Pis'ma v ZhETF, vol. 91, iss. 10, pp. 548 – 550 © 2010 May 25

Effects of Intrapulse Stimulated Raman Scattering and Intermodal Dispersion on Short Pulse Propagation in a Nonlinear Two-Core PCF Coupler

M. Liu[1], *Y. Chen, D. Wang*

College of Communication Engineering, Chongqing University, Chongqing, China

Submitted 11 January 2010
Resubmitted 2 April 2010

The switching dynamics of ultrashort pulse under the effects of intrapulse stimulated Raman scattering (ISRS) and intermodal dispersion in a nonlinear two-core photonic crystal fiber (PCF) coupler is investigated theoretically. A general model is proposed that includes all the significant linear and nonlinear effects. In particular, we demonstrate with numerical examples how the interaction of ISRS and intermodal dispersion affects the pulse shape.

1. Introduction. Photonic crystal fiber (PCF) has attracted a lot of attention owing to its unusual characteristics, important applications, and the development of successful fabrication technologies [1]. In PCFs, light confinement is achieved by a regular array of air holes running along the fiber. It has been shown that a two-core PCF, which consists of two identical cores, can operate as a compact all-fiber directional coupler [2 – 4]. Recent studies report the fabrication and investigation of two-core PCF for broadband directional coupling. In such a device, all-optical switching and nonlinear coupling have been demonstrated theoretically [5] and experimentally [6].

Intermodal dispersion in a two-core fiber has been identified as a linear mechanism that can cause pulse breakup in the fiber and thus upset pulse switching [7 – 9]. We have 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 [10, 11]. In this Letter, we also include a nonlinear mechanism known as intrapulse stimulated Raman scattering (ISRS) [12] that can affect the switching of short pulses in a two-core PCF coupler. It has been shown that ISRS is responsible for the soliton self-frequency shift in soliton pulses propagating in a single-mode fiber [12]. 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 and intermodal dispersion affect pulse propagation in a two-core PCF coupler. We present numerical examples to demonstrate the interaction between these two mechanisms, i.e., ISRS and intermodal dispersion.

2. Analysis and Discussion. The structure of a two-core PCF coupler is shown in Fig.1, where d is the air-hole diameter, Λ is the hole-to-hole distance, and C is the core separation. Optical power transfer between the two cores of a two-core PCF coupler (assumed lossless) can be described approximately by a pair of nonlinear coupled-mode equations:

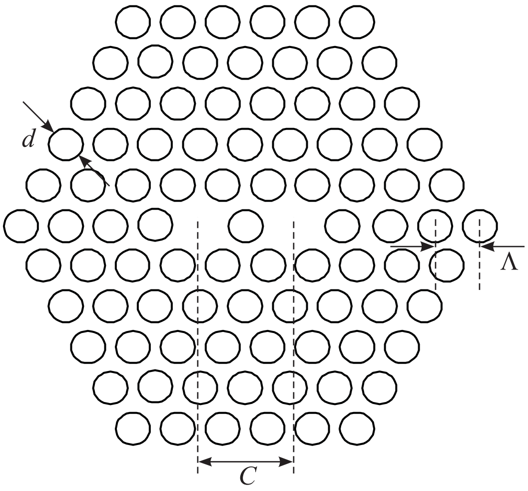

Fig.1. Cross-section of a two-core PCF coupler

$$i\frac{\partial a_1}{\partial z}-\frac{\beta_2}{2}\frac{\partial^2 a_1}{\partial t^2}-i\frac{\beta_3}{6}\frac{\partial^3 a_1}{\partial t^3}+\frac{\beta_4}{24}\frac{\partial^4 a_1}{\partial t^4}+$$
$$+\gamma|a_1|^2a_1+i\frac{\gamma}{\omega}\frac{\partial(|a_1^2|a_1)}{\partial t}-\gamma a_1T_R\frac{\partial|a_1|^2}{\partial t}+$$
$$+\kappa_0a_2+i\kappa_1\frac{\partial a_2}{\partial t}=0, \qquad (1)$$

$$i\frac{\partial a_2}{\partial z}-\frac{\beta_2}{2}\frac{\partial^2 a_2}{\partial t^2}-i\frac{\beta_3}{6}\frac{\partial^3 a_2}{\partial t^3}+\frac{\beta_4}{24}\frac{\partial^4 a_2}{\partial t^4}+$$

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

$$+\gamma|a_2|^2a_2 + i\frac{\gamma}{\omega}\frac{\partial(|a_2^2|a_2)}{\partial t} - \gamma a_1 T_R\frac{\partial|a_2|^2}{\partial t} +$$
$$+\kappa_0 a_1 + i\kappa_1\frac{\partial a_1}{\partial t} = 0.$$

In the above equations, z is the distance along the fiber; t is the time coordinate with reference to the transit time of the pulses; a_1 and a_2 are the amplitude envelopes of the pulses carried by the two cores, respectively; β_2, β_3, and β_4 are the group-velocity dispersion (GVD), third-order dispersion, and fourth-order dispersion, respectively; γ is the nonlinear parameter that accounts for self-phase modulation (SPM); the time-varying term next to the SPM term represents self-steepening (where ω is the angular optical frequency); T_R is the Raman scattering coefficient ($T_R = 3\,\text{fs}$ for silica fiber [13]); κ_0 is the coupling coefficient which accounts for the well-known phenomenon of periodic power transfer between the two cores; and κ_1 is the intermodal dispersion given by $\kappa_1 = \partial\kappa_0/\partial\omega$ (evaluated at the pulse carrier frequency).

In our study, we assume that a 100-fs pulse is launched into one of the cores of the PCF coupler, namely,

$$a_1(0,t) = a_0\text{sech}(t), \quad a_2(0,t) = 0, \tag{2}$$

where a_0 is a real constant. The peak power of the pulse is a_0^2 and the total pulse power is $2a_0^2$. We solve the equations numerically with a Fourier series analysis method [10, 11].

We first consider the case where the intermodal dispersion is negligible (i.e., $\kappa_1 = 0$). We analyze the two-core PCF coupler with the air-hole diameter $d = 2.0\,\mu\text{m}$, the hole-to-hole distance $\Lambda = d/0.9$, the core separation $C = 2\Lambda$, and the coupling length $L_c = 1.8\,\text{cm}$. The corresponding parameters for Eq. (1) are $\beta_2 = -47\,\text{ps}^2/\text{km}$, $\beta_3 = 0.1\,\text{ps}^3/\text{km}$, $\gamma = 3.2\cdot10^{-3}\,(\text{w.m})^{-1}$ (for an effective area $A_{\text{eff}} = 41\,\mu\text{m}^2$), and $\gamma/\omega = 2.6\cdot10^{-18}\,\text{s/(w.m)}$ [14]. The carrier wavelength is $\lambda = 1.55\,\mu\text{m}$. The dynamics of pulse propagation along a 39-cm-long fiber is shown in Fig.2, where $U = |a_1|^2/a_0^2$ and $V = |a_2|^2/a_0^2$ are the normalized power envelopes of the pulses. As can be seen from Fig.2, all-optical switching and nonlinear coupling can occur under the effects of ISRS. However, we find that, in both cores, the high pulse peak corresponding to the red-shift spectrum components falls behind the low pulse peak corresponding to the blue-shift spectrum components. The physical reason is in that due to ISRS effect, the energy in the PCF coupler is transferred to red-shift components from blue-shifted components continuously; hence the group velocity of red-shift components decreases. Our results are consistent with the observations of [13].

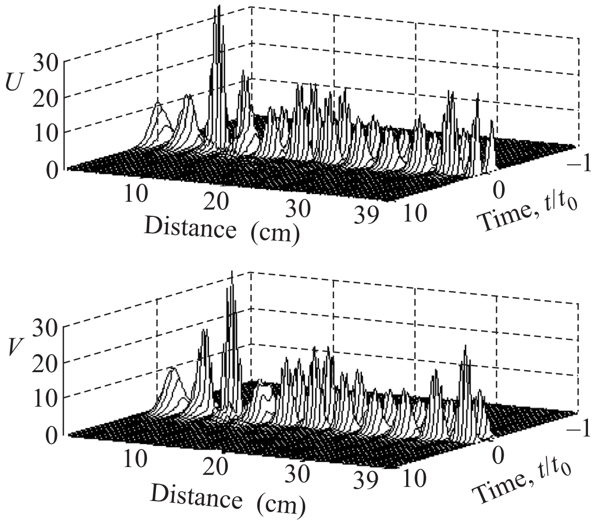

Fig.2. Pulse propagation dynamics along a 39-cm-long two-core PCF calculated for a 100-fs input pulse in the presence of ISRS with $\kappa_1 = 0$

We next incorporate the intermodal dispersion in the analysis (i.e., $\kappa_1 \neq 0$). It has been shown that the intermodal dispersion in a two-core fiber can break up the input pulses [7–9]. To calculate the intermodal dispersion κ_1, we first calculate the coupling coefficient κ_0, which is the difference between the propagation constants of the even and odd modes of the two-core fiber, and then differentiate it with respect to the angular optical frequency at the carrier frequency. By analyzing the modes of the two-core PCF of concern with a numerical method [4], we obtain $\kappa_1 = -410\,\text{fs/m}$ at $1.55\,\mu\text{m}$ for the PCF coupler. For the intermodal dispersion to be negligible, the propagation length L must be sufficiently short [7]:

$$L < 0.2\frac{t_0}{|\kappa_1|}, \tag{3}$$

where t_0 is the pulse width. With $t_0 = 100\,\text{fs}$ and $\kappa_1 = -410\,\text{fs/m}$, the propagation length must be shorter than $\sim 5\,\text{cm}$. Therefore, for a propagation distance of 39 cm, we should expect strong pulse distortion and pulse break-up effects due to the intermodal dispersion in the fiber, as shown in Fig.3.

The pulse propagation under the effects of ISRS and intermodal dispersion has been shown in Fig.4. The interaction between ISRS and intermodal dispersion can change the pulse propagation significantly. As the two-core PCF coupler allows the light to be confined in a small core area, it can produce strong nonlinear effects even in the presence of large intermodal dispersion. We can see that although optical coupling exists, the pulse distortion is very severe. The group velocity of the pulse in both cores is also changed greatly. And the most

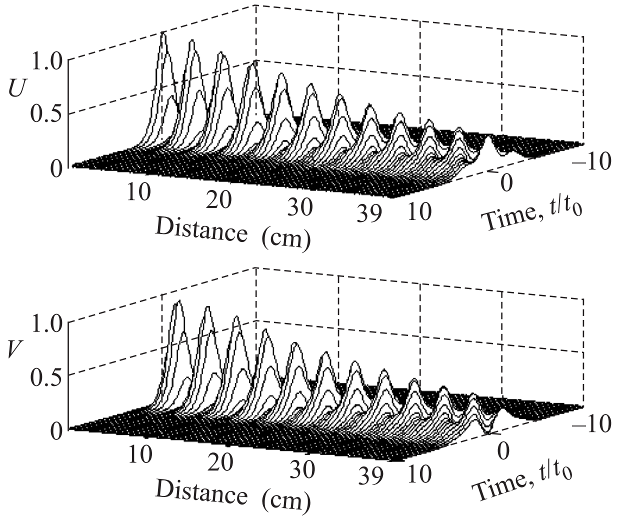

Fig.3. Pulse propagation dynamics along a 39-cm-long two-core PCF calculated for a 100-fs input pulse in the presence of intermodal dispersion with $\kappa_1 = 410\,\mathrm{fs/m}$

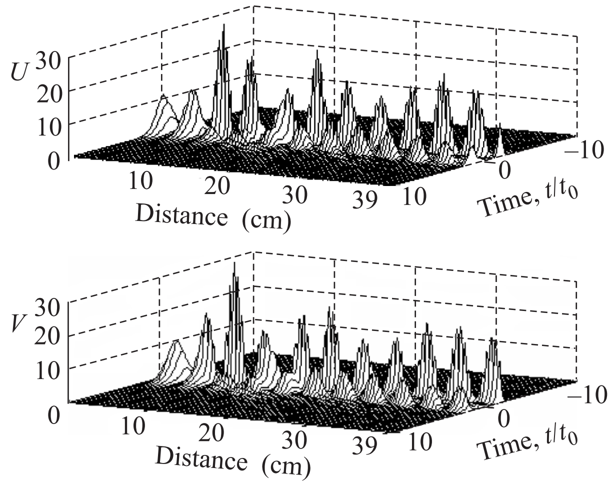

Fig.4. Pulse propagation dynamics along a 39-cm-long two-core PCF calculated for a 100-fs input pulse in the presence of both ISRS and intermodal dispersion

outstanding difference is that the group velocity of high pulse peak is faster than that of low pulse peak, which is opposite the observations of Fig.2. This phenomenon can be explained as the suppression of the red-shift effect due to ISRS by the pulse break-up effect due to the intermodal dispersion in the PCF coupler. The pulse break-up effects due to the intermodal dispersion dominates over ISRS effect in such a device. No matter each case (only the existence of ISRS or intermodal dispersion, or both their existence), due to the conservation of energy, the pulse amplitude is inversely proportional to the pulse width.

3. Conclusion. The effects of ISRS and intermodal dispersion on the propagation of short pulses in a nonlinear two-core PCF coupler have been investigated theoretically. We show that the interplay between ISRS and intermodal dispersion can change the pulse propagation significantly. As for the two-core PCF coupler, the pulse break-up effect due to intermodal dispersion dominates over ISRS effect. Our model based on Eq. (1) should be general enough to describe a wide range of nonlinear effects in a two-core PCF coupler.

This project was supported by Natural Science Foundation Project of CQ CSTC 2009BB2196.

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