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Pulse Propagation in a Nonlinear Two-Core Fiber under the Effects of Intrapulse Stimulated Raman Scattering

M. Liu[1)]

College of Communication Engineering, Chongqing University, Chongqing, China

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The switching dynamics of short pulses under the effects of intrapulse stimulated Raman scattering (ISRS) and intermodal dispersion is studied. It is found that ISRS can generally reduce the pulse width and slow down the pulses simultaneously. With numerical examples, we demonstrate that the pulse narrowing effect of ISRS can be weakened by the intermodal dispersion.

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1. Introduction. Pulse switching in a nonlinear two-core fiber has attracted considerable interest over the years because a two-core fiber can provide a long interaction length and hence lower greatly the required switching power. Intermodal dispersion in a two-core fiber has been proposed [1] and confirmed experimentally to have the effect of causing pulse breakup in the fiber [2]. In the experiment, it has been demonstrated that the intermodal dispersion can be strong enough to break up picosecond pulses with a meter-long two-core fiber. As the strength of the intermodal dispersion increases inversely with the pulse width, a center-meter long fiber is sufficient to distort femtosecond pulses. The pulse breakup effect in a two-core fiber has in fact been applied to the generation of ultra-high-bit rate pulses [3]. The effects of intermodal dispersion in a passive two-core fiber have been investigated in detail [4 – 6]. We have also shown that, in an active two-core fiber, the pulse breakup effect caused by the intermodal dispersion in the fiber can be suppressed by limiting the gain bandwidth of the active medium [7, 8].

To the best of our knowledge, in previous study on two-core fibers, the effects of intrapulse stimulated Raman scattering (ISRS) [9], a nonlinear effect which is responsible for the soliton self-frequency shift, have been intentionally neglected. In this Letter, we extend the research to study the effects of ISRS in a nonlinear two-core fiber. Since ISRS can change the spectral content of a short pulse, it can generally cause pulse distortion. It is therefore of practical interest to understand how ISRS affects pulse propagation in a two-core fiber. We present numerical examples to demonstrate the interaction between these two mechanisms, i.e., ISRS and intermodal dispersion.

[1)]e-mail: pg00384190@ntu.edu.sg

2. Analysis and Discussion. A lossless fiber with two parallel identical single-mode cores embedded in a common cladding is analyzed. The propagation of short pulses in the fiber is described by a pair of nonlinear coupled-mode equations:

$$i\left(\frac{\partial a_1}{\partial Z}+R'\frac{\partial a_2}{\partial T}\right)+\frac{1}{2}\frac{\partial^2 a_1}{\partial T^2}+Ra_2+|a_1|^2a_1=\tau_{\rm R}\frac{\partial |a_1|^2}{\partial T}a_1, \quad (1)$$

$$i\left(\frac{\partial a_2}{\partial Z}+R'\frac{\partial a_1}{\partial T}\right)+\frac{1}{2}\frac{\partial^2 a_2}{\partial T^2}+Ra_1+|a_2|^2a_2=\tau_{\rm R}\frac{\partial |a_2|^2}{\partial T}a_2, \quad (2)$$

where a_1 and a_2 are the normalized envelopes of the pulses carried by the modes of the two cores, respectively. $Z = z/IL_{\rm D}$ is the normalized propagation distance along the fiber with $L_{\rm D} = T_0^2/|k''|$ the dispersion length, k'' the group-velocity dispersion ($k'' < 0$ assumed), and T_0 the width of the input pulse. $T = (t-z/\nu_{\rm g})/T_0$ is the normalized time coordinate with $\nu_{\rm g}$ the group velocity of the pulses. The parameter R is the normalized coupling coefficient, which depends on the overlap of the mode fields in the two cores and accounts for the well-known phenomenon of periodic power transfer between the two cores. The parameter R' is known as the intermodal dispersion, which is a measure of the dependence of R on the angular optical frequency. It can cause pulse distortion or even pulse breakup when the input pulses are sufficiently short [4 – 6]. For a typical two-core fiber, the range of R and R' for a 100-fs pulse are 0.01 to 1000 and -0.01 to -10, respectively [5]. The above equations differ from the previous ones [4] in having the new terms on the right-hand sides that account for the effects of ISRS [9]. The parameter $\tau_{\rm R}$ is known as the normalized Raman scattering coefficient. It can be expressed as $\tau_{\rm R} = T_{\rm R}/T_0$, where $T_{\rm R}$ has a value of ~ 6 fs for a typical glass fiber.

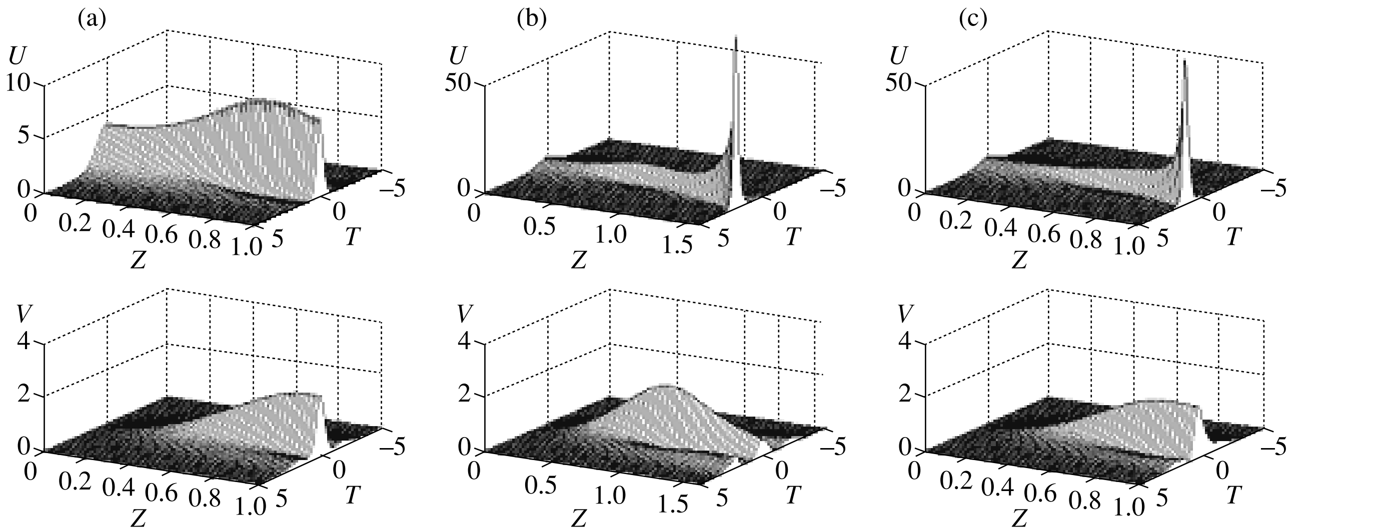

Fig.1. Pulse propagation in a nonlinear two-core fiber in the absence of intermodal dispersion $R' = 0$ with $R = 1.0$ and $A = 2.0$ for (a) $\tau_R = 0$, (b) $\tau_R = 0.04$ and (c) $\tau_R = 0.08$

In our study, we assume that a pulse is launched into one of the cores of the fiber, namely,

$$a_1(0,T) = A\text{sech}(T) \quad \text{and} \quad a_2(0,T) = 0, \tag{3}$$

where A is the normalized amplitude of the pulse. Equations (1) and (2) are solved numerically by the Fourier series analysis method [10].

In order to observe the effects of ISRS, we first consider the case where the intermodal dispersion is negligible (i.e., $R' = 0$). When the input amplitude is small, the pulse couples back and forth between the two cores with little distortion. When the input amplitude becomes sufficiently large, the nonlinear change in the refractive index of the launching core becomes large enough to trap the input pulse in that core along the fiber. The propagation dynamics with $R = 1.0$ for high-power situation $A = 2.0$ is shown in Fig.1a. In the figures, $U = |a_1|^2$ and $V = |a_2|^2$ denote the output light intensities in the two cores. The pulse is mainly trapped in the launching core, as described. We now increase the effect of ISRS progressively (which is equivalent to decreasing the pulse width). The propagation dynamics for $\tau_R = 0.04$ ($T_0 \sim 150\,\text{fs}$), and 0.08 ($\sim 75\,fs$) are shown in Fig.1b,c, respectively. It can be seen from these figures that an increase in τ_R results in a reduction in the pulse width and hence an increase in the peak intensity of the pulse. The peak intensity of the pulse in the input core at $Z = 1.0$ is increased from 7.3 to 66.9 when τ_R is increased from 0 to 0.08. The corresponding change in the normalized pulse width is from 2.5 to 1.7. In addition, the pulse shifts in the time domain, which indicates a reduction in the group velocity, and the amount of time shift increases with τ_R. The reason is that ISRS tends to transfer the pulse energy from higher-frequency components to lower-frequency components which travel at lower speeds (because $k'' < 0$). For example, the pulse gets an additional delay of 1.3 (comparing with the case for $\tau_R = 0$) at $Z = 1.0$ for $\tau_R = 0.08$, as shown in Fig.1c. This delay is comparable to the width of the compressed pulse, and therefore very significant.

We next incorporate the intermodal dispersion in the analysis (i.e., $R' \neq 0$). It has been shown that the intermodal dispersion in the fiber can broaden the pulse and eventually break up the pulse into two for lower input amplitude [4–6]. When the input amplitude is larger than the critical amplitude, the effects of intermodal dispersion become less significant [6], and this is because the pulse is trapped mainly in the input core. The pulse propagation under the effects of ISRS and intermodal dispersion has been shown in Fig.2. The propagation dynamics calculated for $R = 1.0$, $R' = -0.25$, and $A = 2.0$ at $\tau_R = 0$, 0.04, and 0.08 are shown in Fig.2a-c, respectively. The results for stronger intermodal dispersion $R' = -0.5$ with other parameters remained the same are shown in Fig.3a-c. A comparison of Fig.1a, Fig.2a, and Fig.3a confirms that the effects of intermodal dispersion are not significant when the input pulse amplitude is sufficiently large. The interaction between ISRS and intermodal dispersion, however, can change the pulse propagation significantly. In general, the pulse-narrowing process of ISRS is slowed down by the intermodal dispersion in the fiber. With $\tau_R = 0.04$, the propagation distance at which the peak intensity of the pulse reaches 50, denoted as Z_{50}, is 1.6

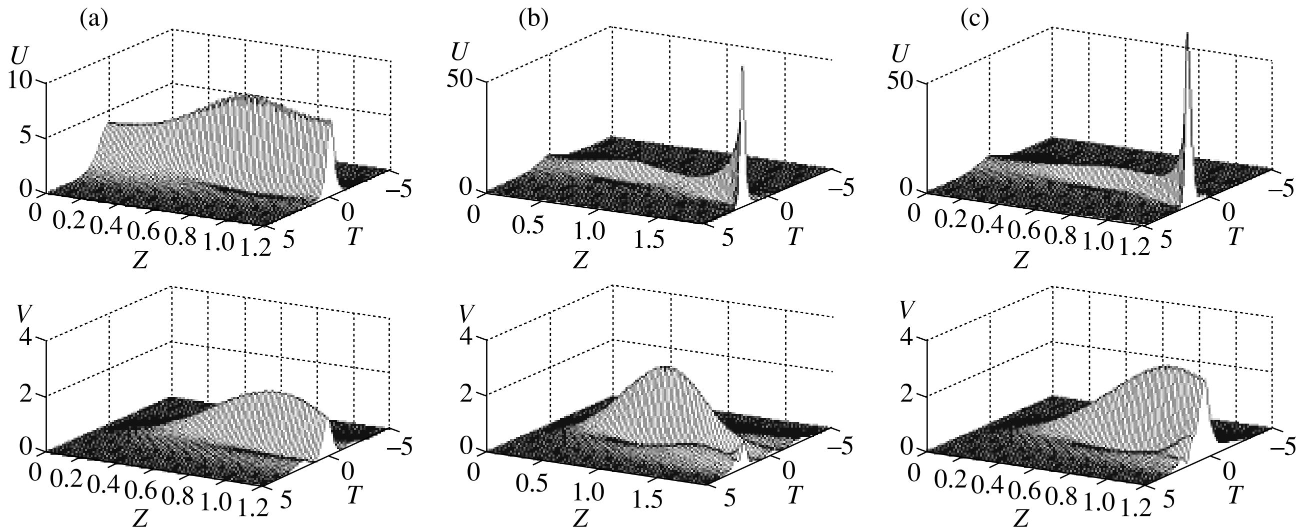

Fig.2. Pulse propagation in a nonlinear two-core fiber in the presence of intermodal dispersion $R' = -0.25$ with $R = 1.0$ and $A = 2.0$ for (a) $\tau_R = 0$, (b) $\tau_R = 0.04$, and (c) $\tau_R = 0.08$

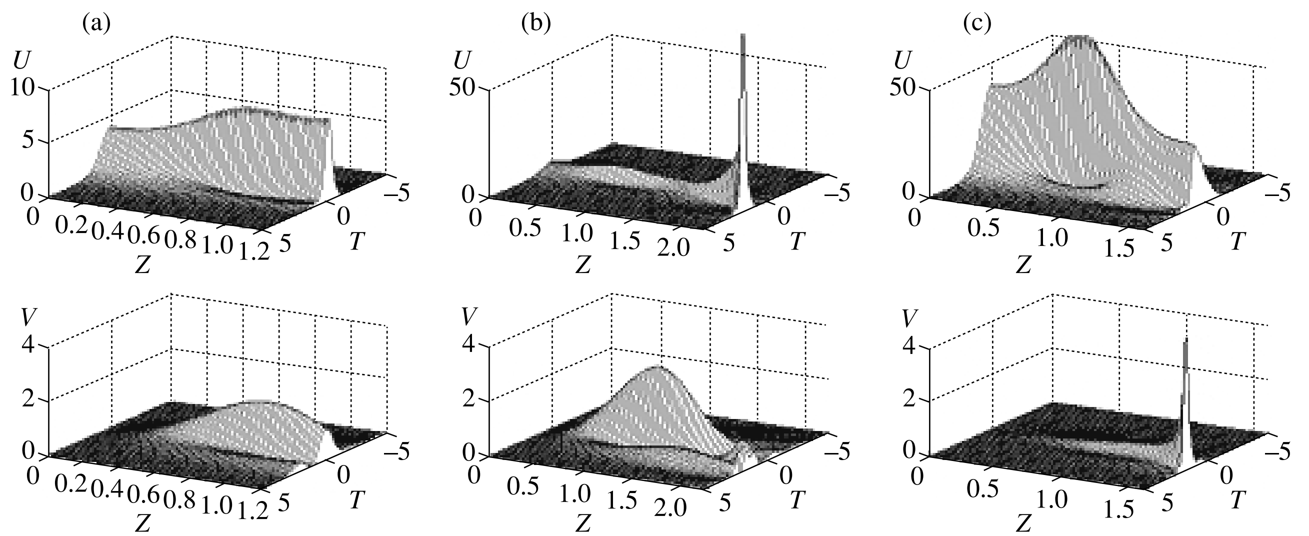

Fig.3. Pulse propagation in a nonlinear two-core fiber in the presence of intermodal dispersion $R' = -0.5$ with $R = 1.0$ and $A = 2.0$ for (a) $\tau_R = 0$, (b) $\tau_R = 0.04$, and (c) $\tau_R = 0.08$

for $R' = 0$, as shown in Fig.1b. The value of Z_{50} increases to 1.9 for $R' = -0.25$, as shown in Fig.2b, and to 2.2 for $R' = -0.5$, as shown in Fig.3b. The effect becomes more pronounced as τ_R becomes larger. We have similar observations with $\tau_R = 0.08$, as shown in Fig.1c and Fig.2c. The change in the group velocity is also less significant in the presence of intermodal dispersion. The phenomenon can be explained as the compensation of the pulse-narrowing effect due to ISRS by the pulse-broadening effect due to the intermodal dispersion in the fiber. On the other hand, unlike all previous cases, the power transferred to the other core grows rapidly and pulse narrowing takes place in the coupled core, as shown in Fig.3c. The group velocity of the pulse in the coupled core is also changed significantly.

3. Conclusion. The effects of ISRS and intermodal dispersion on the propagation of short pulses in a nonlinear two-core fiber have been investigated theoretically. We show that the ISRS can reduce significantly the pulse width and hence increase the peak intensity of the pulse. It can also slow down the pulse distinctly. The pulse-narrowing effect due to ISRS can be weakened by the intermodal dispersion in the fiber. When both ISRS and intermodal dispersion are strong, their interaction can increase significantly the power transfer from the launching core to the coupled core and result in less pulse distortion.

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