Degenerate-Cross-Phase Modulation of Femtosecond Laser Pulses in a Birefringent Single-Mode Optical Fiber

Q. D. Liu, L. Shi, P. P. Ho, R. R. Alfano, R.-J. Essiambre, and G. P. Agrawal, *Fellow, IEEE*

***Abstract*— Degenerate-cross-phase modulation has been observed for femtosecond laser pulses propagating through a short birefringent single-mode optical fiber. The difference in the spectral broadening of the two output polarization components of a single laser pulse was attributed to the combination of self-phase modulation and degenerate-cross-phase modulation processes in the optical fiber. Theoretical simulations based on the solutions of the two coupled nonlinear Schrodinger equations are in good agreement with the measured results.**

***Index Terms*— Optical fibers, optical frequency conversion, nonlinear optics, phase modulation.**

INTERACTIONS of intense optical pulses propagating in a nonlinear medium lead to a variety of nonlinear phenomena [1]. Cross-phase modulation (XPM) occurs when the effective refractive index governing the phase of one optical wave depends on the intensity of another copropagating wave [2]–[5]. When the two optical waves have the same wavelength, it is called degenerate-cross-phase modulation (DXPM) [6]. The intensity-induced refractive index can also modulate the phase of an optical pulse itself; an effect known as self-phase modulation (SPM) [7]. SPM and XPM result in the spectral broadening of pulses propagating in a nonlinear medium. Over the past several years, XPM and SPM have stimulated the interests of many researchers for many real-world applications [8]–[12]. XPM processes is typically observed using two separate laser pulses propagating in an optical fiber. XPM conversion spectral range can vary from ultraviolet to infrared, and may even be extended to the X-ray region. For a single optical pulse, a DXPM process will occur between the two orthogonal polarization modes associated with the pulse. Recently, DXPM has been observed for a *single* elliptically polarized picosecond laser pulse propagating in a nonbirefringent single-mode optical fiber [12].

In this letter, we report on the observation of DXPM between the two perpendicular linearly polarized components of a *single* linearly polarized femtosecond laser light pulse propagating in a birefringent single-mode optical fiber. The spectral broadening of the two linearly polarized components was measured for several energies of the laser pulse. Different spectral characteristics of these two linearly polarized components have been attributed to SPM and DXPM due to these two polarization components.

The schematic diagram of the experiment is shown in Fig. 1. A Ti:Sapphire laser (Model: Coherent Mira 900-B), operating near 780 nm, was used for the experiment. The laser produced a 76-MHz pulse train of 120 fs pulse of spectral bandwidth of about 5 nm. The average output power of the laser is 1.4 W, corresponding to a pulse energy of 18 nJ. The power fluctuations are estimated to be 2%. The output pulse train first passed through an optical isolator (Faraday rotator) to avoid feedback into the laser cavity. The duration of laser pulses after the optical isolator was 230 fs because of group-velocity dispersion (GVD). The spectrum of the input laser pulse had a bandwidth of 5 nm as shown in Fig. 1. A calcite crystal polarizer was used to linearly polarize the laser beam with a ratio better than 10^5. The 230 fs laser pulses were then coupled into and out of a one-meter-length birefringent single-mode optical fiber with two $10\times$ micro-objective lenses. The birefringent (polarization-preserving) fiber (Newport Corp. FSPV-10 model) had a core diameter of 2.6 μm and a cladding thickness of 125 μm. The output from the optical fiber passed through a polarizing displacement prism for spatially separating the two linearly polarized components. The spectra of the two linearly polarized components were measured with a spectral analysis system consisting of a spectrometer and a computer controlled charge-coupled-device (CCD) camera. Both polarization components were measured simultaneously by placing the image of the beams at different positions of the slit as shown in Fig. 1. The images were localized on different positions of the CCD camera for wavelength display. The resolution of this system is 1.5 nm with a dispersion of 0.24 nm per pixel.

For the (polarization-preserving) birefringent single-mode optical fiber, the linearly polarized pulses were first coupled along one of the optical axes of the optical fiber. The output laser pulses at the fiber exit were linearly polarized. The polarizing displacement prism was aligned parallel to the output linear polarization. Hence, there was only one linearly polarized component after the polarizing displacement prism. By rotating the optical fiber by a small angle (6°), laser light was also coupled into the perpendicularly linearly polarized

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Q. D. Liu, L. Shi, P. P. Ho, and R. R. Alfano are with the Institute for Ultrafast Spectroscopy and Lasers, New York State Center for Advanced Technology for Ultrafast Photonic Materials and Applications, Departments of Electrical Engineering and Physics, The City College and Graduate School of The City University of New York, New York, NY 10031 USA.

R.-J. Essiambre and G. P. Agrawal are with The Institute of Optics, University of Rochester, Rochester, NY 14627 USA.

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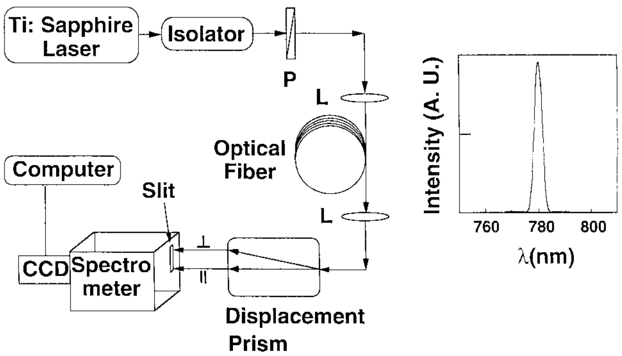

Fig. 1. Experimental set-up: P is a polarizer, L's are microscope objective lenses, a polarizing displacement prism is used to separate the two linearly polarized components; the spectral analysis system has a resolution of 1.5 nm with a dispersion of 0.24 nm/pixel. The insert is the normalized incident laser spectrum with a FWHM bandwidth of 6 nm.

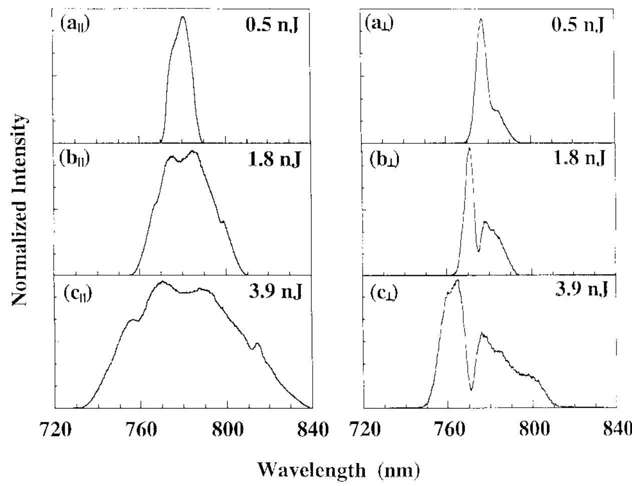

Fig. 2. The measured spectra of single linearly polarized laser pulses propagating in a 1-m-length birefringent single-mode optical fiber. The intensity ratio of the pump(||) component to the probe(⊥) component was 20. Left and right columns are the spectra of || and components, respectively. ($a_{||}$), ($b_{||}$), and ($c_{||}$) are the pump component spectra for pulse energies of 0.5, 1.8, and 3.9 nJ, respectively. (a), (b), and (c) are the corresponding spectra of probe component at the same pulse energies.

mode. The intensities of the two linearly polarized components from the same pulse were adjusted to the ratio of 20. The intense component (||) is considered as the pump light, and the weak one (⊥) is the probe light. DXPM is recognized by the spectral broadening of the weak probe component.

The spectra of the two linearly polarized components of femtosecond laser pulses propagating through a birefringent single-mode optical fiber were observed at different input pulse energies (intensities). The measured spectra are shown in Fig. 2 for input pulse energies of 0.5, 1.8, and 3.9 nJ. The left and right columns of Fig. 2 are the normalized spectra of the pump (parallel) and probe (perpendicular) components, respectively. The spectra of the pump component (parallel polarization) in Fig. 2($a_{||}$), ($b_{||}$), and ($c_{||}$) were broadened symmetrically with bandwidths of 10, 25, and 45 nm at the central wavelength of 780 nm, respectively. This intensity-induced spectral broadening was attributed to a SPM process of the pump component itself. The spectra of the probe(⊥) component (perpendicular polarization) as shown in Fig. 2(a⊥), (b⊥), and (c⊥) have two peaks. One is at the incident central wavelength of 780 nm, the other was shifted to the anti-Stokes side at 777, 770, and 763 nm for pulse energies of 0.5, 1.8, and 3.9 nJ, respectively. The intensity of the probe(⊥) component was too weak to induce any significant spectral broadening through SPM. In fact, this asymmetrical spectral broadening could not possibly be caused by SPM which always induces symmetrical spectral broadening. This nonlinear asymmetrical spectral broadening of the probe(⊥) component which is introduced by the pump (||) component is attributed to the DXPM process.

The different characteristics of the measured spectra for the two linearly polarized components of a single femtosecond pulse in a birefringent single-mode fiber can be explained by considering the polarization evolution in optical fibers. In a birefringent fiber, the two orthogonal linearly polarized components are the stable propagation eigen modes. Hence, a linear polarization base should be used.

Since the laser pulse had a repetition rate of 76 MHz that is much larger than the response of the shutter of the CCD camera, the measured spectral profiles are the averaged over multiple pulses. At this pulse repetition rate and because of the short length of the fiber, interaction between neighboring pulses is negligible, and the spectral broadening is solely from the result of SPM and DXPM between the two polarization components of *the same pulse*. The electric field envelope can be expressed as a superposition of the two linearly polarized components with amplitudes of A_x and A_y, respectively. Using the slowly varying envelope approximation, the coupled nonlinear wave equations that govern the evolution of the two polarization components can be written as [1]

$$\frac{\partial A_x}{\partial z} + \frac{1}{v_{gx}}\frac{\partial A_x}{\partial t} + \frac{i}{2}k^{(2)}\frac{\partial^2 A_x}{\partial t^2} = i\,\frac{\omega_x n_2}{c}\left[\left(|A_x|^2 + \frac{2}{3}|A_y|^2\right)A_x + \tfrac{1}{3}A_y^2 A_x^* \exp(-i2\Delta k z)\right] \tag{1a}$$

$$\frac{\partial A_y}{\partial z} + \frac{1}{v_{gy}}\frac{\partial A_y}{\partial t} + \frac{i}{2}k^{(2)}\frac{\partial^2 A_y}{\partial t^2} = i\,\frac{\omega_y n_2}{c}\left[\left(|A_y|^2 + \frac{2}{3}|A_x|^2\right)A_x + \tfrac{1}{3}A_x^2 A_y^* \exp(i2\Delta k z)\right] \tag{1b}$$

where v_{gx} and v_{gx} are the group velocities for light polarized along the x axis and y axis, respectively; $k^{(2)}$ is the group-velocity dispersion (GVD), n_2 is the nonlinear refractive index, and $\Delta k = k_x - k_y$ is the propagation-constant mismatch between the two linear polarization eigen-modes. The first two terms on the right-hand side of (1) are due to SPM and DXPM which modulate the phase of the propagating pulses. The third term is due to the degenerate four-wave mixing (DFWM), which affects the amplitude as well as the phase of the optical pulse.

The observed spectra seen in Fig. 2 can be understood by using (1). After a single pulse is coupled into the birefringent optical fiber, the two linearly polarized components propagate like two laser pulses. A key term which will affect the output laser light spectrum caused by DXPM is the walk-off effect between the two polarization components since the two linear components propagate at a different velocity. In the experiment, the intense component (pump) was coupled to the fast optical-axis of the fiber while the probe component propagated along the slow optical-axis. Therefore, the probe component sees only the trailing part of the pump. The phase of the probe component is modulated by the induced index change caused by the tailing edge of the pump component, the spectrum of the probe component is shifted to the anti-Stokes (blue) side only. This is shown in the right column of Fig. 2. Since the coefficient of DXPM is 2/3 compared with that of SPM, probe spectral broadening would be 2/3 of that of the pump in the absence of walk off. As the result of the walk-off effect, the observed spectral broadening of the probe (3, 10, and 17 nm in Fig. 2) are less than 2/3 of that of the pump (10, 25, and 45 nm) for pulse energies of 0.5, 1.8, and 3.9 nJ, respectively.

The strength of the DFWM process depends on the phase matching between the two linear polarization modes characterized by the beat length $L_B = 2\pi/(|k_x - k_y|)$. When the length, L, of the optical fiber, satisfies $L \gg L_B$, the contribution of the DFWM terms in (1) can be neglected. This is true for the 1-m-length birefringent fiber with a typical beat-length of $L_B = 2$ mm. Another effect that must be considered during pulse propagation is the GVD. Since our optical fiber has a dispersion of -108 ps/(nm.km) at the central wavelength of 780 nm, GVD causes the pulse intensity to decrease because of pulse broadening. We solve (1) numerically to account for the GVD, SPM, and DXPM effects occurring simultaneously.

Fig. 3 shows the numerical results under the experimental condition excluding the DWFM term. It was necessary to include an initial linear chirp on the input pulse for a good agreement with the experimental data. The input pulse amplitudes are taken to be

$$A_{x(o,t)} = \sqrt{\left(\frac{20}{21}\right)P_0}\,\mathrm{sech}\left(\frac{t}{T_0}\right)\,\exp\left[\frac{-iC\left(\dfrac{t}{T_0}\right)^2}{2}\right] \quad (2)$$

with $T_0 = 130$ fs, linear chirp $C = 0.5$, and $A_{y(0,t)} = A_{x(0,t)}/\sqrt{20}$ where $2P_0T_0$ is the input pulse energy. The GVD parameter $k^{(2)}$, propagation-constant mismatch Δk, and nonlinear refractive index n_2 are 35 ps^2/km, 1.2 ps/m, and 3.2×10^{-20} m^2/W, respectively. Qualitative agreement with the experiment can be seen as shown in Fig. 3. The spectra of probe and pump components at low input light power (0.5 nJ) show the least agreement with the experiment. We believe that this may be due to an overestimate of the linear chirp [1] of the light pulses. The two sidelobes in the spectra in Figs. 2($c_{||}$) and 3($c_{||}$) indicate optical-wave breaking [13]. The spectral broadening at high input light power (3.9 nJ) in the simulation is in good agreement with the experiment.

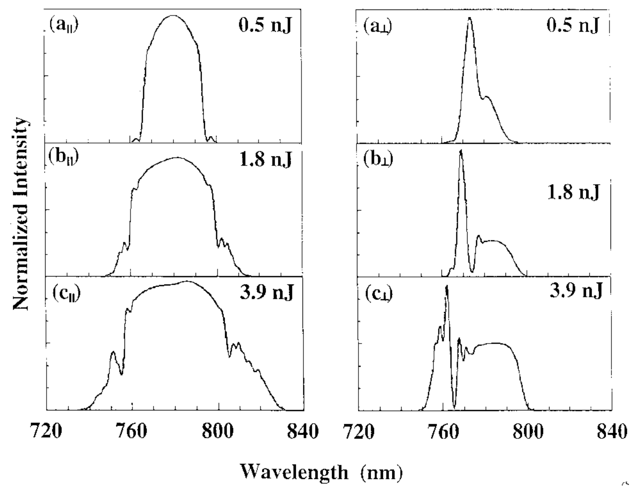

Fig. 3. Spectra obtained from numerical simulations of the set of (1) under similar conditions at the experiment. The parameters used are given in the main text.

In summary, a DXPM process has been observed for single femtosecond laser light pulses propagating in a birefringent single-mode optical fiber. The difference of the spectral broadening of the two output polarization components of a single laser light pulse was attributed to SPM and DXPM processes in the optical fiber. Walk-off, GVD, and linear chirp effects of the two polarization components are important in femtosecond pulse propagation.

References

[1] G. P. Agrawal, *Nonlinear Fiber Optics,* 2nd ed. New York: Academic, 1995, ch. 7.

[2] R. R. Alfano, Q. X. Li, T. Jimbo, J. T. Manassah, and P. P. Ho, "Induced spectral broadening of a weak picosecond pulse in glass produced by an intense ps pulse," *Opt. Lett.,* vol. 11, pp. 626–628, 1986.

[3] C. C. Yang and A. J. S. Wang, "Cross-polarization cross-phase modulation of femtosecond pulses in erbium-doped fiber amplifiers," *J. Opt. Soc. Amer. B,* vol. 9, pp. 682–686, 1992.

[4] M. N. Islam, L. F. Mollenauer, R. H. Stolen, J. R. Simpson, and H. T. Shang, "Cross-phase modulation in optical fibers," *Opt. Lett.,* vol. 12, pp. 625–627, 1987.

[5] P. L. Baldeck, R. R. Alfano, and G. P. Agrawal, "Induced-frequency shift of copropagating pulses," *Appl. Phys. Lett.,* vol. 52, pp. 1939–1942, 1988.

[6] Q. Z. Wang, P. P. Ho, and R. R. Alfano, "Degenerate cross-phase modulation for pulse compression and amplification of ultrashort laser pulses," *Opt. Lett.,* vol. 15, pp. 1023–1025, 1990.

[7] R. R. Alfano and S. L. Shapiro, "Emission in the region 4000–7000 Å via four-photon coupling in glass," *Phys. Rev. Lett.,* vol. 24, pp. 584–587, 1970; "Observation of self-phase modulation and small scale filaments in crystals and glasses," *Phys. Rev. Lett.,* vol. 24, pp. 592–595, 1970.

[8] R. Fork, C. Shank, C. Herliman, R. Yen, and W. J. Tomlinson, "Femtosecond white light continua generation," *Opt. Lett.,* vol. 8, pp. 1–3, 1983.

[9] G. Yang and Y. R. Shen, "Spectral broadening of ultrashort pulses in a nonlinear medium," *Opt. Lett.,* vol. 9, pp. 510–512, 1984.

[10] K. J. Blow, N. J. Doran, and B. P. Nelson, "All-fiber pulse compression at 1.32 μm," *Opt. Lett.,* vol. 10, pp. 393–395, 1985.

[11] B. Crosignani, B. Daino, and P. D. Porto, "Depolarization of light due to the optical Kerr effect in low-birefringent single-mode fibers," *J. Opt. Soc. Amer. B,* vol. 3, pp. 1120–1123, 1986.

[12] Q. D. Liu, J. T. Chen, Q. Z. Wang, P. P. Ho, and R. R. Alfano, "Single-pulse degenerate-cross-phase modulation in a single-mode optical fiber," *Opt. Lett.,* vol. 20, pp. 542–544, 1995.

[13] W. J. Tomlinson, R. H. Stolen, and A. M. Johnson, "Optical wave breaking of pulses in nonlinear optical fibers," *Opt. Lett.,* vol. 10, pp. 457–459, 1985.