Two-dimensional imaging of continuous-wave terahertz radiation using electro-optic detection

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(Received 5 April 2002; accepted for publication 5 June 2002)

We report the demonstration of two-dimensional electro-optic imaging using continuous-wave THz radiation. Two single-frequency laser diodes serve as the optical source for both the generation and detection processes. The generation process occurs by mixing in a photoconductive emitter, while the detection process utilizes an electro-optic crystal and charge coupled device camera. The method permits far-IR imaging using only conventional optical components held at room temperature. In this demonstration, we image the two-dimensional properties of a THz beam focused into a ⟨110⟩ ZnTe electro-optic detection crystal.
[DOI: 10.1063/1.1497190]

Optical imaging is ubiquitous in our society and the new uses are being rapidly introduced. In most applications, the various imaging modalities utilize visible or near-IR light, since sensitive sensor materials are readily available, although x-ray imaging has found significant application in medical diagnostics. As one moves further towards the infrared, however, two-dimensional imaging arrays become increasingly difficult to fabricate and exhibit reduced sensitivity. In the mid-IR, thermoelectrically cooled array detectors are available, although they are typically quite costly. As one moves to even longer wavelengths, in the far-IR, multichannel detectors require cryogenic cooling in order to sufficiently reduce detector noise. To our knowledge, such arrays are not commercially available. One possible solution to this problem is to shift the frequency of the far-IR radiation to a region of the electromagnetic spectrum where detection capabilities are better developed. As discussed below, these detection schemes have the added benefit of being phase sensitive, and thus allow one to obtain more information than is typically obtained using detectors that are only sensitive to the optical power.

Hu and Nuss[1] were the first to demonstrate imaging of coherent far-IR pulses. In their approach, ultrafast laser-driven optoelectronic devices were used to generate and detect terahertz (THz) electromagnetic pulses. In this scheme, the far-IR radiation was focused at a given location on the sample and imaging was accomplished by performing THz time-domain spectroscopy[2] as a function of the spatial position of the beam. In order to create an image, one then measures the temporal wave form for each pixel, performs a Fourier transform to obtain spectral information, and integrates over the relevant portion of the spectrum to assign a signal level to each pixel. Since the optoelectronic detector is a single-pixel device, the sample is spatially scanned and data for constructing an entire image is obtained serially. This approach has proven its efficacy in applications that include environmental sensing, biomedical imaging, and imaging of semiconductor wafers and electronic packaging.[3] More recently, it has been shown that the temporal properties of the reflected THz wave form obtained for each pixel can be used to obtain depth information.[4]

With the advent of free-space electro-optic detection,[5–7] there emerged the possibility of collecting the image in a parallel manner. In contrast to the aforementioned technique, the electro-optic detection process coherently *upconverts* the far-IR infrared radiation from THz frequencies to optical frequencies. This permits the use of standard optical detectors, including multichannel arrays. Wu *et al.*[8] demonstrated the possibility of exploiting two-dimensional optical imaging capabilities to capture two-dimensional images of the THz radiation.[8] In this approach, the THz field modulates the optical probe beam in an electro-optic crystal. The modulated beam is then imaged using a charge-coupled device (CCD) camera, allowing one to collect information for each pixel in an image simultaneously. If a femtosecond laser oscillator is used as the optical source for generating and detecting THz pulses, the modulation depth in the probe beam is typically somewhat small, requiring data averaging over multiple frames. However, if an amplified femtosecond laser system is used as the optical source, the modulation depth can be relatively large, allowing for single-shot detection capability.[9]

Both of the approaches described thus far for THz imaging require ultrafast lasers for the generation and detection processes. We have recently shown that a pair of continuous-wave (cw) lasers detuned from one another by the desired frequency can be used to generate and coherently detect narrowband THz radiation in an analogous fashion.[10] Viewed in the frequency domain, the detection scheme involves the coherent upconversion of the THz field into the optical part of

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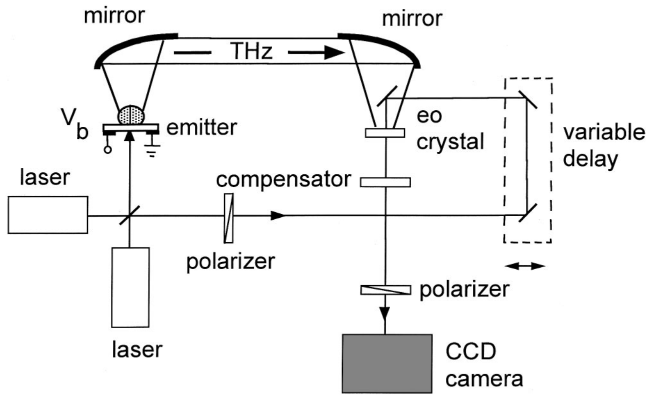

FIG. 1. Schematic drawing of the experimental setup for imaging freely propagating cw THz radiation. The electro-optic detection was performed in a ⟨110⟩ ZnTe crystal.

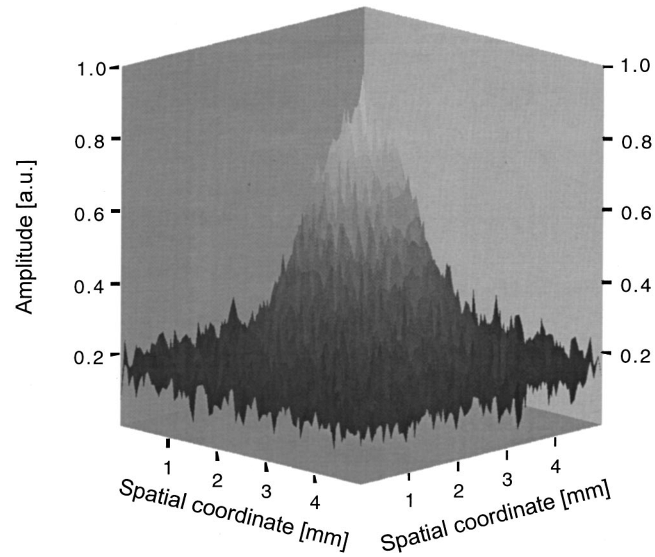

FIG. 2. Image of the THz field distribution in the ⟨110⟩ ZnTe crystal. The frequency of the far-IR radiation is 0.5 THz and the field amplitude is approximately 50 mV/cm.

the spectrum, combined with optical homodyne detection. As we showed earlier, this detection process may also be treated using standard electro-optic analysis.[10] In this latter approach, the magnitude and phase of the THz radiation can be obtained by measuring the change in optical probe beam intensity. Specifically, the change in the probe beam intensity, ΔI_{EO}, is directly proportional to the product of the optical probe intensity, the amplitude of the THz field, and a trigonometric function that incorporates the phase of the THz field.

In this letter, we describe a proof-of-principle demonstration of two-dimensional imaging of cw THz radiation using electro-optic detection. For the purposes of this demonstration, we measure (image) the two-dimensional properties of a THz beam focused into the electro-optic detection crystal. There are two attractive features of cw THz imaging that are worth noting. First, in the case of cw THz radiation, the frequency content is always spatially homogeneous. This is not true for pulsed THz radiation. Furthermore, cw THz imaging requires less computational processing in order to obtain an image. As just mentioned, imaging of THz pulses using an $N\times N$ pixel camera requires performing N^2 Fourier transforms. In the case of cw THz imaging, it is only necessary to determine N^2 local maxima (or minima). While the information content in an image obtained at a given frequency is obviously less than in a complete spectrally resolved image, the cw technique introduced here permits measurement at any desired frequency (or set of frequencies) and can thus capture appropriate image contrast.

The experimental setup for generating and imaging freely propagating cw THz radiation is similar to the system[10] in which the use of cw sources for coherent THz measurements was previously introduced. As illustrated in Fig. 1, two single-mode distributed Bragg reflector laser diodes operating at a wavelength of ~850 nm were combined with a 50/50 beamsplitter. The pump beam, with an average power limited to 40 mW, was used to drive a 100 μm long dipole emitter fabricated on low-temperature-grown GaAs.[11] The device was antireflection coated to minimize optical back reflections into the lasers. The resulting THz beam was modulated by applying a 10 Hz square wave voltage, with an amplitude that varied from +30 to −30 V, to the emitter.

We collimated and refocused the cw THz radiation into a 10 mm×10 mm×6.7 mm thick ⟨110⟩ ZnTe crystal using two off-axis paraboloidal mirrors. A pellicle beamsplitter was interposed in the THz beam line to allow for co-propagation of the optical probe and THz beams through the electro-optic crystal. The crystal was antireflection coated to minimize optical reflections within the crystal. The probe beam was optically biased near its null point by a Soleil–Babinet compensator in a crossed polarizer arrangement. While quarter-wave static phase retardation is often used in electro-optic measurements,[12] operating near the null point allows for the largest fractional modulation in the probe intensity for a given THz field strength, while maintaining a linear response in the THz field.[13,14] In this crossed polarizer geometry, we achieved an extinction ratio of ~1000:1, yielding a factor of ~16 improvement in the fractional modulation relative to quarter-wave biasing conditions. This relatively low value for the extinction is limited by the presence of scattering and inhomogeneous stress-induced birefringence in the ZnTe crystal.

The two-dimensional intensity profile of the optical probe beam was measured with a scientific-grade digital camera operating in frame transfer mode (Princeton Instruments). We used a 512 pixel×512 pixel image region of the camera, corresponding to an area of 11.5×11.5 mm^2. By binning pixels into 4×4 groups (90 μm×90 μm), we were able to increase the effective well capacity as well as the frame transfer rate. We set the frame rate of the camera to twice the THz emitter modulation frequency (20 frames per second), allowing us to subtract alternate frames. This approach allows for a factor of 2 enhancement in the THz signal[10] compared with a conventional on–off modulation scheme for differential detection.

Figure 2 shows a measured two-dimensional image of a focused cw beam as obtained by electro-optic detection. We generated coherent cw far-IR radiation at a frequency of 0.5 THz. This was achieved simply by setting the wavelength detuning between the laser diodes to ~1.25 nm. With respect to the detection process, it is important to achieve a phase-matched interaction between the THz and optical waves in the electro-optic crystal. For detection of 0.5 THz radiation by an optical probe beam of wavelength ~852 nm, the coherence length for phase matching in our ZnTe crystal is calculated to be ~17 mm.[15] Since this length significantly exceeds that of the actual crystal, no degradation of detection sensitivity from imperfect phase matching is expected. In the measurements, the difference in path length between the pump and probe arms was set to zero, so that the phase difference between the THz and probe beams was zero.[10] This setting maximized the amplitude modulation in the probe beam. The fractional modulation induced by the THz electric field was $\sim 4\times 10^{-5}$. From Fig. 2, the measured beam profile appears to be approximately symmetric about the peak with a Gaussian spatial distribution. The $1/e$ beam diameter along both the x and y axes is ~2 mm. We estimate that the THz electric field amplitude was 50 mV/cm, corresponding to an average power of ~300 nW. In such measurements, phase information may also be obtained by varying the pathlength difference and collecting the corresponding images. Further refinement in the signal-to-noise properties of the detection process is desirable for such measurements.

In order to obtain the image shown in Fig. 2, we had to average over 5×10^4 frames, which required 40 min. Since the full well capacity of each effective pixel was $\sim 10^6$ electrons, the photon shot noise was ~1000 electrons. Thus, in the shot noise limit, the smallest observable modulation change in the optical probe beam for single frame acquisition was $\sim 10^{-3}$. The extremely low noise properties of semiconductor laser diodes used in this study allowed us to achieve nearly shot noise limited detection. Thus, frame averaging reduced the minimum observable modulation depth to $\sim 4\times 10^{-6}$.

There are a number of refinements that can be readily implemented to reduce the data acquisition time. As an example, Brown has proposed a photoconductive emitter design that may be capable of producing ~7 μW at 0.65 THz.[16] This would represent a factor of 20 increase in THz power over what we have achieved and would lead to a corresponding reduction in acquisition time. For detection purposes, there exist numerous materials that exhibit electro-optic coefficients that are larger than ZnTe. Many of these materials have not been carefully examined for cw THz applications, due to the focus on wideband THz applications. These materials may, however, be well suited for the present application where the linewidth of the cw THz radiation is extremely narrow. In the present experiments, the relatively low extinction ratio of the crossed polarizer geometry required the attenuation of the optical probe beam intensity in order to prevent saturation effects in the camera. By carefully screening crystals that allow for higher extinction ratios ($\sim 10^4:1$),[8] significantly higher probe beam intensities may be used. The reduction in acquisition time scales directly with the increased extinction ratio, if one assumes identical probe beam characteristics exiting the crossed polarizer arrangement. Implementation of these two refinements alone can reduce the data acquisition time by more than two orders of magnitude.

In conclusion, we have demonstrated coherent two-dimensional imaging of cw THz radiation based on a pair of slightly detuned laser diodes as the optical source for both the generation and detection processes. The far-IR light is produced in a photoconductive emitter by nonlinear mixing, while the detection takes place using an electro-optic crystal. This detection process involves frequency upconversion of the THz radiation combined with optical homodyning. The resulting amplitude-modulated optical signal is imaged with a digital CCD camera for parallel detection. In contrast to other approaches to far-IR imaging, the method introduced here relies on standard optical components and does not require the use of cryogenics. Moreover, the far-IR frequency for the imaging system can be readily tuned over a broad spectral region by adjustment of the difference frequency between the two diode lasers.

One of the authors (T.F.H.) would like to acknowledge support by the Air Force Office of Scientific Research.

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