The effect of Polarization-Mode Dispersion on Transmission of Soliton and Interaction of Solitons

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Abstract: In optical fiber communication, polarization mode dispersion(PMD) effect optical soliton transmission. Through coupled Schrodinger equation, the paper analyses the adaptability of optical soliton pulse drift and self-trapping effects separately with the single pulse. The simulated result indicates PMD can lead to distortion of optical soliton and optical soliton pairs. As a result, frequency shift and pulse width is happened what will be more and more obvious with group velocity mismatch of soliton normalization between the two polarization components (δ). The self-trapping effect that make soliton transmission maintain free-distortion can counteract PMD effect only when δ is small.

Keywords: Polarization mode dispersion; optical soliton; coupled non-linear Schrodinger equation; self-trapping effect; optical fiber communication

1 Introduction

Soliton transmission system has great potentiality over high speed and long-distances transmission. To make use of high speed optical soliton transmission we are likely to improve the current performance of fiber-optic network. Compare with current conventional fiber optic communication system which is based on linear optics theory, the most obvious advantage of soliton communication system basing on nonlinear optical theory is its huge communication capacity [1]. The transmission capacity is 1-2 orders of magnitude higher than current best communication system and the relay distance is up to several hundred km. It is considered as the most promising way of transmission in next generation.

2 The influence of PMD effects on high speed optical fiber communication system

Polarization mode dispersion (PMD) has more and more obvious role in limiting the capacity of optical soliton communication and becomes an important factor of limiting high-speed transmission system [2]. According to reports, when the PMD is very small, self-trapping effects can limit the soliton pulse splitting [3]. In the case of soliton self-trapping, two orthogonal polarization solitons can make velocity movement in group. Despite their different pattern of refractive indexes (there is polarization mode dispersion), but still they can move in the same group velocity[4]. The existence of soliton self-trapping effect due to the presence of cross-phase modulation, cross-phase modulation causes nonlinear coupling and make two solitons transmit by the same group velocity. Soliton is considered to have resistant ability on polarization mode dispersion; it can inhibit pulse splits and excess-broadening[1]. Making use of polarization multiplexing method we can double the capacity of soliton systems.

Nonlinear Schrödinger equation (NLSE) is an equation which calculates evolution rules of light pulses which simultaneously exist in nonlinear optical fiber and dispersion situation; it is the basic equation to study the transmission of light pulses in the fiber. Typically nonlinear terms in NLSE only include self-phase modulation (Self-phase modulation, referred to as SPM), and in the multi-wavelength system there is cross-phase modulation (Cross phase modulation, referred to as XPM).In the broad sense of NLSE it should also include non-elastic stimulated scattering in fibers, mainly influenced by Stimulated Raman scattering (Stimulated Raman Scattering, referred to as SRS) and Stimulated Brillouin scattering (Stimulated Brillouin Scattering, referred to as SBS).

3 Theoretical model

Please acknowledge collaborators or anyone who has helped with the paper at the end of the text.

In optical fiber communication, considering the slowly varying envelope approximation and first-order perturbation theory, we can get the fundamental equation of optical pulse under nonlinear dispersive optical fiber transmission. [2]

$$i\frac{\partial A}{\partial z}+\frac{i\alpha}{2}A-\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2}+\gamma|A|^2 A=0 \tag{1}$$

In the formula, A (z, t) is the slowly varying amplitude, α represents loss of optical fiber, represents group velocity dispersion which is related with pulse width.

γ is Non-linear coefficient. In the special case α = 0, the equation is called nonlinear Schrödinger equation (NLSE). Nonlinear Schrödinger equation is a basic equation of nonlinear science which has been widely used to studies on soliton.

While neglect fiber loss and make use of transmission characteristics of light pulse along with two main axes of two orthogonal polarizations, we can adopt normalized coupled nonlinear Schrödinger equation to describe it and the specific equation is as follows:

$$i\frac{\partial u}{\partial \xi}+i\delta\frac{\partial u}{\partial \tau}+\frac{1}{2}\frac{\partial^2 u}{\partial \tau^2}+\left(|u|^2+B|v|^2\right)u=0 \qquad (2.1)$$

$$i\frac{\partial v}{\partial \xi}-i\delta\frac{\partial v}{\partial \tau}+\frac{1}{2}\frac{\partial^2 v}{\partial \tau^2}+\left(|v|^2+B|u|^2\right)v=0 \qquad (2.2)$$

In this formula, u, v are the normalized amplitude changing along the fiber axis, ξ is the normalized distance along the optical transmission, τ is normalized time, δ describes the group velocity mismatch between the two polarization components in normalization. B is coupling parameter of birefringence fiber cross-phase modulation (XPM), here we chose 2/3. The normalized variables are: $\xi = z / LD$, $\tau = (t-\beta_{1z}) / T_0$,$\delta = (\beta_x-\beta_y)\, T_0 / 2\, |\, \beta_2\, |$. Where $LD = T_{02} / |\, \beta_2\, |$ is the dispersion length, T_0 is the initial incident pulse width, β_x and β_y respectively represents the transfer constants in x, y direction. Ordinary optical fiber in the vicinity of 1550nm the typical value is β_2 = 17ps2/km, γ = 2W-1/km. Select the full width half maximum TFWHM = 20ps, pulse width T_0 = TFWHM/1.763.

4 Numerical simulation results and discussion

4.1 Optical soliton transmission without PMD

Fourier method is adopted to simulate the soliton transmission in optical fiber.The initial input of soliton pulses is in manakov form:

$$A(0,t)=\sqrt{\frac{9}{8}}\sec h(t/T_0) \qquad (3)$$

In the formula A and T_0 have the same meaning as before. We can get evolution map of optical solitons which is shown in Figure 1. It can be seen from Figure 1 that the optical soliton maintains its original shape well in the transmission. The reason is that the input soliton pulse makes the fiber dispersion effect be exactly compensated by nonlinear optical fiber, so the pulse shape and amplitude remain unchanged.

4.2 Important Information

Fourier method is adopted to simulate the soliton transmission in optical fiber.The initial input of soliton pulses is in manakov form:

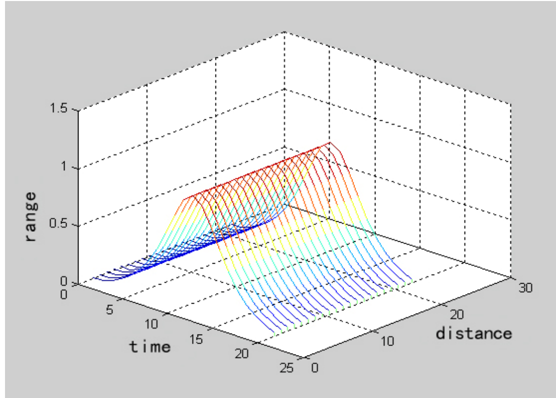
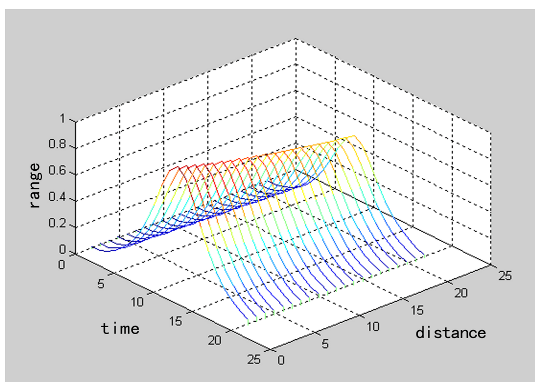


Figure1: Distortion-free transmission of optical soliton

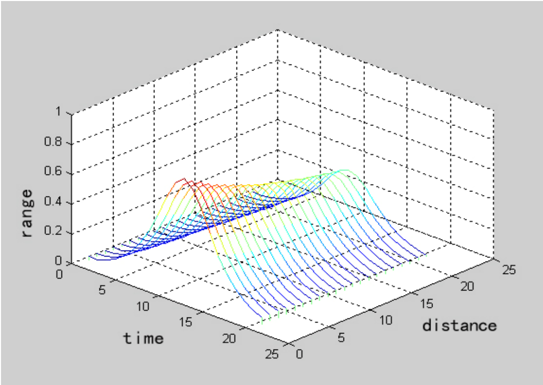
As statistical characteristics of random change in PMD along the optical fiber, it will divide a number of equal length segments randomly in computing model along the length of birefringence optical fiber. The birefringence intensities of each segment are same, namely every section's normalized time delay is same [5]. Making assumption that beat-length of fiber is less than the dispersion length and each subparagraph length. It can adopt numerical simulation on the influences of polarization mode dispersion phenomenon on soliton propagation properties. The role of polarization mode dispersion phenomenon is reflected in following case: the birefringent axes go through certain distances and get a random rotation on an angle of θ, while between the two polarization components they can produce a random phase difference φ. While the later numerical simulation, θ and φ is changed between [-π, π] and [-π / 2, π / 2] randomly. Junction in the optical fiber can satisfy the following relationship:

$$\begin{bmatrix} u_{out} \\ v_{out} \end{bmatrix}=\begin{bmatrix} \cos\theta & \sin\theta\exp(i\phi) \\ -\sin\theta\exp(-i\phi) & \cos\theta \end{bmatrix}\begin{bmatrix} u_{in} \\ v_{in} \end{bmatrix} \qquad (4)$$

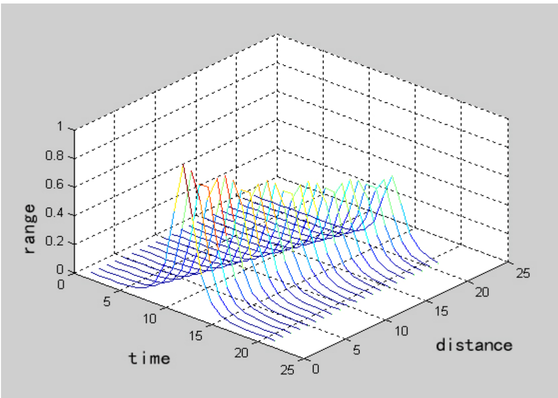
Through computer simulation we can get optical soliton graph which is shown in Figure 2 which contains PMD.



(a)δ = 0.03



(b)δ = 0.3



(c) δ = 1.0

Figure 2: Exist optical solitons transmission in polarization mode dispersion

It can be seen from Figure 2 that when soliton normalization between the two polarization components has smaller group velocity mismatch, that is, when the δ value is smaller, two soliton polarization components can move in similar group speed. Soliton pulse width does not change obviously; the peak frequency of soliton does not drift, only the optical soliton pulse amplitude decrease to a certain extent. This shows that under the influences of polarization mode dispersion it generates radiation wave, a part of the energy of radiation. Soliton self-trapping effect is caused by the XPM nonlinear coupling to bring along the fast axis of the solitons slow down, speed up the soliton along the slow axis to allow the two component solitons get time domain synchronization. From Figure 2 (a) we can see that although there is group velocity mismatch between the two components, the soliton self-trapping effect can make optical soliton transmission maintain free-distortion.

However, when the δ value increases as it is shown in Figure 2 (b), disturbance of optical soliton pulses generates frequency drift and pulse broadening phenomenon. In Figure 2 (c) the optical soliton pulse has a clear distortion, center frequency drift and occurrence of pulse broadening phenomenon. At this time, the self-capture effect of optical solitons can not guarantee distortion-free soliton transmission. The balance between second-order optical soliton group velocity dispersion and nonlinear effect is damaged by PMD; the two polarization components have delay difference which resulting in distortion of optical solitons.

4.3 Interactions between polarization mode dispersion contains optical soliton

As we all know, the interaction between solitons is the factor we must take into account during soliton transmission. This paper chooses two neighboring solitons to PMD for analysis on the impact of soliton. With polarization mode dispersion for two optical solitons, we can adopt coupled Schrodinger equation to make simulation. Clearly, only when two solitons are close enough to overlap at the end, they begin to influence each other. We write the total optical field as $u = u_1 + u_2$, where

$$u_j(\varepsilon,\tau) = \eta_j \operatorname{sec}h[\eta_j(\tau - q_j)]\exp(i\phi_j - i\delta_j\tau) \quad (j = 1,2) \qquad (5)$$

At this time, not u u_1 and u_2 but u satisfies the nonlinear Schrödinger equation. In fact, taking equation into (1), we can get nonlinear Schrödinger equation to meet the following soliton perturbation of u_1:

$$i\frac{\partial u_1}{\partial \varepsilon} + \frac{1}{2}\frac{\partial^2 u_1}{\partial \tau^2} + |u_1|^2 u_1 = -2|u_1|^2 u_2 - u_1^2 u_2^* \qquad (6)$$

We can change u_1 and u_2 and get the equations which can meet u_2. At the right of the equation we can see as entry perturbation, it is related with two adjacent nonlinear soliton effects.

The relative distance between the two solitons is related with their relative phase q. Whether the two solitons attract each other or mutually exclusive, depending on their initial phase ψ.

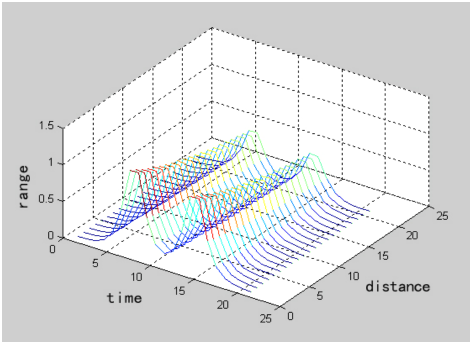
Using split-step Fourier method to solve the problem and the initial inputs of soliton pulses are:

$$u(0,\tau) = \sqrt{\frac{9}{8}}\{\operatorname{sec}h(\tau - q_0) + r\operatorname{sec}h[(r(\tau + q_0)]\exp(i\theta)\} \qquad (7.1)$$

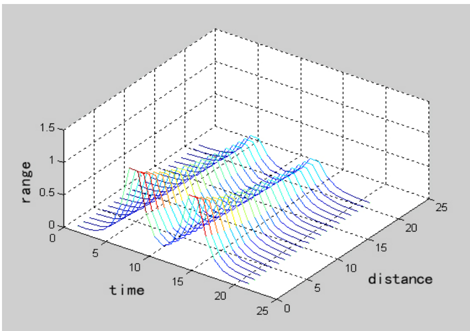
$$v(0,\tau) = 0 \qquad (7.2)$$

In the formula, r is the relative amplitude, θ is the initial phase, $2q_0$ is the initial distance between the two solitons. In order to minimize the interaction realtionship between solitons and highlight the impacts of polarization mode dispersion, we choose r = 1.1, ie two solitons have the different amplitudes. The initial phase choice is π / 2, which is positive between the two solitons cross the polarized state. The initial distance between the two soliton select $2q_0 = 8$.

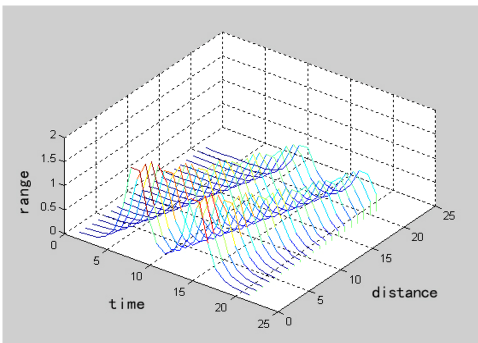
So we can get evolution map two solitons in the optical fiber with PMD as shown in Figure 3.



(a)δ=0.03



(b) δ =0.3



(c) δ =1.0

Figure 3: Two optical solitons transportation with PMD

As it can be seen from Figure 3, since the choice of initial phase and amplitude, the interaction between solitons is almost completely inhibited[3], but the impact of PMD has brought obvious radiation which makes optical soliton pairs have great losses in the transmission. With the strength of PMD becoming from small to large, the exchange of energy between two solitons increases, optical soliton transmission changes into more significant frequency shift and pulse width from the previous state.

For practical optical fiber communication systems, we often use WDM or DWDM system. The WDM system which exists polarization mode dispersion have different channel and will lead to the optical soliton interaction in the same channel soliton polarization. If the system uses polarization division multiplexing (PDM) technology and maintains the different soliton amplitudes, it can guarantee better features for optical soliton transmission system.

5 Conclusion

It can be seen from the above analysis that polarization mode dispersion has very serious influences on optical soliton transmission system. For high speed optical soliton communication, the increasing rate increases will give rise to intensified polarization mode dispersion. This will not only lead to increased optical soliton communication system bit error rate and decreased capacity, the system will create a range of issues such as timing jitter. Therefore, we need to control the optical soliton transmission system. In the time domain we adopt sliding frequency filter technology to place periodic band-pass optical filter in the transmission line. In the frequency we adopt synchronous amplitude modulation and modulate the transmission of optical soliton to implement periodic sine wave modulation.

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