Detection of Concealed Explosives at a Distance Using Terahertz Technology

A prototype terahertz standoff detection system is shown to be able to sense explosives at a distance of one meter, through several layers of clothing, employing safe-to-use non-ionizing radiation.

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ABSTRACT | Terahertz imaging and spectroscopy has been shown to have the potential to use very low levels of nonionizing radiation to detect and identify objects hidden under clothing. In this paper we discuss some of the important factors involved in addressing practical systems in the security industry, and describe our recent work on the development of a prototype terahertz standoff detection system. Using this system we demonstrate the spectroscopic detection of concealed explosives at a standoff distance of 1 m, both real time, in reflection, and under normal atmospheric conditions.

KEYWORDS | Standoff detection of explosives; terahertz

I. INTRODUCTION

The terahertz (THz) region of the electromagnetic spectrum is typically considered to occupy 300 GHz to 10 THz, bridging the gap between millimeter waves and the infrared. Recent developments have started to address the previous lack of sources and sensitive detectors in this range [1], [2]. Consequently, the technological advances have been accompanied by much interest in possible applications in the security [3], [4], pharmaceutical [5], nondestructive testing (NDT) [6], and medical industries [7], [8].

There are unique properties of THz radiation that make it a potentially powerful technique in security screening. Firstly, THz radiation penetrates many everyday physical barriers such as typical clothing and packing materials with modest attenuation [3]. Secondly, many chemical substances and explosive materials exhibit characteristic spectral responses at THz frequencies that can be used for threat object identification [4], [9]–[11]. Additionally, being at submillimeter wavelengths, THz radiation is nonionizing. THz techniques therefore combine safe-to-use high-resolution imaging and the identification through spectroscopy of threat materials—even when hidden in packages or under clothes.

THz imaging systems can be passive, simply detecting the THz part of the thermal black-body radiation given off by objects. Alternatively, active schemes can be implemented whereby the object being imaged is illuminated by a THz source. Whilst passive systems may be effective for 2-D low frequency (e.g. 100 GHz) millimeter wave imaging, chemical/structural analysis of suspect objects is restricted to higher frequency techniques, since there appears to be virtually no spectroscopic features in solids below 500 GHz [4]. Active techniques, such as terahertz pulsed imaging (TPI), and terahertz continuous wave (TCW) imaging can be several times more sensitive. Pulsed techniques enable 3-D imaging, much like radar by using time of flight analysis providing increased contrast and discrimination.

Thus by combining imaging and spectroscopy THz has the potential to be an important tool for the detection of hidden metallic and nonmetallic objects, such as ceramics and explosives, for people screening.

In this paper, we discuss some of the important factors involved in addressing practical systems in the security industry, and describe one of our ongoing development programmes for use in people screening applications—a standoff detection system, aimed at detecting threats such as explosives using spectroscopy at a distance.

Manuscript received October 10, 2005; revised April 2, 2007. This work was supported in part by the U.K. Government.

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Digital Object Identifier: 10.1109/JPROC.2007.900329

0018-9219/$25.00

II. TERAHERTZ SYSTEMS

Established THz systems are largely based on photoconductive switches, which rely on the production of few-cycle THz pulses using an ultrafast laser to excite a biased photoconductive antenna. This technique is inherently broadband, with the emitted power distributed over several THz (typically 0.1–4 THz). Pulsed THz emission in photoconductive antennas is produced when the current density j of a biased semiconductor is modulated on sub-picosecond timescales $E_{\mathrm{THz}} \propto (dj/dt)$ [12]. The change in current density, and hence photocurrent, arises from two processes: the rapid change of the carrier density via femtosecond laser illumination, and the acceleration of photogenerated carriers under an external electric field [13]. Coherent detection of the incident THz radiation can be performed in a similar photoconductive antenna circuit [14], [15]. By gating the photoconductive gap with a femtosecond pulse synchronized to the THz emission, a dc signal that is proportional to the THz electric field may be measured. Further, by varying the optical path length to the receiver, the THz pulse can be acquired in the time domain. Hence both the amplitude and phase of the incident THz wave can be obtained, and a dynamic range of 60 dB demonstrated using time-gated detection [16].

In a typical pulsed THz system (see Fig. 1), the beam from the ultrafast femtosecond laser is split by a beamsplitter into two components, a pump beam and probe beam, used to illuminate the emitter and receiver respectively. A motorized delay stage is then incorporated into the probe beam to vary the difference in optical delay around zero between the incoming THz pulse and the probe laser pulse at the detector.

A rapid scanning delay line is often utilized since it allows both the delay position and the lock-in output to be digitized and reinterpolated to obtain the THz field as a function of optical delay in real time. The frequency Fourier transform can then also be displayed in real-time on a computer display. Typically, the output from the THz emitter is coupled from the rear surface of the device using a high-resistivity silicon lens, which, in combination with off-axis parabolic mirrors/lenses, allows the THz beam to be manipulated as required. Additionally, to couple the THz radiation from free-space into the receiver, a second silicon lens in contact with the rear of the receiver chip is used.

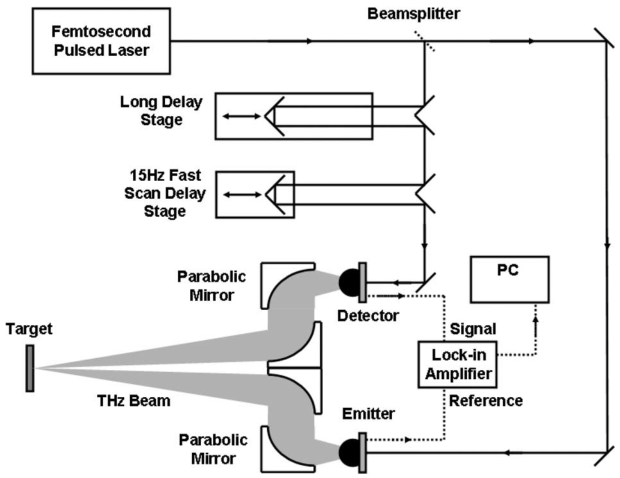

Fig. 1. ***Schematic of a THz photoconductive system. In this example, specifically designed for standoff explosives detection, the THz beam is manipulated for reflection spectroscopy of a target material.***

The THz emitter and detector are manufactured from SI and LT GaAs materials respectively, using, for the detectors, recently developed materials processing techniques [17]. A bias of 50 V was applied across the emitter electrodes, and the gated output signal from the receiver was fed to a lock-in amplifier.

III. SPECTROSCOPY OF EXPLOSIVE MATERIALS

To validate that THz technology is capable of detecting explosives, we first measured the spectrum of various common explosives in transmission. This was performed using a commercially available transmission spectrometer, TPI spectra 1000. In transmission the THz field is modified by dispersion and the absorption of the media under examination. The ratio of the electric field strength before $E_r(\omega)$ and after transmission $E_s(\omega)$, is given by

$$\frac{E_s(\omega)}{E_r(\omega)} = t_{n(\omega)} \exp\left(-\frac{\alpha(\omega)d}{2} + i\frac{(n(\omega)-1)\omega d}{c}\right) \tag{1}$$

$$t_{n(\omega)} = \frac{4n(\omega)}{(n(\omega)+1)^2} \tag{2}$$

where d is the thickness of the sample, ω the frequency of the radiation, c the speed of light, and $t_{n(\omega)}$ is the reflection loss at the sample surface as defined above. Hence, in transmission spectroscopy both the refractive index $n(\omega)$ and the absorption coefficient $\alpha(\omega)$ can be determined from the measured amplitude and phase information by

$$\alpha(\omega) = \frac{2}{d}\left[-\Re\left\{\log\frac{E_s(\omega)}{E_r(\omega)}\right\} + \log\frac{4n(\omega)}{(n(\omega)+1)^2}\right] \tag{3}$$

$$n(\omega) = 1 + \frac{c}{\omega d}\Im\left\{\log\frac{E_s(\omega)}{E_r(\omega)}\right\}. \tag{4}$$

In Fig. 2 we show the measured absorption spectra and refractive index of various common explosive constituents RDX, and PETN. We note from these measurements that

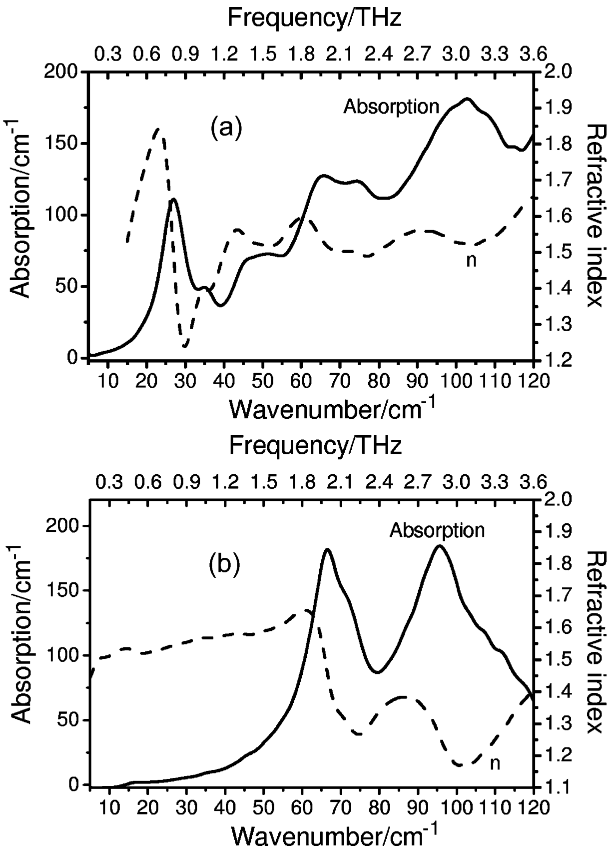

Fig. 2. ***The THz absorption spectra (solid line) and refractive index (dashed line) of: (a) RDX and (b) PETN.***

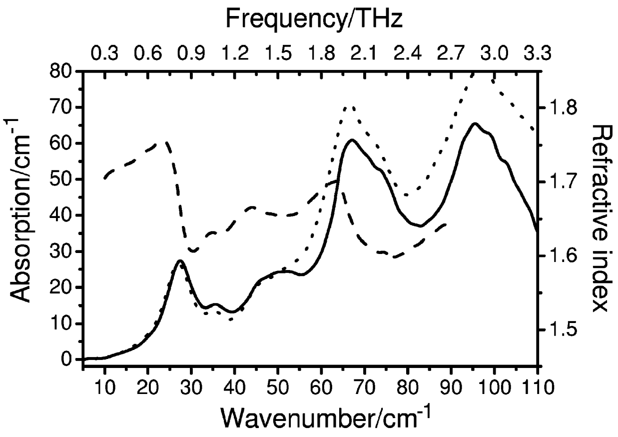

Fig. 3. ***The THz absorption spectra (solid line) and refractive index (dashed line) of Semtex-H. The dotted line shows the combined absorption spectra of RDX and PETN.***

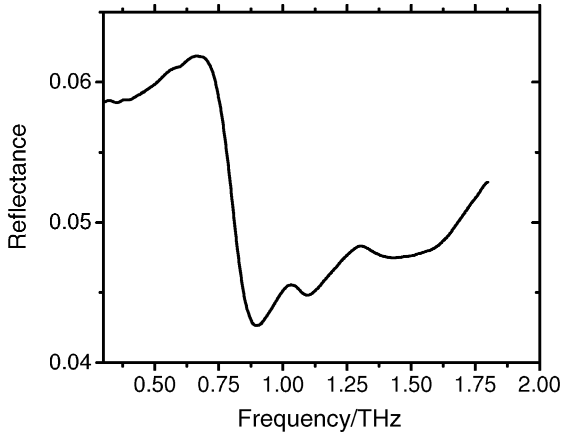

Fig. 4. ***The calculated reflection spectrum of Semtex-H, as determined from absorption data and (5).***

there are clear and unique spectral features corresponding to each of the explosives. These results agree well with previous reports [3], but with extended spectral coverage (5–120 cm^{-1}), and superior spectral resolution (1 cm^{-1}). These signatures also appear to be distinct from the spectral features of harmless materials such as pharmaceutical compounds and sugars.

In Fig. 3 we show the absorption spectrum (solid line) and refractive index (dashed line) of Semtex-H. The features appearing in the absorption spectrum of Semtex-H can be understood from the constituent explosives. Semtex-H consists of approximately equal amounts of RDX and PETN, with the remainder comprising poly(butadiene-styrene) and oil. It can be seen that the absorption of Semtex-H is the sum of its active constituents, shown as the dotted line.

Despite the high sensitivity and dynamic range of THz pulsed spectroscopy (TPS) techniques any practical implementation of a people screening system will need to work in reflection rather than transmission geometry. From the refractive index, as determined from transmission spectroscopy, the reflectance can be determined. The reflectance, defined as the frequency-dependent ratio of the reflected intensity to the incident intensity, is related approximately to the refractive index by

$$R(\omega) \approx \left(\frac{n(\omega) - 1}{n(\omega) + 1}\right)^2. \tag{5}$$

Thus using transmission spectroscopy it is possible to determine the expected result from a reflection spectroscopy measurement. Fig. 4 shows the expected reflectance of Semtex-H as determined from the above equation.

IV. STANDOFF EXPLOSIVES DETECTION

For many THz applications, including security screening, it may be necessary to perform measurements in reflection over a distance through the atmosphere. In this paper we demonstrate for the first time the spectroscopic detection of concealed explosives at a standoff distance of 1 m, both real time, in reflection, and under normal atmospheric conditions.

A schematic of the pulsed THz photoconductive system used is shown in Fig. 1. In our setup, a coherent Vitesse laser was used to generate pulses of average power 800 mW, at 800 nm center wavelength, 80 MHz repetition rate, and with a bandwidth limited pulse duration of 80 fs. As described in Section II, the output of the ultrafast laser was split into two components, a pump beam and probe beam, used to illuminate the emitter and receiver respectively. This was achieved by using a high-energy beamsplitter, with 80% of the beam being reflected into the probe beam, and 20% transmitted as the pump beam. A rapid scanning delay line oscillating at 15 Hz, and a 1000 mm delay stage were incorporated into the probe beam. The optical laser powers at the emitter and receiver were controlled by using neutral density filter wheels in both the pump and probe beams. In this arrangement, the pump and probe laser powers incident on the photoconductive devices were measured to be 5 and 20 mW respectively.

The optical scheme for the THz radiation was as follows: the generated THz radiation from the photoconductive emitter was coupled from the rear surface of the device using a high-resistivity silicon hyperhemispherical lens, which, in combination with an f/1 off-axis gold parabolic mirror, collimated the THz beam. This was then focused and directed onto a target object at a standoff distance of 1 m by second off-axis parabolic reflector. The reflected THz beam from the target object then followed an identical reverse scheme, using two parabolic mirrors and a hyperhemispherical silicon lens, allowing the THz beam to be focused onto the photoconductive gap of the receiver. This allows us to perform single point reflection spectroscopy of targets at a standoff distance of 1 m.

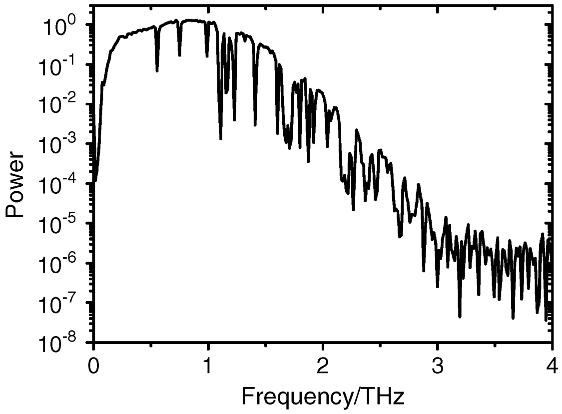

Fig. 5. ***The power spectrum from the standoff system with a mirror as the target material. The sharp absorption lines in the spectrum are due to atmospheric water vapor, with the THz path length equal to 2.4 m.***

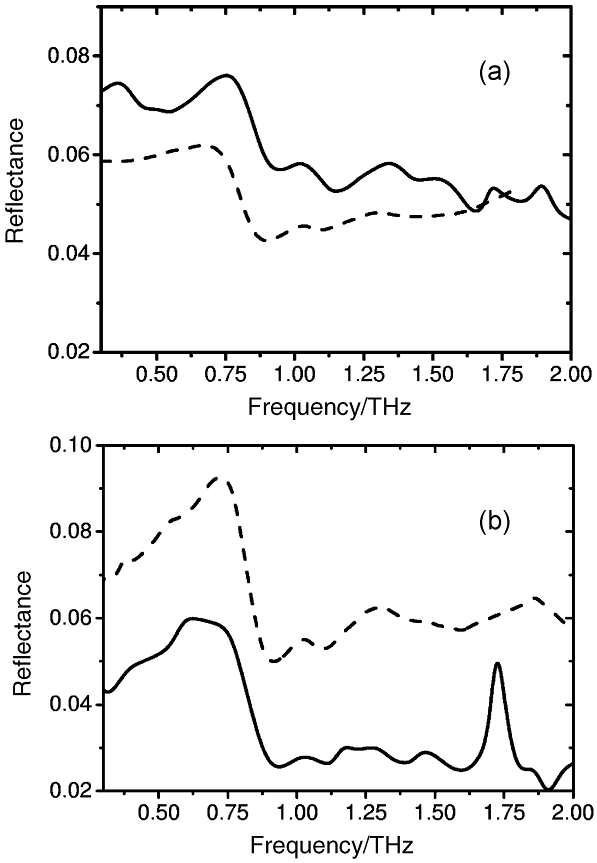

Fig. 6. ***The measured (solid line) and calculated (dashed line) reflectance spectra of: (a) Semtex-H and (b) SX2 at a standoff distance of 1 m, under normal atmospheric conditions, taken real time (single 1/15 s scan). The calculated spectra were derived from transmission spectroscopy data.***

As a demonstration of the performance (measured in rapid scan and collected in a time of 1/15 s), Fig. 5 shows the measured power spectrum with a mirror placed at the focal plane. From Fig. 5, we show that, at a standoff distance of 1 m, a system dynamic range of > 60 dB, and a spectral bandwidth extending from 0.1 to about 3.0 THz is demonstrated. Sharp absorption features can be seen in the THz spectrum shown in Fig. 5, which correspond to atmospheric water vapor lines—these can be removed algorithmically from the spectrum since the underlying target spectrum has only relatively broad features. These absorption bands in the THz spectrum are occurring after traversing a total path length of 2.4 m through the atmosphere. It can be seen that there are numerous water attenuation windows through which the signal is relatively unattenuated.

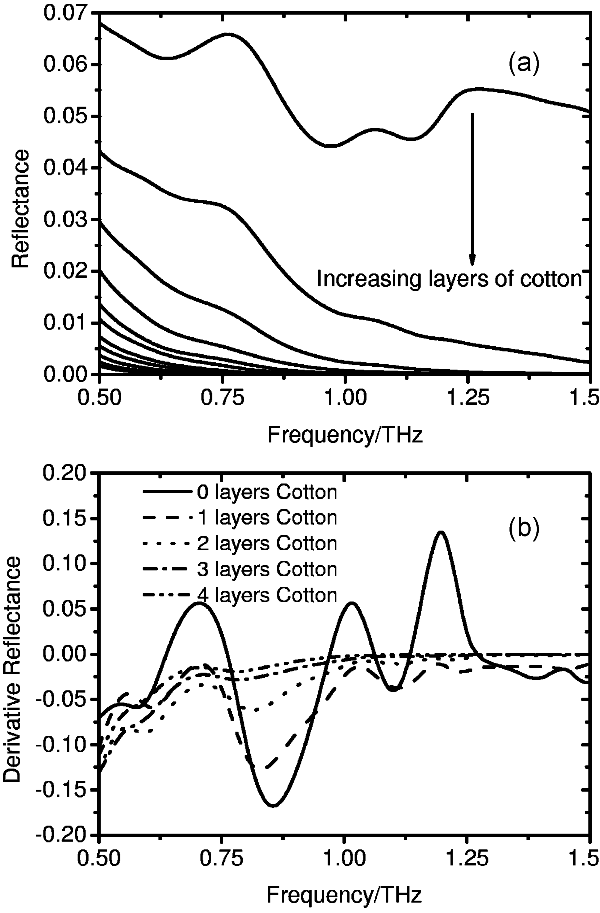

Fig. 7. ***(a) The reflectance of SX2 behind cotton clothing. (b) The first derivative of the reflectance of SX2 behind cotton clothing. The RDX spectral feature is visible in (b) through several layers of cotton.***

In Fig. 6, we show a reflection measurement from two explosive samples, (a) Semtex-H and (b) SX2, taken using the standoff instrument at a distance of 1 m, measured in rapid scan and collected in a time of 1/15 s. The absolute reflectance was determined by division of the measured power spectrum, by a power spectrum from a mirror reference, measured in an otherwise identical fashion (see Fig. 5). Also shown in Fig. 6(a) and (b) are the predicted reflection spectra of Semtex-H and SX2. The agreement between calculation and experiment is good, with features being observed in both spectra at 0.8, 1.05, and 1.4 THz. For the measured spectra, data processing techniques were applied real time to the dataset to remove the water vapor absorption lines, i.e., both the data acquisition and data processing was performed in 1/15 s.

Also, there is agreement between the frequencies of the spectral features of Semtex-H and SX2. This is to be expected because both explosives contain substantial proportions of RDX, which dominates the spectral features over the frequency range of the figure. Since SX2 is predominately RDX (over 80% by volume), whereas Semtex-H contains only around 40%, the spectral features in SX2 are stronger than those from Semtex-H.

Clearly, clothing is crucial to the prospect of practical standoff detection. We have performed a series of measurements of explosives hidden behind increasing numbers of clothing layers. Shown in Fig. 7(a) is the effect of increasing numbers of clothing layers on the 1 m spectrum of SX2 sheet explosive. The clothing layers were from a typical cotton/polyester shirt loosely placed in front of the explosives, in a manner consistent with normal wear. As before these measurements were taken at a distance of 1 m, in a time 1/15 s, and with automated water vapor removal. The rapidly diminishing reflectance, as the frequency rises, is a straightforward consequence of the exponentially increasing attenuation of clothing layers with frequency—the clothing layers acting as a low-pass filter to the spectrum. The effects of this can be visually removed by taking the derivative the reflectance spectrum, as shown in Fig. 7(b). The reflectance feature of SX2 centered at 0.8 THz manifests itself as an oscillation in the derivative spectrum. Although difficult to recognize from the linear scaling of Fig. 7(a), the derivative spectra [Fig. 7(b)] clearly shows that we can convincingly identify spectral features through several layers of clothing at least at the frequencies around 1 THz. Increased system signal-to-noise ratio will be needed to identify higher frequency features.

As we have discussed in this paper, there are characteristic spectral features in many common types of explosives materials at THz frequencies. Relatively few other materials have strong spectral features in the range of 0.5 to 1.0 THz. A substance that does exhibit interesting features in this range is D-tartaric acid, as shown in Fig. 8.

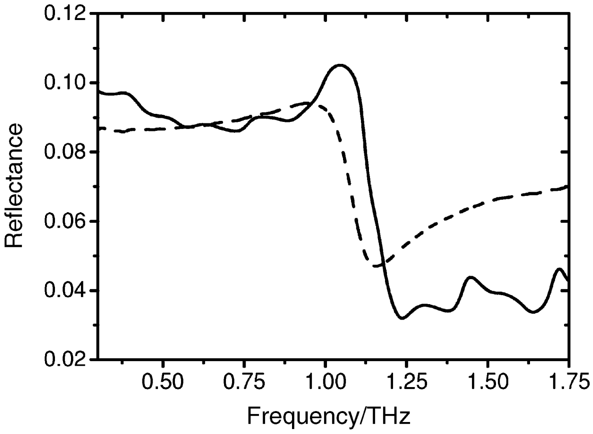

Fig. 8. ***The measured (solid line) and calculated (dashed line) reflection spectrum of tartaric acid at a standoff distance of 1 m. This demonstrates the ability of the technique to distinguish between materials.***

This measurement was performed in reflection at a standoff distance of 1 m, and was acquired under normal atmospheric conditions, and data processing algorithms were again used to remove water vapor noise features. Both acquisition and data processing were performed in a time of 1/15 s. For comparison the calculated reflectance spectra of D-tartaric acid is shown as the dashed line in Fig. 8, as determined from transmission spectroscopy. Again we can see good agreement between calculation and experiment. Although the form of the reflection spectrum of D-tartaric acid is similar to that of RDX, the center frequency and magnitude is different, demonstrating that we can spectrally distinguish between explosives and other materials in reflection.

V. CONCLUSION

In this paper, we have discussed some of the important factors involved in addressing practical systems in the security industry, and have demonstrated a prototype terahertz standoff detection system. Using this apparatus we have verified spectroscopic detection of explosives at a standoff distance of 1 m, both real time, in reflection, under normal atmospheric conditions, and behind several layers of clothing. Although the present work has focussed on spectroscopy at a single pixel, the approach could be extended to produce spectroscopic images, by use of scanning or detector arrays. Other issues, such as localizing the returned pulses in time from a target at arbitrary distance, also need to be addressed and may lead to the use of alternative terahertz methods [18], [19].

It is envisaged that such systems will become more sophisticated and sensitive as the software and technology evolves and, indeed, this will be necessary before practical, deployable systems can be developed. However, indications are that such systems will represent a significant new capability for people screening. ■

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