Influence of Glass Fiber Nonlinearity and Dispersion on Light propagation in Double Core Optical Fiber

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Abstract. Influence of coupling and intermodal dispersion coefficient on pulse splitting in double core optical fibre was investigated by using solutions of normalized coupled nonlinear Schrödinger equations. It was found that if coupling coefficient and intermodal dispersion coefficient was small, and then nonlinearity cannot balance intermodal dispersion effect. Consequently, pulse was distorted. Furthermore, if intermodal dispersion coefficient was large enough, then pulse splitting occurred. Increasing coupling coefficient avoids pulse splitting and the pulse was stable.

Keywords: double core fiber, coupled nonlinear Schrodinger equation, intermodal dispersion.

1. Introduction

The communication system can transmit information from one place to another that separated by a great distance. In the optical communication system, information is carried by high carrier frequency (~ 100 THz) in the infrared region. The optical communication system is a system that uses single mode fiber optics to transmit information.

The transmission of signals through optical fiber has advantages when compared to electric wave transmission systems and microwaves. Among others, its size is very small and lightweight so easy in handling and their installation. Light waves are unaffected by electrical interference and magnetic fields. Large capacity optical fiber transmission, so that it can transmit large amounts of information and quick. One of the tools developed is a fiber optic double-core (directional coupler) that function as components of optical switching, wavelength division multiplexing device, and breaking power or power divider [1].

Double-core optical fiber (DCF) is often used in modern optical communication systems [2]. DCF fiber is a fiber that consists of two identical optical fibers, each of which has a bimodal structure that supports the mode symmetry and asymmetry mode [3]. When power is launched into one of the cores, then a power is transferred from the first core to the second core. In general, these two modes have different group velocity, so that input pulse will broaden and be split after propagating a certain distance. Effect that causes the pulse became distorted called intermodal dispersion (IMD). IMD can create distorted pulses and pulse splitting occurs. Furthermore, Tan et al showed that DCF is effective to be applied in highly power CW fiber laser construction [4].
Power transfer mechanism in two-core optical fiber is characterized by the parameter coupling coefficient. In general, the coupling coefficient depends on the wavelength. This leads to the intermodal dispersion. Intermodal dispersion can limit the bandwidth of the two-core optical fiber, as well as the pulse splitting, can occur. It was found that the pulse splitting can be suppressed by making the dispersion intermodal is quite small, the coupling coefficient is quite large, and large input power is injected into.

The investigation of the propagation of light in optical fibers has been done. However, the investigation on the effect of the interaction of intermodal dispersion and nonlinearity presented by coupling coefficient to minimize the pulse distortion and even avoid the pulse splitting in two-core optical fiber in detail yet done [5-9].

2. Propagation of optical pulse in double-core optical fiber (DCF)

DCF is a fiber that consists of two single-mode core. The physical mechanism of transfer of power between two-core DCF can be explained using couple mode theory, as shown in Figure 1. Based on couple mode theory, when the pulse is launched in one of the cores, then part of the pulses is coupled to the other core as it passes through the area along the $L_C$ coupling interaction. Beam pulses that are not coupled to the output of cores will come out first.

![Figure 1. The mechanism of propagation of light in DCF [3].](image)

DCF has a bimodal structure, which consists of even mode (symmetry) and the odd mode (anti-symmetry), respectively. The propagation of supermode into double-core optical fiber is described by the following set of normalized coupled nonlinear Schrödinger equations [3, 9] For a symmetric coupler with two identical cores, the coupled-mode equations for symmetric couplers are:

$$\frac{\partial A_1}{\partial z} + \frac{1}{v_g} \frac{\partial A_1}{\partial t} + \frac{i \beta_2}{2} \frac{\partial^2 A_1}{\partial t^2} = i \kappa A_2 + i \gamma \left| A_1 \right|^2 + \sigma \left| A_2 \right|^2 A_1$$  \hspace{1cm} (1)

$$\frac{\partial A_2}{\partial z} + \frac{1}{v_g} \frac{\partial A_2}{\partial t} + \frac{i \beta_2}{2} \frac{\partial^2 A_2}{\partial t^2} = i \kappa A_1 + i \gamma \left| A_2 \right|^2 + \sigma \left| A_1 \right|^2 A_2$$  \hspace{1cm} (2)

For a symmetric coupler, the general solution of Equation (1) and Equation (2) can be written in a matrix form as

$$\begin{pmatrix} A_1(L) \\ A_2(L) \end{pmatrix} = \begin{pmatrix} \cos(\kappa L) & i \sin(\kappa L) \\ i \sin(\kappa L) & \cos(\kappa L) \end{pmatrix} \begin{pmatrix} A_1(0) \\ A_2(0) \end{pmatrix}$$  \hspace{1cm} (3)

The determinant of the 2×2 transfer matrix on the right side is unity, as it should be for a lossless coupler. Typically, only one beam is injected at the input end. The output powers, $P_1(L) = \left| A_1 \right|^2$ and $P_2(L) = \left| A_2 \right|^2$, are then obtained from Equation (3) by setting $A_2(0) = 0$ and are given by
\begin{align}
R_1(L) &= P_0 \cos^2(\alpha L), \\
R_2(L) &= P_0 \sin^2(\alpha L),
\end{align}

where \( P_0 = A_0^2 \) is the incident power at the first input port. The double-core optical fiber acts as a beam splitter, and the splitting ratio depends on the parameter \( \alpha L \).

\begin{align}
\frac{\partial A_1}{\partial z} + \kappa_1 \frac{\partial A_2}{\partial T} + \frac{i \beta_2}{2} \frac{\partial^2 A_1}{\partial T^2} + \frac{i k_2}{2} \frac{\partial^2 A_2}{\partial T^2} &= i \kappa_0 A_2 \\
\frac{\partial A_2}{\partial z} + \kappa_1 \frac{\partial A_1}{\partial T} + \frac{i \beta_2}{2} \frac{\partial^2 A_2}{\partial T^2} + \frac{i k_2}{2} \frac{\partial^2 A_1}{\partial T^2} &= i \kappa_0 A_1
\end{align}

In case of pulse propagation in a linear DCF which the nonlinear terms in Equation (1) and Equation (2) were ignored, Li et al. showed that the strong effects of intermodal dispersion will split pulses propagating in linear DCF. The results of Li [10] show clearly that group velocity dispersion (\( R \)) and coupling coefficient (\( R_i \)) exert different effects on pulse propagation, both of which will destroy the integrity of the pulse. Now, the question is whether the nonlinearity can balance the both effects of group velocity dispersion (\( R \)) and coupling coefficient (\( R_i \)) to keep the integrity of the pulse over a long distance. This questions will be numerically investigated in this article.

3. Research Method

The physical model of pulse propagation in dcf is derived from a set of generalized coupled nonlinear schrödinger equations, Equation (6) and Equation (7), by varying the parameters of group velocity dispersion (\( r \)), coupling coefficient (\( r_i \)) and power input, it can be analyzed the effect of variation those parameters on the pulse propagating in DCF. Pulses injected into one of the cores in double-core optical fiber are expressed by Equation (8) and Equation (9).

\begin{align}
R_1(L) &= P_0 \cos^2(\alpha L), \\
R_2(L) &= P_0 \sin^2(\alpha L),
\end{align}

where \( P_0 \) is the input power. In terms of normalization, \( P_0 = 1 \) actually corresponds to one soliton power [3], the power required for soliton formation in single-core fibers. Equation (8) and Equation (9) are numerically solved with the initial condition of Equation (6) by employing pseudo-spectral method in the time domain and fourth-order Runge-Kutta method in the spatial domain with the adaptive step-size control [9-12]. Effect of intermodal dispersion (\( R_i \)) and the coupling coefficient (\( R \)) were studied by varying \( R_i \) and \( R \) for two different input power values. Thus, the influence of the input power to the pulse propagation in the double core optical fiber can also be known.

4. Results and Discussion

Table 1 shows pulse propagation for various intermodal dispersion coefficient. Coupling coefficients are kept constant, \( R = 1 \). For a relatively weak power \( P_0 = 1 \), significant pulse distortion appears even at a very weak intermodal dispersion value as illustrated in Table 1(a) for \( R_i = -0.15 \). As intermodal dispersion becomes strong, distinct pulse splitting is observed as shown by Figure 1(c) for \( R_i = -1 \) and Table 1(e) for \( R_i = -2 \). It is seen that pulse splitting occurs at strong IMD values.

The power \( P_0 = 1 \) is sufficient to balance the effects of intermodal dispersion. For a strong input power \( P_0 = 4 \), pulse propagations are shown by Table 1(b), Table 1(d), and Table 1(f). When input power \( P_0 \) is stronger, \( P_0 = 4 \), pulse distortion occurs (Table1(b)). As intermodal dispersion becomes strong, distinct pulse splitting is observed as shown by Table 1(d) for \( R_i = -1 \) and Table 1(f) for \( R_i = -2 \). It can be concluded that for small \( R_1 \) and \( R \), pulse splitting still occurs even if the input power is stronger.
**Table 1.** Comparison of pulse propagation in a nonlinear two-core fiber between at $P_0 = 1$ and at $P_0 = 4$ with $R = 1$ for (a) and (b) $R_1 = -0.15$; (c) and (d) $R_1 = -1.0$; (e) and (f) $R_1 = -2.0$.

| $P_0$ | $R$ | $R_1$ | Normalized slowly varying amplitude envelope of electric field in core of DCF |
|-------|-----|-------|--------------------------------------------------------------------------------|
| 1     | 1   | $-0.15$ | ![Image](image1.png) |
| 4     | 1   | $-0.15$ | ![Image](image2.png) |
| 1     | 1   | $-1.0$  | ![Image](image3.png) |
| 4     | 1   | $-1.0$  | ![Image](image4.png) |
| 1     | 1   | $-2.0$  | ![Image](image5.png) |
Table 2. Comparison of pulse propagation in a nonlinear two-core fiber between at $P_0 = 1$ and at $P_0 = 4$ with $R_1 = -0.15$ for (a) and (b) $R = 5$; (c) and (d) $R = 10$; (e) and (f) $R = 20$.

| $P_0$ | R  | $R_1$ | Normalized slowly varying amplitude envelope of electric field in core of DCF |
|------|----|-------|--------------------------------------------------------------------------------|
| 1    | 5  | -0.1 5| ![Diagram](4.png)                                                                 |
| 4    | 5  | -0.1 5| ![Diagram](5.png)                                                                 |
| 1    | 0  | -0.1 5| ![Diagram](6.png)                                                                 |
Table 2 shows pulse propagation for various coupling coefficient. Intermodal dispersion coefficients are kept constant, $R_1 = -0.15$. For a relatively weak power $P_0 = 1$ and $R$ is small, significant pulse distortion appears as illustrated in Table 2(a) and Table 2(b) for $R_1 = -0.15$. As coupling coefficient increases, the pulse splitting is suppressed, as shown in Table 2(c) and Table 2(d) for $R = 10$ and Table 2(e) and Table 2(f) for $R = 20$. When $P_0$ and $R$ are large enough, the pulse splitting vanishes as shown in Table 1(f).

5. Conclusion
Pulse splitting and pulse distortion can be effectively avoided by increasing the Kerr nonlinearity of the fiber. The presence of nonlinearity of optical fiber will balance the effect of dispersion. Nonlinearity of optical fiber can be increased by increasing the power $P_0$. The power of pulse required to balance the two effects must be several times of one soliton power. Intermodal dispersion coefficient $R_1$ required to balance must be smaller than 1 and the coupling coefficient $R$ must also be very strong, i.e. $R >> 1$. 
6. References

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