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Free-space electro-optic sampling of terahertz beams

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Free-space electro-optic sampling is an alternative method for the characterization of freely propagating terahertz beams with subpicosecond temporal resolution. In contrast to resonant photoconductive dipole antennas, free-space electro-optic sampling via the linear electro-optic effect (Pockels effect) offers a flat frequency response over an ultrawide bandwidth and the potential for a simple cross-correlation signal of the terahertz and optical pulses.

In the ultrafast electronics and optoelectronics communities, especially in the subfield of applied terahertz beams, the detection of freely propagating picosecond microwave and millimeter-wave signals is primarily being carried out via photoconductive antennas and far-infrared interferometric techniques.[1–8] Photoconductive antennas have superior detection responsivity, and their signal-to-noise ratios are typically far better than liquid helium cooled bolometers. Further, the detection bandwidth of a photoconducting antenna with a short dipole length can exceed 5 THz. However, the limitation of these antenna-based detectors is the resonant behavior of their Hertzian dipole structure. This type of device structure has a resonant wavelength at twice the dipole length and therefore the signal waveform, which includes the resonant detector response function, is not a simple cross-correlation of the incoming terahertz and optical gating pulses. Even if the temporal resolution of photoconductive antennas, which is limited by the finite lifetime of photocarriers in the optical gate and antenna geometry, is reduced below 100 fs, the measured signal will still not provide an accurate representation of the actual terahertz waveform. In comparison, although far-infrared interferometric techniques provide an autocorrelation of terahertz pulses, important phase information is still lost. In most field-matter interaction applications, knowledge of the entire terahertz waveform, including both the amplitude and phase, is crucial. Thus, to support a variety of advanced scientific and technological applications, there is a need for the development of suitable sensing devices.

In this letter, we report the use of an alternative optoelectronic method, free-space electro-optic sampling, to characterize freely propagating terahertz bandwidth pulsed electromagnetic radiation. Generation and detection of electro-optic Cherenkov radiation in $LiTaO_3$ has been reported previously.[9] Our current work is an extension of conventional electro-optic sampling,[10,11] which is primarily used for local field characterization, to free-space applications. Free-space electro-optic sampling is based on the Pockels effect, whereby, through proper velocity matching, the measured waveform can be an exact cross-correlation of the incident terahertz and optical pulses. This technique is particularly attractive because, if we assume the spectrum of the terahertz pulses being characterized lies below the first phonon resonance of the sensor crystal, it offers a flat frequency response over an ultrawide bandwidth, and overcomes the limitations of photoconductive antennas that result from their resonant dipole structure and the effects of finite photocarrier lifetime. Further, since electro-optic sampling is purely an optical technique, it does not require electrode contact or wiring on the sensor crystal.

Figure 1 schematically illustrates the experimental setup for free-space electro-optic sampling. A cw Ar^+ laser pumped, mode-locked Ti:sapphire laser (Coherent MIRA) provides 150 fs optical pulses at 820 nm with a 76 MHz repetition rate. A GaAs photoconductive emitter, triggered by femtosecond laser pulses, radiates the terahertz pulses.[12] The planar emitter has a 2 mm photoconductive gap between the electrodes. The bias field is 1.5 kV/cm and the average optical power on the emitter is 400 mW.

Fundamentally, the electro-optic effect is a nonlinear coupling between a low frequency electric field (terahertz pulse) and a laser beam (optical pulse) in the sensor crystal. Modulating the birefringence of the sensor crystal via an applied, polarized electric field will modulate the polarization ellipticity of the optical probe beam passing through the crystal. The ellipticity modulation of the optical beam can then be polarization analyzed to provide information on both the amplitude and phase of the applied electric field.

In Fig. 1, when a pulsed electromagnetic radiation (tera-

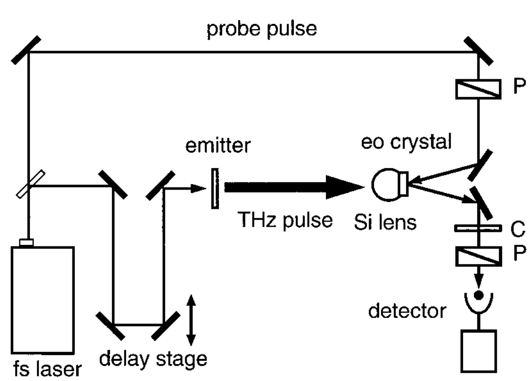

FIG. 1. Experimental setup for free-space electro-optic sampling. An electro-optic crystal is attached to the silicon lens. P's are polarizers and C is the polarization compensator.

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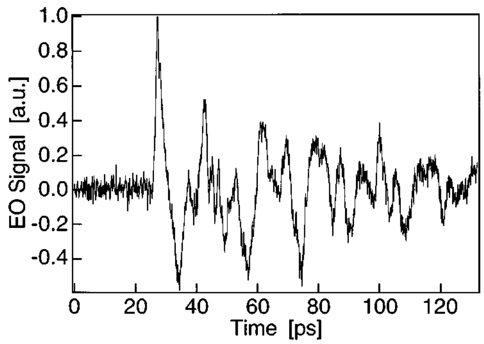

FIG. 2. Signal measured via free-space electro-optic sampling. The emitter is a biased photoconductive antenna, located 10 cm from the sensor crystal.

hertz beam) illuminates the electro-optic crystal, the index of refraction is modulated via the Pockels effect. A femtosecond optical pulse probes the field-induced change in the index of refraction by passing through the crystal with a focus spot of 10 μm. To convert the field-induced ellipticity modulation into an intensity modulation, the probe pulse is analyzed by a compensator (C) and polarizer (P), then detected by a photodetector. In this experiment, a 500 μm thick $LiTaO_3$ crystal was used as a Pockels cell with its c axis parallel to the electric field polarization of the incoming radiation. To improve detection efficiency, the terahertz beam is focused by a high resistivity silicon lens, thereby significantly increasing the transient bias of the sensor crystal. An optical chopper modulates the laser pump beam and a lock-in amplifier is used for noise reduction.

Figure 2 displays the measured transient waveform. Here, the sensor crystal is 10 cm away from the emitter. The risetime of the first peak is 740 fs. The minor peaks following the main peak are mainly due to multiple reflections of the electrical pulse in the photoconductive emitter (impedance mismatch along the biased electrodes), and the terahertz pulse in the sensor crystal. The experimental setup in Fig. 1 does not satisfy the velocity-matching condition, which requires an angle of 71° between the terahertz beam and optical beam in $LiTaO_3$. With a careful geometric design of the radiation emitter and a special-cut crystal, these reflections (electrical, optical, and terahertz pulses) in Fig. 2 should be greatly reduced, and better temporal resolution should be achieved.

The field measurement in the free-space electro-optic sampling is a purely electro-optic process, the system bandwidth is mainly limited by the dispersion of the terahertz signal, and the duration of the laser pulse in the crystal, assuming it is velocity-matched.

The comparison between free-space electro-optic sampling and the Hertzian dipole antenna for measurement of freely propagating quasioptical radiation (terahertz beam) is quite similar to the comparison between electro-optic sampling and photoconductive sampling (Auston switch) for the characterization of ultrashort electrical pulses in planar integrated circuits. Electro-optic sampling, via the Pockels effect, is attractive because it can provide a flat frequency spectrum and a true cross-correlation signal. In contrast, photoconductive sampling with a Hertzian dipole detector offers a superior sensitivity. The frequency bandwidth of the two techniques should be comparable. Also, in order to take full advantage of free-space electro-optic sampling, two major issues must be addressed: (1) the velocity-matching condition between the terahertz and optical pulses; and (2) the multireflection of the terahertz pulse and optical pulse within the sensor crystal.

Our current free-space electro-optic sampling system has a minimum field sensitivity of about 100 μV/μm. Selection of sensor crystals with a higher electro-optic coefficient to replace $LiTaO_3$ is essential for the improvement of the signal-to-noise ratio. For example, an organic DAST crystal has an index of refraction of 2.1, static dielectric constant 6.4, and a Pockels coefficient greater than 400.[13,14] DAST crystals have been used to generate the most intense terahertz radiated field among all of the natural nonexternally biased materials via optical rectification.[15] The figure-of-merit (pm/V) of a DAST crystal is greater than 300, while that of $LiTaO_3$ is only 7.6. By choosing the right velocity-matching condition, it is feasible to build an electro-optic sensor with μV sensitivity, and achieve a signal-to-noise ratio exceeding several hundreds-to-one in low-pulse-energy terahertz beam measurements. An estimation shows that if a 100 μm thick DAST sensor crystal is used, the minimum detectable electric field is 23 $\mu\mathrm{V/cm}\sqrt{\mathrm{Hz}}$. The minimum detectable voltage of the free-space electro-optic system may not be superior to some photoconductive antenna-based systems. However, the bandwidth, minimal field perturbation, and true temporal cross correlation of the free-space electro-optic system are unique.

In conclusion, we present the use of free-space electro-optic sampling for the measurement of freely propagating electromagnetic radiation with subpicosecond resolution. It is possible to extract the true terahertz waveform from the cross-correlation signal obtained via free-space electro-optic sampling. Specifically, because this technique eliminates the need for electrical contact with the sensor crystal, terahertz imaging with an electro-optic crystal plate may be more feasible than with a two-dimensional photoconductive antenna array.

Note added in proof. By using velocity-matched scheme, THz wave forms with FWHM of 450 fs and SNR of 170 have been obtained from unbiased GaAs emitter.

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