped dip in CW light "background" is the dark soliton. In other words, the dark soliton is in a fact negation of the bright soliton. Where there is maximum of light in the bright soliton, there is minimum of the light in the dark soliton and vice versa.. A waveguide in which there is either the positive nonlinearity parameter or fiber is in anomalous dispersion regime or the negative nonlinear parameter but is in normal dispersion regime, only then the bright soliton can propagate in it.

3. SIMULATION AND RESULT

Equation (10) can be normalized in the form

$$i\frac{\partial u}{\partial z} - \frac{s}{2}\frac{\partial^2 u}{\partial \tau^2} \pm|u2|u=0 \qquad (12)$$

By using simple conversion

$$\tau = (t-\beta 1Z)/T0,\ z=Z/LD,\ u=\sqrt{|\gamma|L_D}A \qquad (13)$$

Where T0 is pulse width and LD=T02/|β2| is the dispersion length. Using inverse scattering method reveals the solution of above mentioned equation has a form:

u (z,τ) = N* 2/ (eτ + e-τ)* eiz/2 = N sech (τ) eiz/2 (14)

If N is integer, it represents the order of the soliton pulse. Very interesting situation comes when N=1.

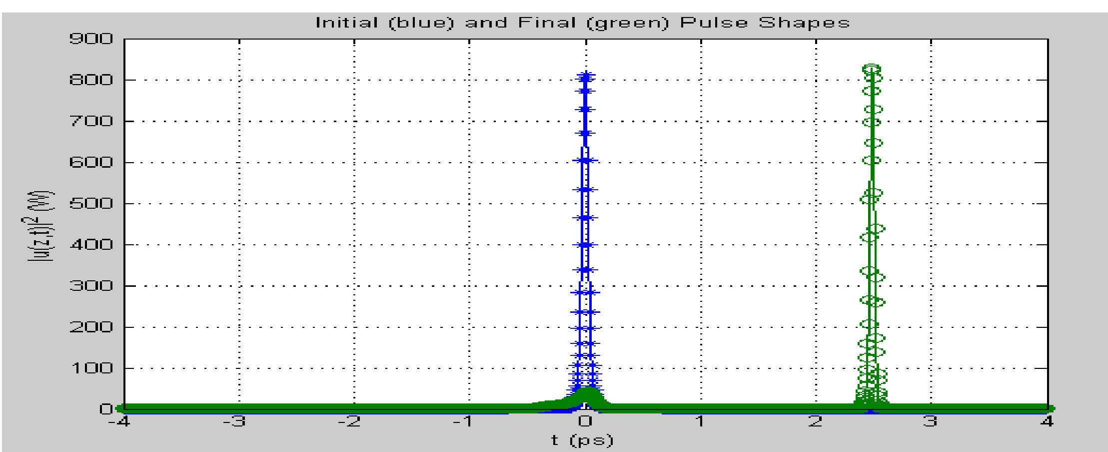

Figure: 1 Pulse intensity versus propagation time

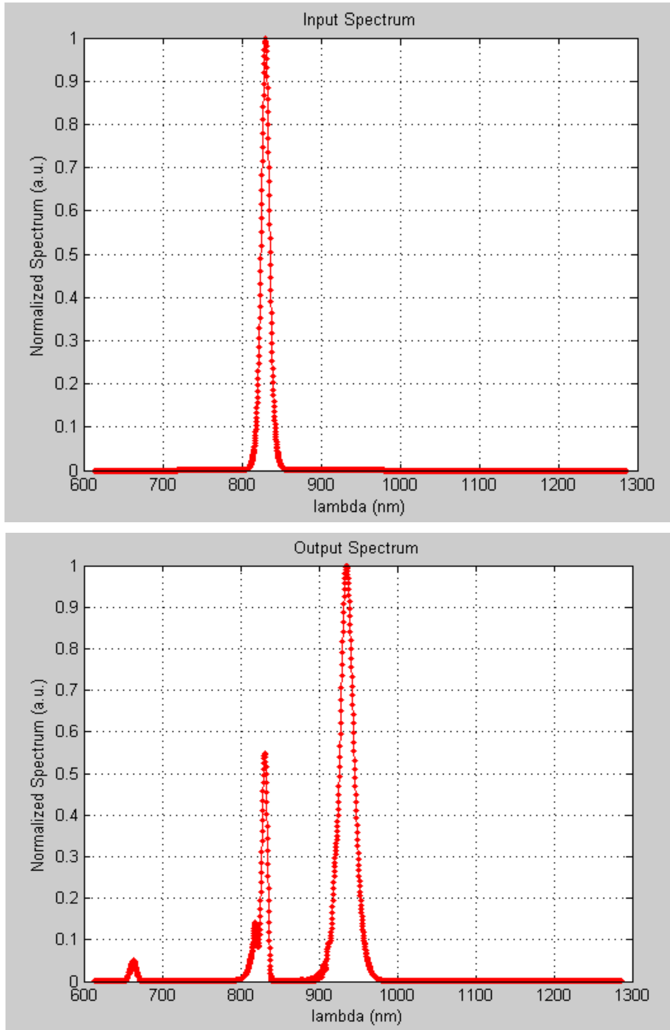

Figure: 2 Input Spectrum Vs. Output Spectrum

As seen from figure 1 and 2 that in this case of first order soliton, the pulse does not change its shape at all as it propagates in optical fiber. In contrast when N is higher than one, pulse shape is not stable and change periodically with soliton period. Z0 = $(\pi/2)$ LD At the end of every period Z0 the soliton resembles its initial simple pulse shape. This shows that inclusion of higher terms alter the pulse in time and quicken its broadening.

By seeing the solitonic behavior there is a fascinating expectation of using the PCFs as dispersion compensating or dispersion managed fibers for optical communication systems .It is evident that for telecommunication purposes the soliton of first order is most suitable, because in this application is necessary to keep a pulse shape stable.

N defines the order of soliton and is defined by:

$$N = T_0\sqrt{\frac{\gamma P_0}{\beta_2}} \qquad (15)$$

Where T0 corresponds to input pulse width, P0 is pulse peak power.β2takes into account group velocity dispersion and γ is nonlinear parameter of the fiber material.

4. CONCLUSIONS:

In this paper a numerical analysis based on simulations have been exploited to know the behavior of the propagation of solitonic pulses in nonlinear PCF. The investigation has been done in time and frequency domain to fully study the nonlinear effect. Several discussion based on numerical result have been conducted.

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