Security applications of terahertz technology

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ABSTRACT

Recent events have accelerated the quest for ever more effective security screening to detect an increasing variety of threats. Many techniques employing different parts of the electromagnetic spectrum from radio up to X- and gamma-ray are in use. Terahertz radiation, which lies between microwave and infrared, is the last part to be exploited for want, until recently, of suitable sources and detectors. This paper describes practical techniques for Terahertz imaging and spectroscopy which are now being applied to a variety of applications. We describe a number of proof-of-principle experiments which show that Terahertz imaging has the ability to use very low levels of this non-ionising radiation to detect hidden objects in clothing and common packing materials and envelopes. Moreover, certain hidden substances such as plastic explosives and other chemical and biological agents may be detected from their characteristic Terahertz spectra. The results of these experiments, coupled with availability of practical Terahertz systems which operate outside the laboratory environment, demonstrate the potential for Terahertz technology in security screening and counter-terrorism.

Keywords: security screening, terahertz, applications, explosive detection, people screening, imaging, spectroscopy

1. INTRODUCTION

Events over the past decade have demonstrated the need for ever more effective security screening and contraband detection against an increasing number of threats and substances. The growth in terrorist groups and individuals prepared to take their own lives in prosecuting an attack has led to new requirements for 100% screening of personnel, checked and hand-carried baggage in aviation. We have also seen the use and threatened use of weapons of mass destruction in for example the Sarin attacks on the Tokyo underground and the postal Anthrax attacks in the US in the aftermath of September 11. These are new types of threat that drive new requirements for screening and detection. The purpose of this paper is to explore the important role which, we believe, imaging and spectroscopic detection using Terahertz light may play in this critical area of the fight against crime and terrorism.

1.1 Critical issues in security screening

A wide variety of techniques are available for security screening to detect the presence of a variety of threats, such as weapons or explosives, or illicit items, ranging from drugs to illegal immigrants. Current methods of bag screening in the US and elsewhere use X-ray inspection techniques with some use of further image analysis, manual search and trace detection equipment. Passenger screening relies heavily on archway and handheld metal detectors which are deployed throughout most airports. However, enhancements could be made in detecting:

- weapons containing a small amount of metal
- ceramic weapons
- explosive materials
- chemical and biological threats

Emerging technologies such as X-ray backscatter and millimetre wave could be used, but X-ray backscatter uses ionising radiation and both technologies are likely to provoke a debate on the privacy issue. In addition, neither technique is capable of carrying out a chemical/structural analysis of suspect objects in the image. Thus, X-ray and millimetre wave portals will prompt further searching whenever the image indicates a suspect item or area.

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False alarms can greatly increase the cost and reduce the throughput of screening systems. Throughput is crucial in high-volume situations such as major airports and systems are needed which have acceptably low false positive and false negative performance. A further factor in, throughput and transaction cost is the high dependence of current techniques on human operators. Any new technique which can move towards reliable, operator-free operation will be of major benefit.

New detection technologies can play an important role in addressing these issues. Whilst there will be stand-alone applications, new approaches will more frequently complement rather than replace established techniques. This will provide 'richer' data which can be fused to provide the basis of highly automated detection systems in multi-threat, multi-modal screening portals.

1.3 Terahertz light and its properties

Terahertz radiation represents perhaps the last unexplored frontier of the electromagnetic spectrum. The so-called "Terahertz gap", where up until recently bright sources of light and sensitive means of detection have not existed, covers the range from 0.1THz up to 130THz, between the microwave and the infra-red. Conventional microwave sources do not work fast enough to produce radiation efficiently above a few hundred Gigahertz, whereas laser diode sources have been limited by thermal effects to the infrared and visible. However, advances in ultra-fast pulsed laser technology have led to the generation and detection of broad bandwidth Terahertz light.

Terahertz light has some of the properties of radio waves and some of the properties of light. It is able to penetrate many non-conducting materials, but unlike X-rays it is a non-ionising radiation and can be used at very low powers. The short pulses produced by laser techniques also allow radar-like imaging in three dimensions, as well as the collection of spectroscopic information as in MRI or optical spectroscopy. This is important because many substances have characteristic intermolecular vibrations at Terahertz frequencies which can be used to characterise them as molecules, rather than the bond vibrations of individual components used in infra-red spectroscopy.

The four key properties of Terahertz imaging which make it a potentially powerful technique in security screening applications are:

- two dimensional imaging– materials reflect and absorb differently at Terahertz wavelengths from their optical and X-ray behaviour: clothing, paper and card are effectively transparent while plastic and ceramic objects easily visible in Terahertz imaging. Plastics and ceramic materials are hard to pick out in backscatter X-ray techniques as there is little contrast between the body and these materials.

- high resolution 3D imaging – the extremely short femtosecond pulses used in pulsed Terahertz techniques enable 3-D imaging, much like radar. For example, thin layers of powder and individual pages can be resolved inside an envelope.

- spectroscopy – this enables characteristic signatures of different chemicals to be detected – even when sealed inside a packet or concealed in clothing.

- safety – Terahertz radiation is non-ionising and can be used at very low power levels in the microwatt range due to the availability of high sensitivity coherent detection schemes[1].

These properties also lead to applications in other areas, for example in medical imaging where it can detect skin cancer[2], in pharmaceutical manufacturing for polymorph detection[3] and in a variety of industrial inspection applications.

2. TERAHERTZ PULSED IMAGING (TPI™)

We have developed a Terahertz spectral imaging technique, Te.rahertz Pulse Imaging (TPI™)[145], operating typically in the frequency range 0.1 THz to 10 THz corresponding to a wavelength range of 3 mm to 30 μm. This frequency range excites the vibrational modes of molecules, providing spectroscopic information as well as image contrast. Short pulses of Terahertz light are generated by illuminating a suitably engineered semiconductor crystal with a pulsed infra-red laser.

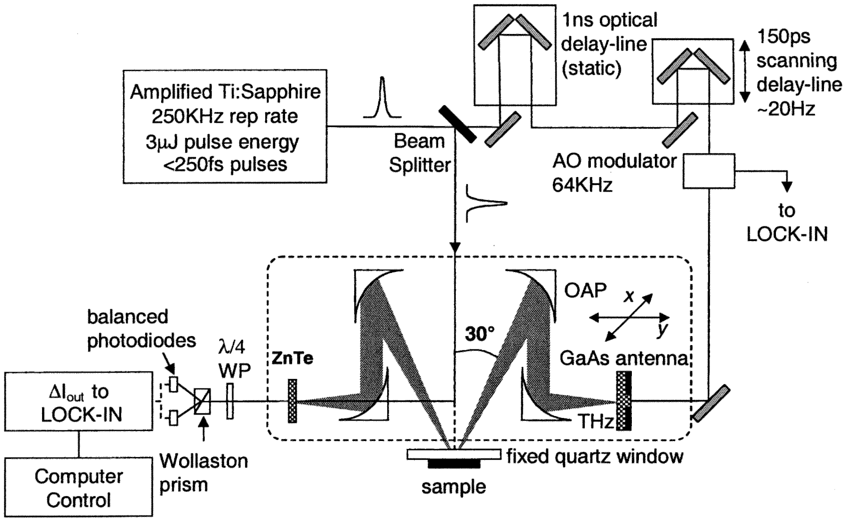

Figure 1. The components of the TPI system in reflection geometry shown in schematic form: the NIR beam path is shown as a solid black line, the terahertz path as a shaded grey line. Shaded boxes indicate mirrors. Abbreviations: OAP – off-axis parabolic mirrors, λ/4 WP – quarter wave plate. The static delay line ensures that the path lengths of the pump and probe beam are equal.

A TPI system using Terahertz reflection geometry and designed for imaging objects a few centimetres in size, is shown in the schematic of figure 1. Optical excitation is achieved by an amplified Ti:Sapphire laser, operating at a 250 kHz repetition rate, emitting 250 fs pulses centred at 800 nm wavelength. A 50:50 beam splitter separates the pulses into two beams, a pump beam used for generation and a probe beam for detection. Generation is by optical excitation of a biased GaAs wide aperture antenna[6,7], giving a bandwidth of 0.1 THz-2.7 THz (3 mm-110 μm) and an average power of over 1 mW[4]. The optical pulse energy delivered to the Terahertz source is typically 1 μJ to 2 μJ. The emitted Terahertz pulses are collimated by a series of off-axis parabolic mirrors and focused onto the image-plane of the system where samples can be placed. The reflected Terahertz pulses from the sample are then re-collimated using another series of off-axis parabolic mirrors and focused onto a ZnTe detector. The mirrors are raster-scanned in the *x-y* plane for imaging, collecting the complete Terahertz waveform at each pixel.

Detection is achieved by the linear electro-optic Pockel's effect[8] as indicated in figure 1. In the presence of Terahertz radiation birefringence is induced in the ZnTe crystal. This is monitored using the probe beam, which experiences a change in polarisation from circular to elliptical detected by the balanced photodiodes. In the presence of the Terahertz radiation a non-zero output current ΔI_{OUT} from the balanced photodiodes results. As the effect is linear and instantaneous the output current is directly proportional to the Terahertz electric field. To reduce noise the pump beam is chopped using an acousto-optic modulator, with lock-in detection of the output current ΔI_{OUT} from the photodiodes. A sinusoidal oscillating delay line scans through the entire Terahertz pulse at a frequency of 20 Hz, allowing both phase and amplitude information to be obtained. The delay position and lock-in output are then digitised and the datasets re-interpolated to obtain the Terahertz field as a function of delay position.

The spatial resolution is diffraction limited with an approximate pan-chromatic lateral resolution of 350 μm. The time resolution of approximately 0.5 ps corresponds to a depth resolution of 20-40 μm depending on the refractive index of the material.

A typical Terahertz waveform, prior to signal processing is plotted in figure 2a. The smaller oscillations after the main pulse are due to atmospheric water-vapour absorption and dispersion in the Terahertz beam path. A small reflection at 10 ps after the main pulse is due to back-reflections off the GaAs antenna substrate. The signal to noise ratio for a typical Terahertz waveform, with a metallic mirror in place of the quartz window is >6000:1 in a single 50 ms scan. The bandwidth envelope, obtained from a Fourier transform of the time-domain waveform is shown in figure 2b; the spectrum peaks at 300 GHz and extends to 3 THz.

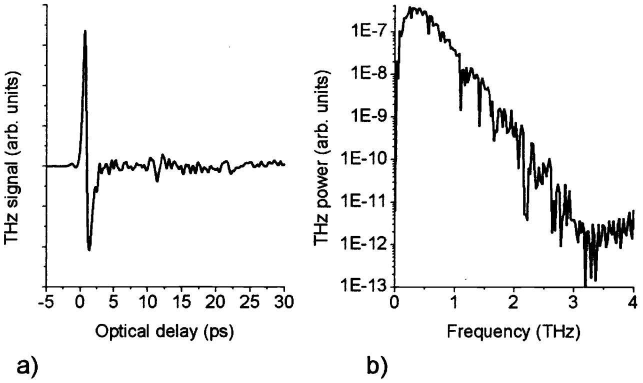

Figure 2. a) A typical Terahertz pulse waveform, prior to signal conditioning (raw), as measured in the imaging system using the step-scan delay. b) The corresponding Terahertz power spectrum. The fine structure in the spectrum is due to atmospheric water vapour absorption.

We have adapted this technique to operate in transmission.

Terahertz Pulsed Spectroscopy (TPS) can also be used to obtain the spectrum of an imaged object or of a material, yielding information on the chemical constituents or structural nature of the material. This is done simply by using Fourier transform of the Terahertz pulse in the time domain to produce a spectrum – see figure 2b. The bandwidth or range of frequencies covered by the Terahertz pulse can be adjusted and optimized depending on the type of ultra-fast pulsed laser employed and the semiconductors used in generating and detecting the radiation.

3. PROOF-OF-PRINCIPLE EXPERIMENTS FOR SECURITY SCREENING

We have carried out a number of proof-of-principle experiments to explore how Terahertz imaging may be used in security screening. Much of this work was carried out under a contract for the UK Government whose support is gratefully acknowledged.

3.1 Detecting objects hidden under clothing

The purpose of this experiment was to determine whether Terahertz imaging can be used to detect metallic and non-metallic objects hidden under clothing. To make the experiment more realistic and to make the test conditions more challenging, multiple layers of clothing were used. Test objects, approximately 1cm across were placed next to the subject's skin. These were covered with two layers of woollen sweater material and four layers of cotton shirt material. Images were taken in reflection using a TPI system similar to that described in section 2.

Figure 3 shows images of a metal scalpel blade, a square of alumina ceramic, a triangular sample of acrylic plastic and a square of SX2 plastic sheet explosive. The upper row of images shows the maximum amplitude of the reflected pulse whilst the lower row shows a depth profile or 'b-scan' through the centre of the image.

In each case, the object can clearly be detected beneath the several layers of clothing. Note that the test objects give rise to stronger reflections clothing which aids their identification

Experiments were also carried out on a variety of natural and synthetic clothing materials. All of them were found to be practically transparent at Terahertz frequencies.

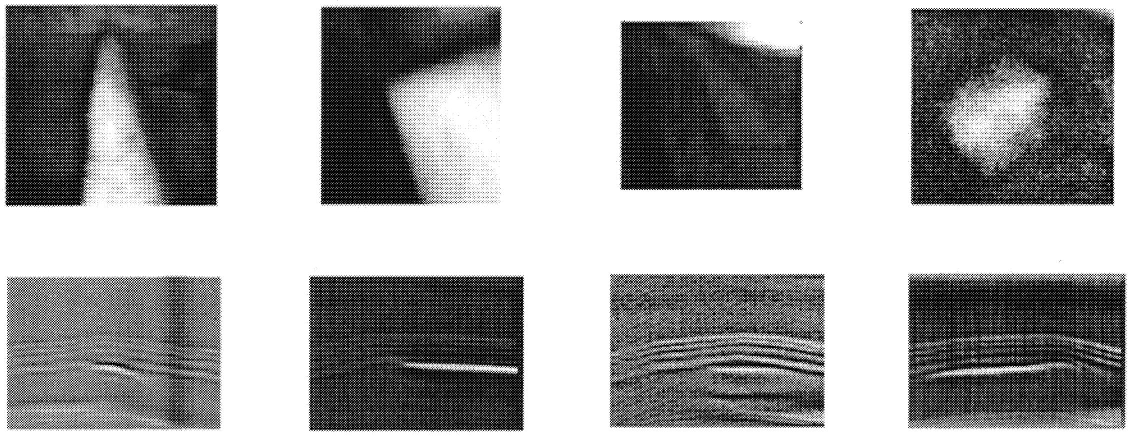

Figure 3. Terahertz images of objects hidden against skin, beneath two layers of woollen sweater material and four layers of cotton shirt material. From left to right: a) metal scalpel blade; b) alumina ceramic; c) acrylic plastic; and, d) SX2 sheet explosive. The top row of images shows the maximum reflected amplitude, the bottom row shows a depth profile through the center of each image like an ultrasound 'b-scan'. In each case the hidden object can be clearly detected.

3.2 3-D imaging of microprocessor chip

In this example, a 486 computer processor chip was imaged using the TPI scanner. The reflected pulse at each point contains time-encoded depth information, so that a single raster scan enables the object to be imaged in three dimensions. Since the ceramic packaging of the integrated circuit is substantially transparent at Terahertz frequencies, the internal connections and the silicon die itself can be seen.

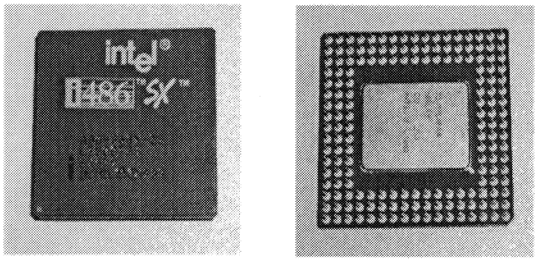

Figure 4. Optical images of 486 chip

Figure 4 shows optical photographs of the top and bottom of the chip. Figure 5 shows the top surface and two slices at depths of approximately 1mm and 2mm through the chip. The images are actually a composite of a mosaic of nine separate images due to the small imaging area of the instrument used in the experiments.

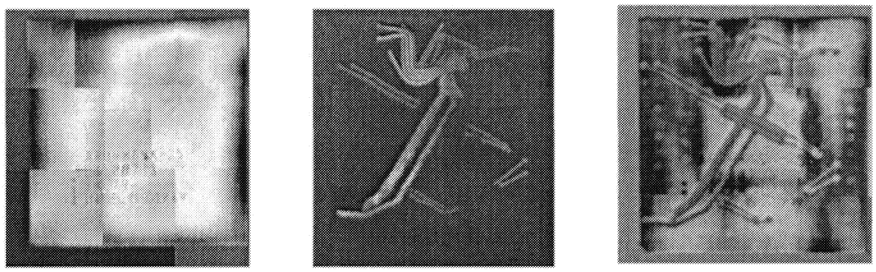

Figure 5. Terahertz images of top surface and two slices through 486 chip

The labelling on the top surface of the chip can be seen and the writing resolved. In the internal images, interconnects, the pins at the bottom of the package and the silicon die itself can be clearly seen, showing that the images are diffraction limited with a resolution of approximately 300μm.

3.3 Reading inside a letter

In this experiment we placed three sheets of common 80g paper with writing in ballpoint pen and laser printed characters in a regular white paper envelope. This was imaged in the TPI scanner. Figure 6 shows the pulse reflection at a single point. The envelope and individual pages can be resolved clearly. Figure 7a show the images of each separate sheet within the envelope and the characters written on them can also be resolved. Note that the ballpoint pen gives better contrast than the printed characters due to the differences in the ink.

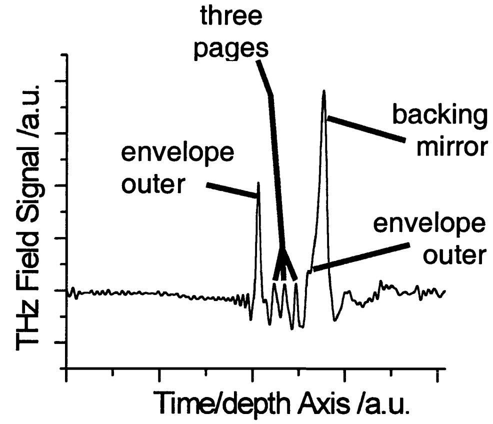

Figure 6. Single Terahertz pulse showing reflections from the individual pages inside an envelope.

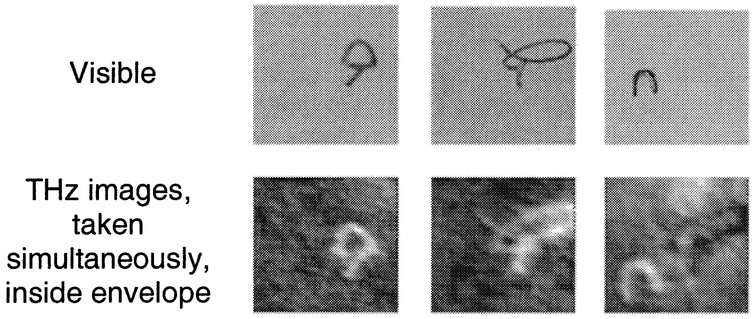

Figure 7a. Terahertz images of individual pages inside an envelope with written text.

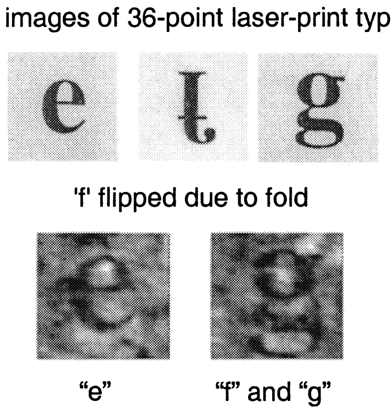

Figure 7b. Terahertz images of individual pages inside an envelope with laser-printed text.

3.4 Explosives detection

To investigate the ability of Terahertz spectroscopy to detect explosives, we measured the absorption spectrum of several explosives samples in the frequency range 0.3 –3 THz. Figure 8 shows the spectra of the raw explosives trinitrotoluene (TNT), tetranitro-tetracyclooctane (HMX), pentaerythritol tetranitrate (PETN) and trinitrotriazcyclohexane (RDX) together with the spectra of the compound explosives PE4 and Semtex H. PE4 consists of RDX mixed with a plasticiser. Semtex H is a mixture of RDX, PETN and plasticiser.

All the raw explosives have distinctive spectra with several peaks in the measurement range whilst the compound explosives have peaks corresponding to the sum of their constituents. We have measured the spectra of a range of other materials and found that many have distinctive spectra, often with sharp features which aid identification. Plastics, paper, cloth and similar packaging and clothing materials have smooth, featureless spectra. We therefore believe that there are good prospects for using Terahertz to develop practical systems for detecting hidden explosives.

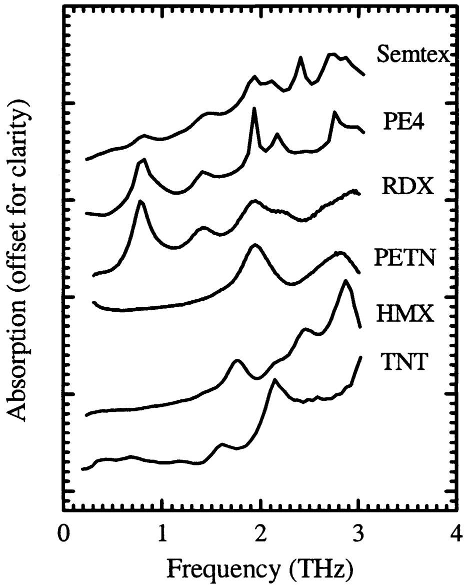

Figure 8. Terahertz transmission spectra of the raw explosive materials TNT, HMX, PETN and RDX together with the spectra of the compound explosives PE4 and Semtex H.

3.5 Chemical and biological substances

As an indication of the ability of the technique to identify and detect the difference between different powdered substances, figure 9 shows three more spectra, this time of powdered glucose, flour and glutamic acid – one of the amino acids a basic building block of proteins in living matter. Again, very distinct differences in absorption and spectral lines are visible.

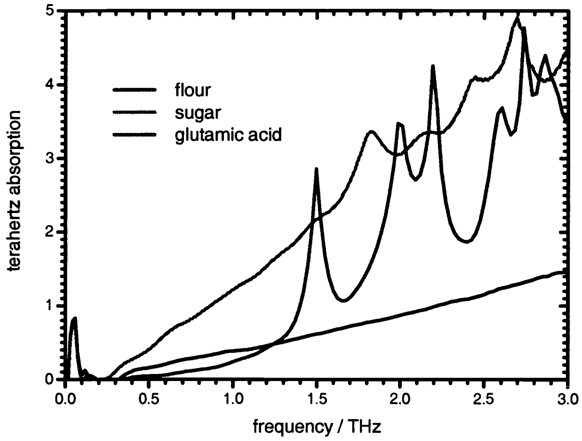

Figure 9. Three Terahertz spectra showing glutamic acid, a basic building block of proteins in living matter, compared with two other common powdered substances.

4. ENGINEERING DEVELOPMENT

Although these proof of principle experiments carried out in the laboratory are promising, the technique will only be useful if it can be engineered to the point where systems can readily be deployed and maintained under operational conditions in the field.

Figure 10 shows a portable Terahertz imaging system working as a flat-bed scanner developed from the system described in section 2. Key features include:

- 1m x 0.5m footprint for portability
- Sub-assembled pre-aligned source and detector modules to remove the need for complex 'optical bench' alignment and for maintainability in the field
- Self aligning optics through active mirror technology to avoid need for frequent re-alignment and calibration
- Stand-alone system with integral PC control

In an alternative configuration, the scanned aperture is part of a remote head attached to an articulated arm This demonstrates how the system can be reconfigured to support different scanning geometries.

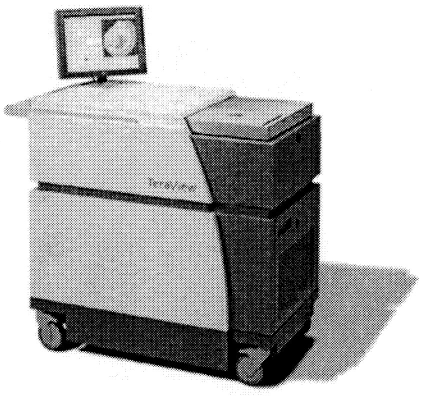

Figure 10. The TeraView TPI Scan Engine

Although initially developed for medical imaging rather than security screening applications, these systems demonstrate that the technology can be deployed in practical systems.

5. CONCLUSIONS

Based on these and other experiments and our success in engineering the system into a robust and rugged form, Terahertz technology will find applications in a number of areas security screening including people screening for non-metallic as well as metallic weapons, explosive detection and postal screening. The non-ionising nature of the radiation and low powers which are necessary make it an attractive technique for people-screening. We believe that although further development is certainly required, Terahertz imaging and spectroscopy, used alone or in combination with other modalities, will become a valuable tool in the detection of hidden weapons, explosives and other threats.

ACKNOWLEDGEMENTS

Parts of this work were carried out under contract for the UK Government whose support is gratefully acknowledged.

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