Induced-frequency shift of copropagating ultrafast optical pulses

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The combined effects of cross-phase modulation and pulse walk-off on copropagating optical pulses are investigated. It is shown that ultrafast pulses which overlap in a nonlinear dispersive medium undergo a substantial shift of their carrier frequencies. This new coherent phenomenon of induced-frequency shift has been demonstrated using strong infrared picosecond pulses which shift the frequency of weak green picosecond pulses propagating in a 1-m-long single-mode optical fiber.

The study of ultrafast optical pulses propagating in nonlinear dispersive media is important for both theoretical understanding and potential applications of optical nonlinearities.[1–3] Self-frequency shift and cross-phase modulation are two of the most recent nonlinear effects investigated in optical fibers as a convenient nonlinear dispersive medium. Self-frequency shift refers to the frequency shift that femtosecond pulses experience because of the finite response time of the nonlinearity,[4] while cross-phase modulation (XPM) governs the nonlinear phase change of an optical field induced by another copropagating field.[5–22] XPM is closely related to the well-known self-phase modulation (SPM) which leads to a wide spectral broadening of picosecond[23] and femtosecond pulses.[24] Spectral effects attributed to XPM were first observed in late 1985, when it was reported that intense picosecond pulses could be used to enhance the spectral broadening of weaker pulses copropagating in bulk glasses.[8,9] Since then, several groups have been studying XPM effect generated by picosecond pump pulses on copropagating Raman pulses,[10–15] second-harmonic pulses,[16,17] and stimulated four-photon-mixing pulses.[18] Recently, subpulse formation from XPM-induced modulation instabilities has been predicted.[19,20]

In this letter, we show that ultrafast pulses which overlap in a nonlinear dispersive medium undergo a substantial shift of their carrier frequency. This new coherent effect, which we refer to as an induced-frequency shift, results from the combined effect of cross-phase modulation and pulse walk-off. In our experiment, the induced-frequency shift is observed by using strong infrared pulses which shift the frequency of weak picosecond green pulses copropagating in a 1-m-long single-mode optical fiber. Tunable red and blue shifts have been obtained at the fiber output by changing the time delay between infrared and green pulses at the fiber input. The experimental results are well explained by an analytic frequency-chirp model. We believe that induced-frequency shifts are of fundamental importance as they could be intrinsic to numerous schemes of ultrashort pulse interactions. Moreover, they could be useful for pulse compression, optical communication, and optical computing purposes.

A schematic of the experimental setup is shown in Fig. 1. A mode-locked Nd:YAG laser with a second-harmonic crystal was used to produce 33 ps infrared pulses and 25 ps green pulses. Theses pulses were separated using a Mach–Zender interferometer delay scheme made with wavelength-selective mirrors. The infrared and green pulses propagated in different interferometer arms. The optical path of each pulse was controlled using variable optical delays. The energy of infrared pulses into the fiber core was adjusted with neutral density filters in the range 1–100 nJ, while the energy of green pulses was set to about 1 nJ. The coupling efficiency of the 1064 nm laser light into the fiber core was maintained at less than 10% to avoid breakdown damage. The nonlinear dispersive medium was a 1-m-long single-mode optical fiber (Corguide of Corning Glass). This length was chosen to allow for a total walk-off without losing control of the pulse delay at the fiber output. The group-velocity mismatch between 532 and 1064 nm pulses was calculated to be about 76 ps/m in fused silica.[25] The spectrum of green pulses was measured using a grating spectrometer (1 m 1200 lines/mm) and an optical multichannel analyzer (OMA2).

The spectra of green pulses propagating with and without infrared pulses are plotted in Fig. 2. The dashed spectrum corresponds to the case of green pulses propagating alone. The blue- and red-shifted spectra are spectra of green pulses copropagating with infrared pulses after the input delays were set at 0 and 80 ps, respectively. The main effect of the nonlinear interaction was to shift the carrier frequency of green pulses. The induced-wavelength shift versus the input delay between infrared and green pulses is plotted in Fig. 3.

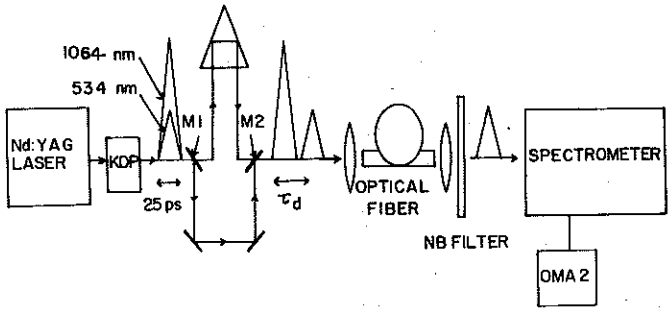

FIG. 1. Experimental setup used to measured the induced-frequency shift at 532 nm pulses as function of the time delay between pump and probe pulses at the fiber input. Mirrors M_1 and M_2 are wavelength selective, i.e., they reflect 532 nm pulses and transmit 1064 nm pulses.

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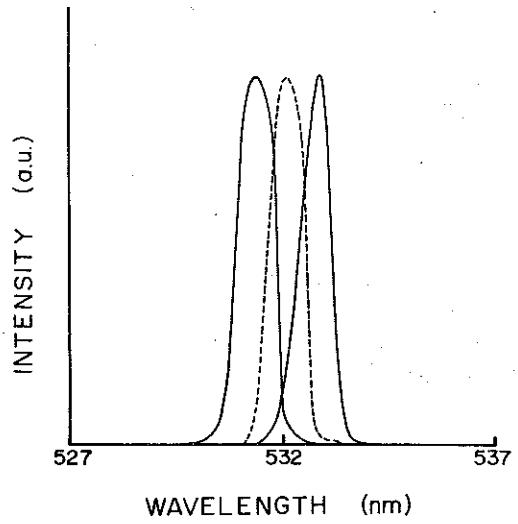

FIG. 2. Cross-phase modulation effects on spectra of green 532-nm pulses. (a) Reference spectrum (no copropagating infrared pulse). (b) Infrared and green pulses overlapped at the fiber input. (c) The infrared pulse was delayed by 80 ps at the fiber input.

The maximum induced-wavelength shift increased linearly with the infrared pulse peak power (Fig. 4). Hence the carrier wavelength of green pulses could be tuned up to 4 Å toward both the red and blue sides by varying the time delay between infrared and green pulses at the fiber input. The solid curves in Figs. 3 and 4 are the predictions of a frequency-chirp model described below.

The blue and red induced-frequency shifts result from the combined effect of the cross-phase modulation and pulse walk-off. During the nonlinear interaction, the refractive index of the green pulse can be approximated by[19]

$$n = n_0 + 2n_2|E_p(\tau - \tau_d + z/L_w)|^2, \tag{1}$$

where the contribution of SPM is ignored and the factor of 2 results from the XPM interaction. The parameters L_w and τ are defined by

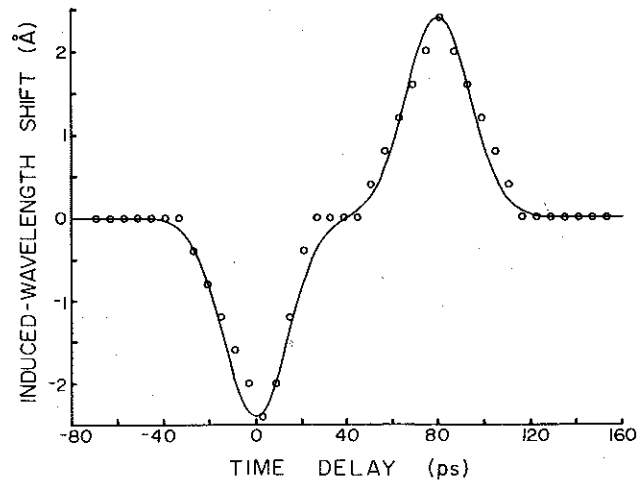

FIG. 3. Induced-wavelength shift of green 532 nm pulses as a function of the input time delay between 532 nm pulses and infrared 1064 nm pulses at the input of a 1-m-long optical fiber: Dots are experimental points. The solid line is the theoretical prediction of Eq. (7).

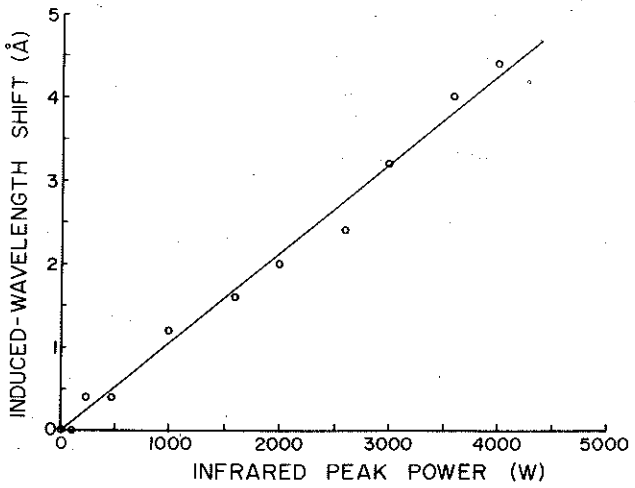

FIG. 4. Maximum induced-wavelength shift of 532 nm pulses vs the peak power of infrared pump pulses. Dots are experimental points. The solid line is the theoretical prediction of Eq. (8).

$$L_w = \frac{T_0}{1/v_{gp} - 1/v_{go}} \quad \text{and} \quad \tau = \frac{t - z/v_{go}}{T_0}. \tag{2}$$

In these equations, n_0 is the low-intensity refractive index at 532 mm, n_2 the nonlinear coefficient, $|E_P|^2$ the infrared pulse intensity, τ the normalized time, T_0 the half-width of pump pulses, L_w the walk-off length, v_{go} and v_{gp} the group velocities at 532 and 1064 nm, respectively, and τ_d the normalized initial delay between pulses.

The nonlinear refractive index gives rise to a dephasing $\phi(\tau)$:

$$\phi(\tau) = 2\frac{\omega_0}{c} n_2 \int_0^L \left| E_p\left(\tau - \tau_d + \frac{z}{L_w}\right)\right|^2 dz, \tag{3}$$

and a frequency chirp $\delta\nu(\tau)$:

$$\delta\nu(\tau) = -\frac{1}{2\pi T_0}\frac{\partial\phi}{\partial\tau}. \tag{4}$$

For Gaussian pump pulses, Eqs. (3) and (4) have analytical solutions[22]:

$$\phi(\tau) = -\sqrt{\pi}\,\gamma_1 P_p L_w [\operatorname{erf}(\tau - \tau_d) - \operatorname{erf}(\tau - \tau_d + \delta)], \tag{5}$$

$$\delta\nu(\tau) = \frac{\gamma_1}{\pi} P_p \frac{L_w}{T_0} \{\exp[-(\tau - \tau_d)^2] - \exp[-(\tau - \tau_d + \delta)^2]\}, \tag{6}$$

where P_p is the pump peak power, $\gamma_1 = 2\pi n_2/(\lambda_0 A_{\text{eff}})$ accounts for the fiber nonlinearity, A_{eff} is the effective core area, and $\delta = L/L_w$ is the normalized walk-off parameter.

When the pulses coincide with the fiber entrance ($\tau_d = 0$), the point of maximum phase is generated ahead of the green pulse peak because of the group-velocity mismatch [Eq. (5)]. The green pulse sees only the trailing part of the XPM profile which leads to a blue induced-frequency shift [Eq. (6)]. Similarly, when the initial delay is set at 80 ps, the infrared pulse has just sufficient time to catch up with the green pulse. The green pulse sees only the leading part of the

XPM phase shift, which gives rise to a red induced-frequency shift. When the initial delay is about 40 ps, the infrared pulse has time to pass entirely through the green pulse. The pulse envelope sees a constant dephasing, and there is no shift of the green spectrum (Fig. 3).

Equation (6) can be used to fit our experimental data shown in Figs. 3 and 4. Assuming that the central part of the pump pulses provides the dominant contribution to XPM, we set $\tau = 0$ in Eq. (6) and obtain

$$\delta\lambda(\tau_d) = -\frac{\lambda^2\gamma_1}{\pi c} P_p \frac{L_w}{T_0} \times\{\exp(-\tau_d^2) - \exp[-(-\tau_d + \delta)^2]\}. \quad (7)$$

The maximum induced-wavelength shift occurs at $\tau_d = 0$ and δ, and is given by

$$|\delta\lambda_{\max}| \approx (\lambda^2\gamma_1/\pi c) P_p (L_w/T_0). \quad (8)$$

Equations (7) and (8) have been plotted in Figs. 3 and 4, respectively. There is a very good agreement between this simple analytical model and experimental data. It should be noted that only a simple parameter (i.e., the infrared peak power at the maximum induced-frequency shift) has been adjusted to fit the data. Peak power values are defined as the true peak powers in the fiber core. Experimental parameters were $\lambda = 532$ nm, $T_0 = 19.8$ ps (33 ps full width half-maximum), $L_w = 26$ cm, and $\delta = 4$.

In summary, we have shown that ultrafast optical pulses which overlap in a nonlinear dispersive medium can undergo a substantial shift of their carrier frequency. This new coherent effect, named the induced-frequency shift, has been demonstrated using strong infrared pulses to shift the frequency of copropagating green pulses. The results are well explained by an analytical model which includes the effect of cross-phase modulation and pulse walk-off. Even though we have observed this effect in a single-mode optical fiber, it should be present in other nonlinear dispersive media. Further work will investigate applications of induced-frequency shift for optical information coding, optical communication, and pulse compression purposes.

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