Chirp reversal of picosecond light pulses in parametric amplification in quadratically nonlinear media

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A real-time chirp reversal of picosecond light pulses has been observed during three-wave parametric amplification in a CDA crystal. A phase conjugation of the time-dependent spectral components of optical signals can be achieved over an exceedingly broad frequency band in media having a second-order nonlinear susceptibility. Chirp reversal has been achieved in a spectral band up to 200 cm^{-1} at an energy gain $\sim 10^4$ and at a signal output power of 0.1 GW.

1. In this letter we report experiments carried out to study a nonlinear optical effect: the reversal of the chirp of pulses in media having an instantaneous nonlinearity $\chi^{(2)}$. Pulse chirp reversal (PCR) is essentially a time-varying analog of phase conjugation (or "wavefront inversion"). Chirp reversal of optical signals during parametric four-wave mixing has been discussed theoretically by Marburger[1] and Yariv *et al.*,[2] who suggested making use of the conjugation of time-varying spectral components to cancel the phase distortions introduced by the dispersion of the group velocity. The primary requirement for achieving chirp reversal over the entire frequency band ($\Delta\nu$) of a phase-modulated pulse is formulated as $\Delta\nu \ll 1/\tau_R$, where τ_R is the time scale of the response of the nonlinearity of the medium. The domination of the third-order nonlinearity by components having a nonzero response time obviously imposes severe restrictions on the frequency band in which PCR can be achieved in isotropic media. On the other hand, parametric three-wave mixing occurs when there is an electron nonlinearity with a response time on the order of a femtosecond. Consequently, phase conjugation of extremely broad (for the optical range) spectral bands can in principle be achieved by using $\chi^{(2)}$. A parametric collinear amplification of signals with a frequency band up to 3000 cm^{-1} has already been demonstrated.[3,4]

2. We have previously reported[5,6] a phase self-conjugation (passive PCR) of time-varying spectral components of picosecond pulses excited in a parametric light source. In the present letter we report a study of an active PCR which occurs during the injection of a picosecond signal with a linear chirp into a parametric amplifier. Using the plane-wave approximation, we can outline a theoretical derivation of PCR in a quadratically nonlinear medium with a parametric amplification of a phase-modulated light signal in the field of a spectrally limited pump pulse. The solution of the corresponding truncated equations[7] for a given pump field and for group matching of the signal and intermediate waves can be written

$$A_1(\eta, z) = \frac{A_{10}(\eta)}{2} \exp\left[\sigma \int_0^l a_{30}(\eta - \nu_{31} z) dz\right], \tag{1}$$

$$A_2(\eta, z) = A_1^*(\eta, z),$$

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where $A_j = a_j \exp(i\varphi_j)$ is the complex wave amplitude, u_j is the group velocity of the wave, $\eta = t - (z/u_1)$, $\nu_{31} = 1/u_3 - 1/u_1$, and σ is the coupling coefficient. We use the notation $A_j(\eta,z)|_{z=0} = A_{j0}(\eta)$. We assume $A_{10} \neq 0$ and $A_{20} = 0$, and we assume that the condition $l \gg l_{nl}$ holds, where l is the length of the nonlinear medium, and $L_{nl} = 1/[\sigma A_{30}(0)]$. We see that the phase modulation of the signal pulse is not distorted ($\varphi = \varphi_{10}$) during the amplification, and a pulse is generated at the free frequency with a conjugate phase ($\varphi_2 = -\varphi_{10}$). A deviation from matching of the group velocities of the amplified pulses and of the pump pulse can cause only some decrease in, or saturation of, the amplification. It is thus possible to conjugate optical signals with either a random or regular phase modulation; specifically, it is possible to reverse a chirp which is linear in the time.

3. In the present experiments we use an arrangement of nearly collinear parametric amplification. A single pump pulse, 4–5 ps long with an energy of 2–3 mJ, is produced in an apparatus with a block diagram analogous to that of Ref. 8. A signal pulse with a linear positive chirp is produced in a single-mode optical fiber[9] 1.3 m long. For this purpose, a pulse with an energy $\sim 0.1\ \mu$J ($\lambda = 1.054\ \mu$m) is coupled into the entrance of the fiber. The phase self-modulation results in a broadening of the spectrum of the pulse to 400 cm^{-1}, on the average, while the length of the pulse increases to ~ 10 ps. As the quadratically nonlinear medium in which to achieve the parametric amplification we selected the crystal CDA ($l = 4$ cm; *e-oo* interaction), which has a 90° matching and an exceptionally broad gain band (Fig. 1). Estimates show that the deviation from matching of the group velocities and also the linear spreading in the crystal of the pulses used in these experiments are insignificant. The signal and the pump pulse are coupled through matching delay lines into the crystal, where an energy gain by a factor $\sim 10^4$ is achieved. Since the pump pulse "cuts out" a corresponding spectral band from the broader signal pulse, the frequency difference between the signal and free pulses decreases to 200 cm^{-1} on the average after passing through the amplifier. The phase and time characteristics of the pulses are studied by dynamic interferometry with a Michelson interferometer and an AGAT-SF-3 camera. Figure 2 shows dynamic interferograms of the pulse at the exit from the optical fiber (a), along with the signal (b) and intermediate (c) pulses at the output from the parametric amplifier. These interferograms were obtained with an interferometer with a free-dispersion region of 555 cm^{-1}. The inclination of a band in the dynamic inter-

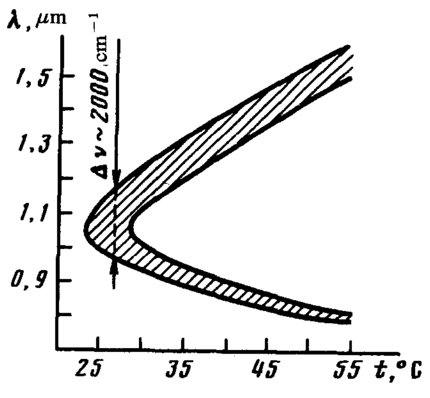

FIG. 1.

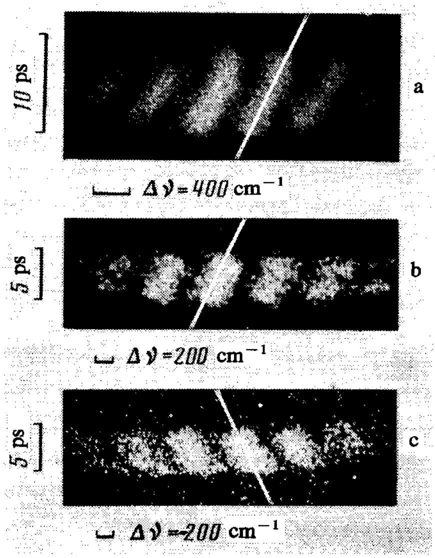

FIG. 2.

ferogram is proportional to the chirp $\Delta\nu/\tau$, where $\Delta\nu$ is the frequency deviation, and τ the pulse length. The direction of the inclination depends on the sign on the chirp. It can be seen from the interferograms in Figs. 2b and 2c that the bands slope in the opposite directions. This result is evidence that there is a link between the phase characteristics of the signal and those of the intermediate pulses.

4. In summary, the results of this study show that a chirp reversal of broad-band optical signals can be achieved during parametric amplification in a quadratically nonlinear medium.

The three-wave PCR produces phase-conjugate picosecond pulses with a linear chirp and a power of 0.1 GW, which meet the requirements for pulse compression to 80 fs in a medium with a positive group-velocity dispersion. Pulse chirp reversal holds promise for use in ultrahigh-time-resolution spectroscopy, in information processing systems, and in quantum electronics in the femtosecond range.

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