

## Cross phase modulation measured in optical fibers

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Nonlinear optics is important for many scientific and engineering applications to have the capability to generate, transmit, and control the spectrum of ultrashort laser pulses. In the past, three nonlinear optical processes have been used to alternate the frequency and amplitude of light. As a laser pulse propagates through a medium, it causes a refractive-index change. This in turn induces a phase change which causes a frequency sweep within the pulse envelope. This process has been called self-phase modulation (SPM) in condensed media.<sup>1-4</sup> Recently, it was found<sup>5</sup> that when a weak pulse of a different frequency propagates through a disrupted medium whose index of refraction was changed by an intense laser pulse, the phase of the weak optical field can be modulated by the time variation of the index of refraction originating from the primary intense pulse. This is called the induced phase modulation (IPM).<sup>5,6</sup> Stimulated Raman scattering (SRS) is an important process which competes with SPM. A theory was developed by us<sup>7</sup> to describe the resonance enhancement of  $\chi^3$  and cross phase modulation (XPM)<sup>7,8</sup> and interference between the SRS and SPM. The Stokes pulse broadens due to a combination of XPM and Raman parametric amplification. The measurement of the spectral broadening about the SRS wavelengths in liquids and recently in glass fibers<sup>9</sup> could originate from either SPM or XPM process. In this Letter, we report an experimental evidence of XPM in optical glass fibers.

The experimental arrangement to measure the spectral behavior of XPM and SPM processes is described as the following. A mode-locked Nd:YAG laser system which emitted 1064-nm pulses with 30-mJ/pulse energy was used to generate 532-nm second harmonics in a single-shot mode. The bandwidth of 532 nm was  $\sim 0.045$  nm, and the pulse duration was  $\sim 25$  ps. After attenuating the pulse energy of the 532-nm laser to  $\sim 1$   $\mu$ J, this laser was coupling into a 10-m long single-mode optical fiber. This optical fiber is a single-mode glass fiber operating at visible wavelengths custom made by Corning Glass Co. The cutoff wavelength of the fiber is 462 nm, core diameter is 2.5  $\mu$ m, cladding diameter is 79  $\mu$ m, refractive-index difference is 0.24%, and silica dispersion at 532-nm  $D(\lambda) = 0.066$ . The output from the fiber was passed into a 1-m Jarell-Ash spectrometer. Dispersed spectra of the output laser pulses were recorded by a PAR OMA2. The overall system resolution of the spectral measurement was 0.25 nm.

Four typical measured spectra of the laser pulse after propagating in 10 m of fiber with different incident pulse energies are displayed in Fig. 1. The vertical axis is a relative intensity in arbitrary unit, and the horizontal axis is the wavelength. There are five salient features of the four curves shown in Fig. 1. First, the output bandwidth of the 532-nm incident wavelength increases as the incident pulse energy is increased. Second, the output peak amplitude of the incident 532-nm line is nearly a constant value when the incident pulse energy is above a threshold value. Third, both the amplitude and spectral bandwidth of the first Stokes output wavelength of 544.5 nm increases as a function

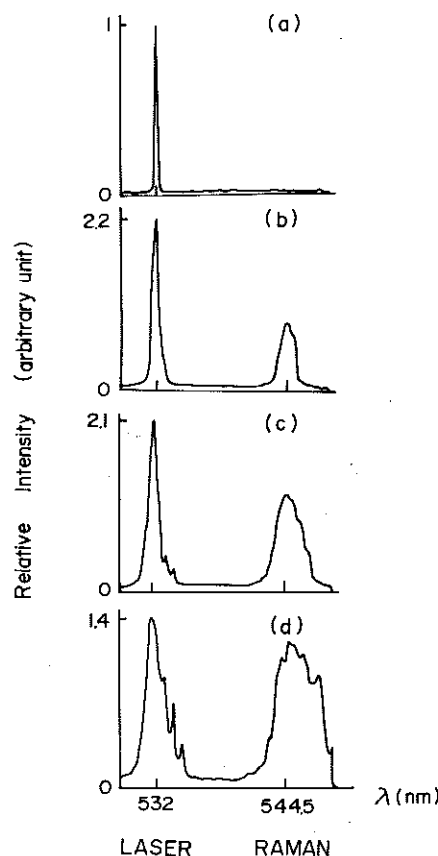


Fig. 1. Measured emission spectra of 25-ps laser pulses of different energies at 532-nm wavelength propagated through a 10-m long single-mode glass fiber. The vertical axis is a relative intensity at the incident laser 532-nm wavelength. The horizontal axis is calibrated as a function of wavelength. The 544.5-nm corresponds to the peak of the first Stokes Raman line. Relative pump pulse energies for the four curves are (a)  $E_0$ , (b)  $7E_0$ , (c)  $12E_0$ , (d)  $20E_0$ .

of incident pulse energy. Fourth, the spectral shape of Raman emission is asymmetrical due to the dispersion and walk-off during the generation process.<sup>8</sup> Fifth, and most important, the broadened spectral bandwidth of the Raman line is larger than that of the incident laser line, and the ratio of the spectral width of Raman line to laser line is 2.85, 3.0, and 2.8 in Figs. 1(b), (c), and (d), respectively.

From our previous theoretical analysis,<sup>7</sup> the spectral bandwidth of the Raman line should be increased as the pulses travel in media and grown dramatically as the pulse duration is shortened. A ratio of the Stokes spectral width to the primary spectral width is predicted without dispersion as<sup>7</sup>

$$X = \Delta\omega_{\text{Raman}}/\Delta\omega_{\text{laser}} = \{4[1 + (\delta/2\beta)^2]\}^{0.5}, \quad (1)$$

where  $\beta = 3n_2\omega^3/(\Gamma n_0c^2)$ ,

$$\delta = \gamma^2\omega/(16\pi\mu\sigma n_0c^2\Gamma^2),$$

where  $\omega$ , incident laser frequency;  $\sigma$ , phonon frequency;  $\mu$ , effective oscillator mass density;  $\gamma$ , coupling of the phonon field to the EM field;  $n_0$ , linear index of refraction;  $n_2$ , nonlinear index of refraction; and  $\Gamma$ , phonon decay rate.

Inserting practical values for the parameters of Eq. (1), such as  $\omega = 3.54 \times 10^{15} \text{ s}^{-1}$ ,  $\sigma = 8.3 \times 10^{13} \text{ s}^{-1}$ ,  $\mu = 1$  (estimated),  $\gamma = 10^6$  (estimated),  $n_0 = 1.5$ ,  $n_2 = 1.2 \times 10^{-13} \text{ esu}$ , and  $\Gamma = 5.7 \times 10^{12} \text{ s}^{-1}$ , we can obtain the ratio  $X = 2$ . Since the calculated value of  $\delta/2\beta$  is  $\ll 1$ , only dramatic

changes of these parameters in Eq. (1) affect the estimation of  $X$ . The theoretical spectral width ratio  $X$  is 2, when the dispersion is negligibly small. Our experimental data have demonstrated the signature of our theoretical prediction<sup>7</sup>: the spectral broadening of the Raman line is larger than that of the laser line, and the measured ratio of these spectral broadenings in all our experimental conditions is  $2.9 \pm 0.1$  under high power excitation.

The spectral broadening due to phase modulation has an important role in communications and signal processing by allowing pulse coding in different frequency regions. Furthermore, phase modulations could be a source of noise on signals due to interference in multiband communications and signal processing applications. Our experimental results present strong evidence for the XPM. Further research on the temporal behavior of XPM follows.

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