Electro-optic time lensing with an intense single-cycle terahertz pulse

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We demonstrate that an intense single-cycle terahertz (THz) pulse can act as a time lens to phase modulate and compress a copropagating ultrashort laser pulse. By using the THz-induced phase modulation as a time lens and a glass plate as a group velocity dispersive element, we have compressed an unchirped ∼165 fs laser pulse to ∼45 fs.

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I. INTRODUCTION

Recent advances in ultrafast and optoelectronic techniques have enabled the generation and detection of single-cycle terahertz (THz) pulses using both electron accelerators and lasers [1–5]. These pulses have center frequencies in the THz range, and can consist of one electric-field oscillation under the pulse envelope. The electric field can exceed 10^7 V/m and vary on a picosecond or subpicosecond time scale. The strong electric field associated with these ultrashort electromagnetic pulses offers the possibility of investigating novel ultrafast and nonlinear phenomena in the single-cycle regime. In this paper, we demonstrate that an intense single-cycle THz pulse can act as a time lens to phase modulate (chirp) an ultrashort laser pulse, when copropagated through a second-order nonlinear medium. Such a laser pulse can then be compressed upon passage through a group velocity dispersive element.

II. TIME LENSING WITH A SINGLE-CYCLE TERAHERTZ PULSE

A time lens, in analogy to a spatial lens, produces a quadratic phase shift in time instead of space on an input optical pulse. A linear frequency chirp is therefore imparted onto the input pulse, which can then be compressed by a dispersive line such as a grating or prism pair. Such time-lensing effects have been previously realized using an electro-optic phase modulator driven by a radio-frequency signal [6,7], by optical wave mixing in a nonlinear medium [8–10], or by cross-phase modulation in an optical fiber [11]. Our method utilizes the time-dependent electric field of an intense single-cycle THz pulse to generate a quadratic phase modulation on a copropagating ultrashort laser pulse in an electro-optical (EO) crystal through the Pockels effect. The THz pulses in the present study are produced by coherent transition radiation emitted by subpicosecond relativistic electron bunches when incident upon a conductor [2,3]. For coherent radiation from an electron bunch having a Gaussian longitudinal distribution, the induced transient current has a Gaussian time dependence [12]. The electric field of the THz radiation follows the temporal derivative of the current, which results in a single-cycle THz wave form

$$E_{\mathrm{THz}}(t) \propto -\frac{2t}{\tau_0^2} E_0 \exp\left[-\frac{t^2}{\tau_0^2}\right], \tag{1}$$

where τ_0 is the $1/e$ length and E_0 is the maximum field of the bunch. This wave form is a good representation of our THz pulses. Therefore, to generate a ∼1-ps-long THz electric-field transient, it is necessary to produce an electron bunch with $\tau_0 \approx$200–250 fs. Consider an optical probe pulse with Gaussian intensity and $1/e$ width of t_0 ($<\tau_0$) copropagating with the single-cycle THz pulse through an EO crystal of length L. In the absence of walk-off effects, the THz pulse imposes a phase shift on the optical pulse that is proportional to the THz E field [3,13,14], i.e., $\Delta\varphi(t) = (2\pi L/\lambda_0)\chi^{(2)} E_{\mathrm{THz}}(t)/n_0$, where λ_0 is the central wavelength of the probe pulse, and n_0 and $\chi^{(2)}$ are the linear refractive index and the second-order susceptibility of the EO crystal, respectively. If the input pulse width is short compared to the half cycle of the single-cycle THz E field, the phase term can be expanded to second order around the crest (maximum) or trough (minimum). Near the two extrema (crest or trough) of the single-cycle pulse, the phase modulation is essentially quadratic, which is given by

$$\Delta\varphi(t) = \pm\frac{4\pi}{\lambda}\frac{\chi^{(2)}L}{n_0}\frac{E_0}{\tau_0^2}t^2, \tag{2}$$

where the positive sign corresponds to the trough and the negative sign to the crest. Such a quadratic phase modulation is the temporal equivalent of a thin lens acting on a beam in space. Note that the phase shift is driven by the electric field instead of the intensity of the THz pulse, and therefore the THz-induced temporal lensing is based on the Pockels EO effect. By adjusting the time delay between the probe and the single-cycle THz pulses, the probe phase and the frequency chirp can be tuned between positive and negative. Consequently, the frequency chirped pulse can be compressed by passage through a dispersive element having either positive or negative group velocity dispersion, the choice depending on the sign of the probe pulse's induced chirp. For example, when the time delay is adjusted so that the probe coincides with the crest of the THz pulse, the phase modulation imparts a positive chirp on the probe pulse, which can be compensated for using a grating or prism compressor. When overlapped with the trough, the probe pulse acquires a negative chirp, which can simplify the compressor to a flat plate of glass. In either case, the compressed pulse width is given by [15] $t = t_0/\sqrt{1+a^2}$, where $a = \pm 8\pi\chi^{(2)} l E_0 t_0^2/n_0\lambda\tau_0^2$. In Fourier optics, focusing a Gaussian beam to a smaller spot size can be achieved by filling the lens with a larger diameter input beam. However, overfilling the lens causes aberration, therefore the

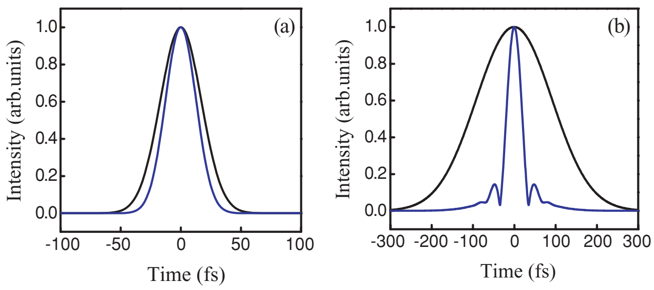

FIG. 1. (Color) Simulated pulse compression with a 40 fs (a) and 180 fs (b) probe pulse. The black and blue lines show input pulse and compressed pulse, respectively. The compression ratio is 1.3 and 4.5 for the 40 and 180 fs input pulse.

focused spot deviates from a true Gaussian. In analogy to Fourier optics, increasing the input probe pulse duration has the potential for shorter output pulse, but only while the THz E field itself retains an ideal quadratic time dependence. Thus, in practice, the ideal temporal lensing is limited to the vicinity of the crest or trough of a single-cycle pulse. Figure 1 shows the calculated compressed (or time-focused) pulse shapes for 40 fs (full width at half maximum or FWHM) and 180 fs (FWHM) input probe pulses copropagated with a 1-ps-long single-cycle THz pulse through a 0.5-mm-thick ZnTe crystal followed by dispersive compression in SF-11 glass. In the simulation, the THz peak electric field is 3.5×10^7 V/m. As shown in Fig. 1(a), a shorter probe pulse will produce a clean compressed pulse, but it leads to a small compression ratio; conversely, a shorter compressed pulse is generated when the duration of the probe pulse matches that of half-cycle of the THz pulse, as shown in Fig. 1(b). The 180 fs incident pulse can be temporally focused to ∼40 fs, and the maximum compression ratio is limited by the THz peak field. However; a considerable portion of the probe pulse receiving a higher order chirp will not be properly compressed, leading to substantial sidelobes or wings on the compressed pulse, as seen in Fig. 1(b).

III. EXPERIMENT AND RESULTS

The schematic diagram of the experimental setup is shown in Fig. 2(a). The THz pulses are generated as coherent transition radiation using a subpicosecond relativistic electron bunch. The THz wave form is measured by a single-shot electro-optic (EO) sampling technique using a chirped laser pulse, [16] in which the time evolution of the THz field is transformed into spectral modulation, and the THz wave form is then extracted as the difference between the spectral profiles of the chirped laser pulse with and without the presence of the THz field. Figure 2(b) shows the retrieved THz wave form to be a ∼1-ps-duration single-cycle E-field pulse. The laser pulse to be compressed is produced by a synchronized Ti:sapphire laser amplifier and is copropagated with the THz pulse through a 0.5-mm-thick ZnTe crystal such that the electric-field vector of the THz is perpendicular to the ZnTe [110] direction and the probe polarization is parallel to the 110 direction [17]. The group velocity mismatch (GVM) between the laser pulse at 795 nm and the THz pulse around 1 THz for 0.5 mm ZnTe is estimated to be ∼70 fs, which is negligible for our frequency range and thus can be ignored. The corresponding E-field strength at the ZnTe crystal is estimated to be ∼3.5×10^7 V/m for which the refractive index change in ZnTe is dominated by the Pockels effect, and the Kerr effect can be neglected [3]. By adjusting the time delay between the laser and THz, the laser pulse can be temporally overlapped with the crest or trough of the THz pulse to yield a maximum quadratic phase modulation (spectral broadening), where the polarity is determined by the THz crest or trough. The laser pulse is then characterized using a second-harmonic generation frequency-resolved optical gating (SHG FROG) device. The intrinsic direction-of-time ambiguity present in the retrieved pulse from the SHG FROG device was removed by an additional FROG measurement after chirping the laser pulse with a piece of glass of known group velocity dispersion.

The probe width is adjusted from ∼110 fs (FWHM) to match the negative half-cycle of the THz pulse; the optimum pulse compression is obtained with a ∼165 fs (FWHM) probe laser. The measurement results are shown in Fig. 3. The first column shows the measured FROG traces of the probe pulse. The temporal and spectral intensity (black) and phase (red) retrieved from FROG traces are shown in columns 2 and 3. The first row of Fig. 3 shows that the probe pulse in the absence of THz has a pulse width of ∼165 fs and a spectral width of ∼5.8 nm. No spectral and temporal modulation on the laser pulse is observed. The laser phase is constant over the pulse duration and the spectrum, and hence represents a transform-limited pulse. The delay is adjusted so that the probe coincides with the trough of the single-cycle THz pulse. The second row shows the FROG trace, and the temporal and spectral shapes of the probe, when it is overlapped with the trough, at which the phase modulation imposed on the probe is approximately quadratic, and the probe pulse develops a negative frequency chirp. The probe pulse is slightly shorter when it interacts with the trough. This is because the THz-induced frequency chirp is

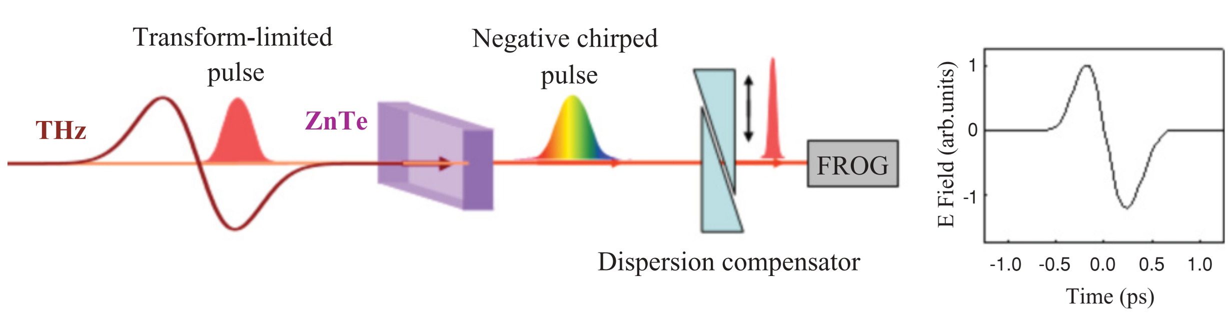

FIG. 2. (Color) (a) Schematic diagram of the experimental setup. (b) Measured THz wave form.

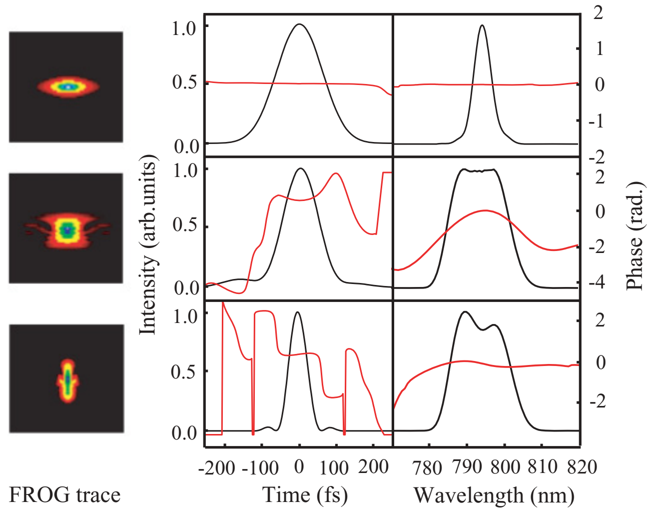

FIG. 3. (Color) Experimental results of FROG measurements. Column 1, measured SHG FROG traces. Columns 2 and 3, retrieved intensity (black) and phase (red) in time and frequency domains. The top and middle rows show the probe pulses in the absence and the presence of THz pulse. The bottom row shows the compressed or focused probe pulse.

negative while the ZnTe dispersion-induced chirp is positive. The two chirp contributions can cancel each other along the center portion of the probe pulse, leading to a slight pulse shortening, and the probe pulse is left with a residual amount of negative quadratic phase.

When overlapped with the trough, the probe spectrum is broadened to ∼25 nm, and both the spectral and temporal phases are predominately parabolic, indicating that the THz *E* field imposes a nearly linear negative chirp across the probe pulse. The temporal phase is fitted to a polynomial, and the resulting group delay dispersion (GDD) coefficient is $\sim 2.3 \times 10^{-4}$ fs^{-2}. A pair of glass (SF-11) wedges that can slide on their hypotenuse, thereby forming a plate with adjustable thickness from 2–12 mm, is inserted into the beam path before the FROG and used to introduce positive group velocity dispersion for frequency-chirp compensation. The third row of Fig. 3 shows that the pulse can be compressed to as short as ∼45 fs, corresponding to a compression ratio of ∼4. This pulse compression is limited by the electric-field strength of THz radiation. The compressed pulse exhibits some residual energy in the sidelobes, which may result due to the nonlinear chirp imposed by the higher order phase modulation, which is consistent with the simulation results in Fig. 1.

IV. CONCLUSIONS

In summary, we have demonstrated that an intense single-cycle THz pulse in an electro-optic medium, combined with dispersion, can serve as a time lens to phase modulate and compress an ultrashort laser pulse. By far the common pulse compression technique relies on the Kerr effect to produce self-phase-modulation (SPM) that is proportional to the pulse intensity, with subsequent compression in a negative dispersive line such as grating or prism pair. Alternative approaches for pulse compression based on molecular phase modulation have been demonstrated recently [18–20], in which a high-intensity pulse impulsively excites a coherent vibration or rotation in a molecular medium and imposes a sinusoidal phase modulation on a time-delayed copropagating weak pulse. As a result, a periodic ultrashort pulse sequence can be obtained by use of either positive or negative GVD compensation. In our study, the THz pulses having peak *E* field of $\sim 3.5 \times 10^7$ V/m have been used with ZnTe to induce phase modulation of an ultrashort laser pulse. The phase shift is driven by the electric field instead of the intensity of the THz pulse. Using an SF-11 glass plate as a dispersion element, we have compressed a ∼165 fs laser pulse to ∼45 fs without using a grating or prism compressor. Our study indicates that the single-cycle THz pulse with a high peak *E* field offers unique opportunities for studying novel ultrafast and nonlinear optical phenomena in the single-cycle regime. Understanding the strong-field phenomena on a time scale of only one optical cycle would be of great interest for both fundamental and applied science.

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