Real-time, continuous-wave terahertz imaging by use of a microbolometer focal-plane array

Alan Wei Min Lee and Qing Hu

Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received April 22, 2005; accepted June 1, 2005

Real-time, continuous-wave terahertz imaging is demonstrated with a 10 mW, 2.52 THz (118.8 μm) far-infrared gas laser and a 160×120 element microbolometer camera. The microbolometer camera is designed for wavelengths of 7.5–14 μm but retains sensitivity at terahertz (THz) frequencies. The setup has no moving parts, and transmission-mode THz images can be obtained at the video rate of 60 frames/s. The peak signal-to-noise ratio is estimated to be 13 dB for a single frame of video, acquired in 16 ms. With this setup, THz imaging through a FedEx envelope is demonstrated, showing the feasibility of real-time mail screening.

OCIS codes: 110.2970, 110.3080, 140.3070.

Terahertz (THz) frequency-range radiation, 0.3–10 THz (1 mm to 30 μm), has been used to demonstrate imaging of objects that are opaque at optical frequencies: integrated circuit packages, leaves, teeth, thin tissue samples, and illicit drugs in envelopes.[1–5] Because of the relatively modest power levels available in most THz sources and the lack of multielement THz detectors, the vast majority of THz imaging has been done by linear scanning of an object through a tightly focused beam, a practice that limits the acquisition time to the mechanical scan rate of the system. With upper limits of hundreds of pixels/s for mechanical scanning, it takes minutes to acquire a complete image.[4]

High-speed terahertz imaging at nearly real-time frame rates (defined here as 30 frames/s or more) was previously demonstrated by use of an electro-optic crystal for frequency upconversion.[6] In this setup, pulsed THz radiation passes through an object and is imaged by a lens onto a ZnTe electro-optic crystal. The two-dimensional THz electric-field distribution changes the polarization of an optical probe pulse by means of the Pockels effect. This optical beam is filtered by a polarizer, and the small changes induced by the two-dimensional THz electric-field distribution can be viewed in real time by a CCD focal-plane camera.

Because of the short THz pulses (<1 ps) used, this scheme is inherently broadband (>1 THz), making it unsuitable for applications that require both real-time operation and frequency-sensitive measurement. For example, the real-time screening of mail for drugs[5] will likely require samples to be rapidly classified by absorption measurements in a few, narrow-frequency bands that correspond to the unique spectral fingerprints of target chemicals. The combination of a narrowband, continuous-wave THz source with an electro-optic frequency-upconversion technique was demonstrated by Nahata *et al.*[7] However, because the electric field of the continuous-wave source is significantly weaker than the electric field of a pulsed source, the electric-field-induced signal is reduced, and much longer integration times (>10 min) are required. Consequently it is not feasible to achieve frequency-sensitive imaging in real time with this scheme.

It is highly desirable to use focal-plane array cameras that can directly detect THz signals with sufficient speed. The coherent radiation source can be provided by solid-state frequency multipliers at submillimeter-wave frequencies and by far-infrared gas lasers or quantum-cascade lasers[8–10] (QCLs) above 1 THz. Because of their compact sizes, QCLs are especially attractive for multispectral imaging applications. Several QCLs with different frequencies can be packaged tightly, forming a frequency-agile coherent radiation source. When it is combined with a focal-plane array camera that is capable of video-rate detection, this system can perform frequency-sensitive THz imaging at a rate far greater than that described by Kawase,[5] allowing real-time THz monitoring and screening to be performed.

In this Letter we demonstrate single-frequency, real-time continuous wave terahertz imaging by use of a focal-plane array camera. Even though it has also been demonstrated with QCLs (at ~3 THz) as the illumination source in our laboratory,[11] for the research reported in this Letter a far-infrared gas laser (S122, Laser Photonics) was used because of its room-temperature operation and good beam pattern. The 2.52 THz (118.8 μm) radiation is generated by pumping CH_3OH (methanol) vapor with a CO_2 laser, producing approximately 10 mW of output power.

The unique enabling component of the real-time THz imaging system is an uncooled (room temperature) microbolometer focal-plane array camera (SCC500L, BAE Systems).[11] The camera uses a 160×120 element array of microbolometers, spaced at a pitch of 46.25 μm. Each microbolometer consists of a thin film of vanadium oxide (VO_x) upon a silicon nitride air bridge, with a reflecting back plane placed $\sim\lambda/4$ away, where λ is ~10 μm, roughly the center of the 7.5–14 μm night-vision wavelength range.

In the 7.5–14 μm band the thermal fluctuation, electrical noise-equivalent power ($\mathrm{NEP_E}$) is rated at $9\times10^{-13}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ with the resultant noise-equivalent temperature difference (NETD) for the camera (including $f/1$ optics) of 40 mK. The optical efficiency of the camera is unknown at 118.8 μm, and therefore the optical NEP, which is the ($\mathrm{NEP_E}$) divided by the optical efficiency, is unknown as well. Naturally the sensitivity of the microbolometers is far from optimum, but it still permits direct detection of THz power; this is to our knowledge the first reported use of existing 7.5–14 μm technology for THz applications. Furthermore, because the system uses a staring focal-plane array, it has no moving parts. As a result, images at the 118.8 μm wavelength are acquired at the full 60 Hz frame rate of the camera.

The experimental arrangement is shown in Fig. 1. The THz beam is allowed to expand at a 1.4° divergence angle of the laser over a path length of 1.5 m, resulting in a beam diameter of 4.5 cm at the 90° off-axis paraboloid mirror ($f=10$ cm). The reflected beam backlights an object with a maximum area of roughly 4 cm × 4 cm, and the transmitted light is collected by a germanium camera lens ($f=1$ cm, antireflection coated for 10 μm wavelength). The focal plane is positioned approximately 1.1 cm behind the germanium camera lens, making the object plane 10 cm in front of the lens. A 6.5 mm thick sheet of high-density polyethylene (HDPE; 2.4 dB insertion loss at 2.52 THz) is placed directly in front of the camera to provide a uniform background. It was observed that, without the HDPE filter, the uneven ~300 K ambient blackbody radiation overwhelms the THz images, because of the high sensitivity (NETD, ~40 mK) of the camera at the ~10 μm wavelength.

The distance between the off-axis paraboloid and the germanium lens is fixed to collimate the light emerging from the lens, which results in underfilling of the 1 cm diameter lens and an illumination of only ~40% of the pixels. However, concentrating the signal over a smaller area improves the signal/noise ratio (SNR). At the brightest illumination point, the center of the image, the SNR is estimated to be 13 dB, decreasing toward the edges where the signal diminishes.

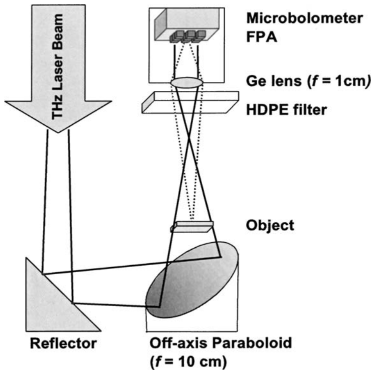

Fig. 1. Experimental setup: solid lines, paths of THz beams. Dotted lines, marginal rays of the camera lens, which are focused to a point on the object. FPA, focal-plane array.

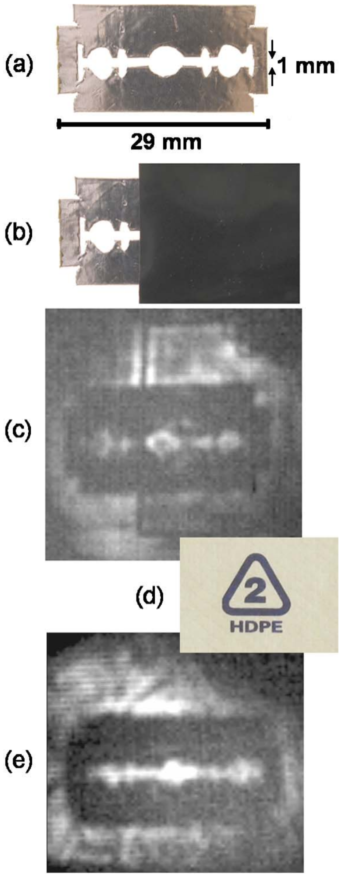

Fig. 2. White-light and terahertz images of a scaled razor blade. (a) white-light image; (b) white-light image partially obscured by a blackened low-density polyethylene sheet; (c) the same image as (b) at 2.52 THz, taken with a 16 ms acquisition time and with the histogram adjusted; (d) sample of a FedEx envelope (made from DuPont Tyvek, a fibrous HDPE material), and marked HDPE; (e) a razor blade completely inside a FedEx envelope at 2.52 THz, taken with a 5 s acquisition time and with the histogram adjusted.

Figures 2(a) and 2(b) show white-light pictures of the test image: a scaled razor blade cut out of aluminum foil, and the same scaled razor blade partially obscured by a sheet of visibly opaque low-density polyethylene (LDPE, 50 μm thickness, 1.1 dB insertion loss at 2.52 THz). The length of the razor blade is 2.9 cm, so it fits well within the THz illumination, where the beam is strongest. Figure 2(c) shows a single frame of real-time video with THz radiation backlighting the razor blade. The interior features and edges of the razor can be seen, as well as the edge of the LDPE sheet. The resolution for the system can be compared to the Rayleigh criterion, which limits the minimum resolvable angle to $\theta\approx1.22\lambda/d$, where d is the 1 cm diameter of the germanium camera lens. At the object plane, 10 cm in front of the lens, resolution is limited to ~1.5 mm. The resolution of the smaller 1 mm features is poor, but the larger 3 mm features are well resolved, indicating near-diffraction-limited optics. The acquisition time for Fig. 2(c) was 16 ms. Even with a reduced number of pixels being illuminated, the system has a pixel acquisition rate of 4.8×10^5 pixels/s, which is more than 3 orders of magnitude faster than a mechanically scanned system.

Figure 2(e) shows a THz image of the razor blade inside a FedEx envelope (made from DuPont Tyvek, a fibrous HDPE material), demonstrating the feasibility of mail screening. The white-light image of a small sample of the envelope is shown in Fig. 2(d). The slightly reduced resolution is due to the additional scattering of the envelope and its fibers. These fibers can be seen around the razor blade.

It should be stressed that, as human eyes are more sensitive to moving objects, the real-time images of a moving target displayed on a monitor are more impressive than the still images of Fig. 2 suggest. The capability of performing real-time video imaging at a specific THz frequency is what distinguishes this system from the other THz imaging systems reported in literature.

In conclusion, our imaging system demonstrates the use of a commercial microbolometer camera for real-time, continuous-wave 2.52 THz imaging with a 10 mW average power source. A peak SNR of 13 dB was obtained for an acquisition time of 16 ms. Near-diffraction-limited imaging was demonstrated on a double-edged razor blade, showing the ability to see through visibly opaque materials such as a FedEx envelope.

This research is only the first step in demonstrating the feasibility of real-time THz imaging with a coherent continuous-wave illumination source. Significant improvements in SNR and spatial resolution can be made by designing focal-plane microbolometer cameras specifically optimized for THz frequencies. These design changes will include using different radiation absorbing materials, correctly placing the reflecting $\lambda/4$ backplane, and using appropriate antireflection coatings and a larger-sized, slower focal lens. We envisage a compact all solid-state system that, in combination with a multicolor QCL illumination source, can perform frequency-sensitive THz imaging in real time.

This research is supported by the Air Force Office of Scientific Research, NASA, and the National Science Foundation. We thank BAE Systems (Lexington, Mass.) for the loan of the SCC500L microbolometer camera. We are grateful to B. S. Williams, S. Kumar, and H. Callebaut for their help in preparing this work. A. W. M. Lee's e-mail address is awmlee@mit.edu.

References

1. B. B. Hu and M. C. Nuss, Opt. Lett. **20**, 1716 (1995).
2. D. D. Arnone, C. M. Ciesla, A. Corchia, S. Egusa, M. Pepper, J. M. Chamberlain, C. Bezant, E. H. Linfield, R. Clothier, and N. Khammo, Proc. SPIE **3828**, 209 (1999).
3. J. Darmo, V. Tamosiunas, G. Fasching, J. Kroll, K. Unterrainer, M. Beck, M. Giovannini, J. Faist, C. Kremser, and P. Debbage, Opt. Express **12**, 1879 (2004).
4. P. H. Siegel and R. J. Dengler, Proc. SPIE **5354**, 1 (2004).
5. K. Kawase, Opt. Photonics News **15**(10), 34 (2004).
6. Q. Wu, T. D. Hewitt, and X.-C. Zhang, Appl. Phys. Lett. **69**, 1026 (1996).
7. A. Nahata, J. T. Yardley, and T. F. Heinz, Appl. Phys. Lett. **81**, 963 (2002).
8. R. Köhler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Ritchie, R. C. Iotti, and F. Rossi, Nature **417**, 156 (2002).
9. M. Rochat, L. Ajili, H. Willenberg, J. Faist, H. Beere, G. Davies, E. Linfield, and D. Ritchie, Appl. Phys. Lett. **81**, 1381 (2002).
10. B. S. Williams, H. Callebaut, S. Kumar, Q. Hu, and J. L. Reno, Appl. Phys. Lett. **82**, 1015 (2003).
11. N. Butler, R. Blackwell, R. Murphy, R. Silva, and C. Marshall, Proc. SPIE **2552**, 583 (1995).