Military Applications of Terahertz Imaging

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Abstract

Recent advances in electronic and electro-optical terahertz sources, and improvements in receiver and system technology, have stimulated interest in imaging applications in the medical, security and non-destructive testing fields. The ability of broadband or frequency-agile terahertz radar to form high resolution 3D images, and to extract detailed information on target composition from spectral data, suggests military applications to target discrimination on the battlefield, in the air and in space. This paper briefly reviews the wide range of sources and detectors currently being developed for these frequencies, and the projected performance of imaging systems for concealed target detection, air and space communication, security imaging, and detection and tracking of war gases and bio-agents.

Introduction

The term terahertz usually refers to the range between millimetre waves up to ~300GHz, and IR frequencies >10THz (30µm). Until recently there were few devices able to generate significant power in this range, so the term “Terahertz Gap” has been coined to refer to this largely unused portion of the spectrum [1,2]. This is now changing due to the extended performance of mm-wave devices, and through improvements in laser and non-linear optics techniques extending the IR spectrum to lower frequencies. Several widely differing technologies are now able to generate power at the µW or mW level over most of this spectrum, and consequently many applications to medicine, materials research, non-destructive testing, security and military uses are being actively researched [3].

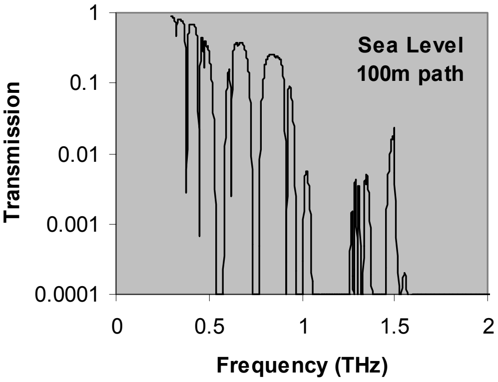

Figure 1: Terahertz transmission over 100m path at sea level (US Standard Atmosphere)

Military uses of terahertz waves are constrained not only by the limited performance of sources and detectors but by strong water vapour absorption in the atmosphere which prevents long range operation at sea level. Figure 1 shows the absorption of a standard atmosphere over a 100m path at sea level [4]. There are several substantial windows below 1THz and above 10THz but the range in between is largely opaque.

Water vapour concentration rapidly decreases with altitude, so aircraft flying at 20,000ft and above can communicate over many kilometres in selected frequency ranges, and transmission from high-flying aircraft into space is possible, either for communication or for long range sensing of space objects.

Interest in military applications has arisen partly from the high-resolution imaging capabilities of terahertz radar and passive imaging, where the lower angular divergence and higher range precision gives greater 3D image resolution than millimetre waves. Perhaps the greatest potential for new applications lies in the strong spectral dependence of the interaction with materials, where resonant absorption by the molecular structure of targets provides information on their composition, and hence the target identity, not readily available by other remote sensing methods.

Transform-limited pulses with terahertz bandwidth have durations <1ps, and corresponding pulse lengths of <0.3mm, so terahertz radar is capable of probing the detailed structure of multi-component targets on a sub-millimetre scale while being able to distinguish between materials in terms of the spectral dependence of dielectric constant or absorption. Weapons or personnel can be detected through camouflage or thin foliage, and targets can be discriminated from background on the basis of spectral response.

THz techniques have similar advantages for security imaging where weapons and explosive packages concealed beneath clothing can be imaged with high spatial resolution and spectral detail, but without the intrusive equipment needed by traditional methods such as x-rays. There is also scope for the detection, identification and tracking of chemical and biological weapons in the atmosphere [5]. Unique THz chemical signatures of war gases due to rotational spectral lines, and phonon excitations of biological warfare agents can be detected in the low-THz range by high-resolution spectroscopy [6].

Sources and Detectors

Most recent work on THz characterisation of materials has used sources based on ultra-fast lasers [7]. Mode-locked, wide-bandwidth lasers such as Ti-sapphire generate sup-ps pulses with energies from microjoules to milljoules. When these strike an ultra-fast photoconductor, large pulses of extremely fast-rising current are produced which contain a broad terahertz spectrum.

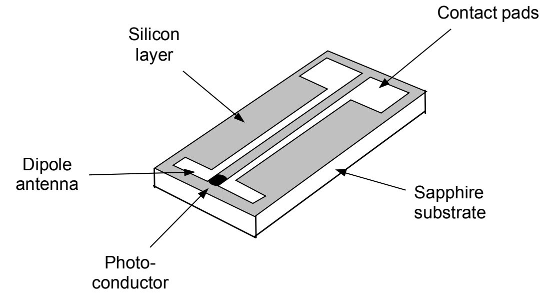

Figure 2: Photoconductively switched THz emitter [7]

Coupling the photoconductor to a half-wave antenna, as shown in figure 2, generates a pulse of THz radiation which can be focused into a narrow beam and projected onto a target by a parabolic mirror. Typically the spectrum contains components from 0.1 to at least 2THz as shown in figure 3.

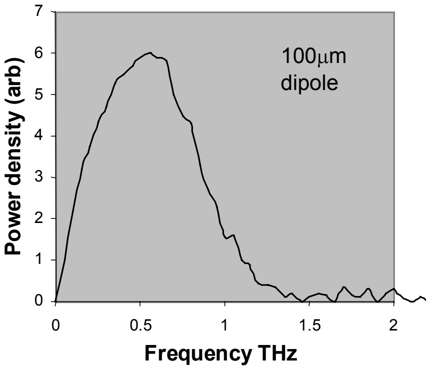

Figure 3: Typical terahertz spectrum of photo-conductive dipole emitter

Optically switched photoconductors can also be used as broadband coherent receivers, by using delayed pulses from the laser to switch the photoconductor at the time when the return pulse arrives at the receiver. This enables the pulse electric field to be measured as a function of the delay time [8], so the time profile gives the range to reflective interfaces within the target. Its fourier transform gives the spectral dependence of the dielectric constant of its material profile.

The mean power emitted by small dipoles (nW) is too small to get detectable signals from targets at a range of more than a few metres, but large area planar photoconductive emitters have produced pulse energies of ~1μJ which are capable of much greater range [9]. Receivers based on a delayed reference pulse require a mechanically adjustable delay, so real-time imaging requires a means for fast mechanical scanning. The use of arrays of photoconductive or electro-optic receivers to improve the image acquisition time has been proposed [10]. Return pulse profiles yield a 3D image and spectral data, although generating both in real time is very computationally demanding.

Comparatively simple radar methods can be used to generate 2D spatial and spectral images. This is more easily achieved with narrow-band sources, tuneable over a range of frequencies, either scanned across the target, or illuminating it continuously in conjunction with an array of separate receivers. Low-noise detection is achievable with heterodyne receivers driven by tuneable terahertz local oscillators.

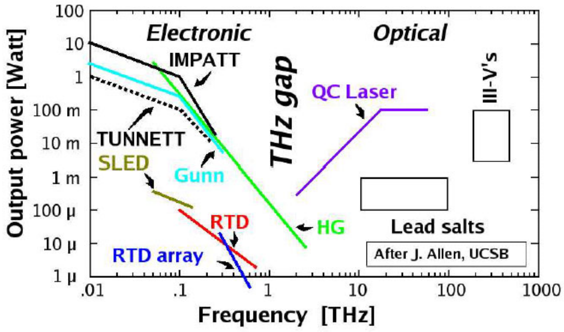

Figure 4: Overview of power generating capabilities of semiconductor devices in the frequency range 0.01-1000THz

Both optical and electronic devices are currently being developed to cover the 0.3-1.5THz atmospheric windows. A performance summary of electronic and laser devices developed to date is shown in figure 4 [11]. The most promising technologies are: multiplied semiconductor millimetre-wave devices, quantum cascade lasers, optical mixers, and parametric oscillators. Much more powerful sources using relativistic electron beams have been demonstrated, such as the free-electron laser [12] and the gyrotron [13], but they need high-energy electron beams and high-field magnets which are currently too bulky for use in mobile equipment. However interesting ideas have been proposed for using harmonic devices to reduce their size and power requirements [14], so powerful sources compact enough for aircraft-mounting may eventually become a reality.

Electronic Sources

Generation of substantial amounts of output power directly with semiconductor devices is difficult in the range from 0.3-3.0THz. Consequently the most common approach is based on frequency multipliers with GaAs Schottky-barrier varactor or heterojunction-barrier varactor (HBV) diodes driven by RF sources at frequencies around 60-100GHz [15,16]. Conventional whisker contacts are still prevalent, but are being rapidly replaced by more rugged technologies, for example Schottky diodes in GaAs frameless membrane monolithic circuits [15,17]. Highest powers have been obtained with multiplier chains using diode arrays in the early stages, and millimetre-wave integrated circuits (MMICs) as drivers [15,17-19]. Up to the present time 12mW has been obtained at 400GHz and 2mW at 800GHz, where both the MMIC and the multipliers were cooled to 80-120K. Triplers with low output power have been reported up to 2.7THz [15].

The highest operating frequency of a fundamental solid-state source (712GHz) has been achieved by InAs/AlSb resonant tunnelling diodes (RTDs) [20], but these currently give only microwatt output power. Fundamental devices with some of the highest powers, lowest noise and greatest development potential are being currently investigated at the University of Leeds [21]. World record figures of over 3.5mW at 300GHz and over 1mW at 325GHz have been obtained from low-noise InP Gunn devices [31].

Electronic Receivers

The most sensitive room temperature receivers are based on heterodyne mixers using GaAs Schottky barrier diodes which operate up to 2.5THz [15]. At least 0.5mW of local oscillator power is needed to achieve low noise performance, and 3-5mW is needed for a balanced receiver to cancel local oscillator noise [15]. This is a demanding requirement either for fundamental or harmonic semiconductor sources.

Greater sensitivities are achievable with low-temperature devices such as the superconductor–insulator-superconductor (SIS) tunnel junction mixer, that can approach quantum-limited performance with very low LO power (μW), can operate up to 1.2THz, and provide GHz bandwidth [15]. High sensitivities are also achievable with hot electron bolometers (HEBs) using extremely small niobium microbridges operating close to the transition temperature [15,22]. Bandwidths of 5GHz have been reported, and the sensitivity is only a few time higher than the quantum limit for niobium devices at 9.3K. Superconducting receivers require multi-stage Stirling-cycle coolers. These can be quite compact and coolers for HEB mixer receivers have been proposed for unattended operation in spacecraft [23].

Optical Sources

Quantum Cascade Lasers

The QCL is a semiconductor laser based on intersubband transitions in quantum wells. The wavelength is not controlled by the material bandgap but by the layer thickness, so operation over a wide range of frequencies, including terahertz is possible. In the middle-IR, 100mW CW output power is produced at room temperature, but cooling is required for operation at terahertz frequencies. The lowest frequency produced so far is 2.8THz, with a pulsed power of 2mW at a temperature of 7K [24]. The maximum operating temperature was 65K. Higher operating temperatures are theoretically possible, and it has been shown that the limiting temperature for operation at 2THz is approximately 95K [21]. Modified semiconductor and lower-loss waveguide structures are being developed to reduce frequencies to the 1-2THz range, and to raise the output power and operating temperature. The narrow linewidth and low noise of QCLs would make them ideal for receiver local oscillators if the frequency can be reduced to the low-THz range of most interest.

Optical Mixing and Parametric Oscillators

Non-linear optical techniques can generate terahertz frequencies tuneable over a wide range. Driving a non-linear crystal from a high-power near-IR laser converts the IR laser output to longer wavelengths [25]. The device can either be used as a mixer to generate a terahertz difference frequency from two laser beams closely spaced in frequency, or as a parametric generator to produce frequencies tuneable over a wide range. Frequency mixing, for example using a two-frequency laser to produce a terahertz difference frequency on a fast photoconductor, has a very low conversion efficiency, so power levels are generally too low for military imaging.

Higher efficiencies are achievable by using high-power pulsed lasers to drive parametric interactions in non-linear crystals. Parametric oscillators use materials such as lithium niobate which transmits at the near-IR pump wavelength and at terahertz frequencies.

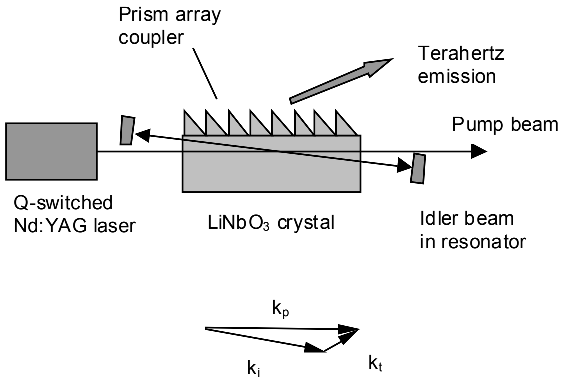

Figure 5: Terahertz optical parametric oscillator with prism array coupler.

Pulses from a powerful pump laser, usually the 1.06μm output of Nd:YAG, are passed through the crystal with a beam intensity sufficient to create significant non-linear frequency conversion. The combination of birefringence and wavelength dispersion creates two other wavelengths, known as the idler and the signal, whose wave vectors are phase-matched as shown in figure 5. By adjusting the crystal angle relative to the pump beam, the frequency of the phase-matched signal wave can be varied over a wide range. The conversion efficiency can be enhanced by resonating the pump and idler waves, but the ultimate efficiency is limited by the Manly-Rowe relations to the ratio of pump to terahertz wavelengths. At 1THz this is about 0.003, so millijoule pump pulses are needed to generate microjoule output pulses. A study of future projections of THz OPO performance by two of the authors [25] has estimated the performance figures shown in Table 1, firstly for a low PRF appropriate for THz radar, and secondly for a 5kHz PRF appropriate for a scanned 2D imaging system.

Table 1: Best-to-Date TNR, Future OPO Prospects

Parameter	**Best-to-date**	**High energy Low PRF**	**Low energy High PRF**
Pump energy per pulse (10ns)	45mJ	45mJ	1mJ
Average pump power	0.45W (10Hz)	0.45W (10Hz)	5W (5kHz)
Single-device tuning range	0.6-2.8THz	0.6-2.8THz	0.6-2.8THz
Max. energy per pulse	1.3nJ	20μJ	0.5μJ
Peak power in 10ns pulse	0.2W	3kW	50W
Average power	13nW (10pps)	0.2mW (10pps)	2.5mW (5000pps)
Linewidth	0.1GHz	0.1GHz	0.1GHz
Beam diverg. /diffrac. limit	1.3	1.3	1.3
Efficiency	4×10^{-6}%	5×10^{-2}%	5×10^{-2}%
Op. conditions	Ambient	Ambient	Ambient

Applications

Imaging Systems for Target Discrimination

A radar system for imaging and target discrimination on the basis of spectral response could consist of a tuneable pulsed OPO, reflective optics for collimating the transmitted and received beams, and a heterodyne receiver using a Schottky diode mixer with a multiplied mm-wave source as local oscillator. Atmospheric transmission is limited to selected wavebands (fig 1), but tuning over several bands should provide sufficient information to characterise target materials.

Approximate figures for achievable range on a single-pulse basis against a solid target at sea level are shown in Table 2. On this basis the OPO is likely to be able to produce either 20μJ per pulse in a low-PRF mode, or 0.5μJ per pulse in a 5000pps scanned imaging mode. A receiver noise temperature of 9000K has been assumed, comparable with systems developed for space use in this frequency range [15], and 10dB overall loss has been assumed to cover antenna coupling and heterodyne mixing efficiencies. Assuming a randomly diffusing target with 10% scattering efficiency, and an antenna aperture of 200mm, appropriate to a portable system, the maximum range for single pulse detection [26] based on a 15dB carrier-to-noise ratio are shown in Table 2.

Table 2: Horizontal-path single-pulse range achievable in a Standard Atmosphere at sea level

Frequency (THz)	Maximum range (m)	
	Energy = 20μJ	Energy = 0.5μJ
0.34	1600	900
0.41	1000	600
0.66	650	450
0.83	340	230

A range of 1km is achievable at sea level in a standard atmosphere, although this will vary greatly with local atmospheric temperature and humidity. This could be sufficient for concealed target recognition roles based on shape and spectral response.

Much greater range is achievable in air-to-air communication or sensing roles at high altitude. For a horizontal path at 20,000ft the achievable range by scattering from a passive target increases to ~10km for a 20μJ pulse and similar optics. At 30,000ft and above, the atmosphere is essentially unattenuating over wide frequency ranges, so air-to-air and air-to-space communication is possible at very long range with these pulse energies.

Response of Target Materials

Metals are fully attenuating and highly reflective at THz frequencies but common polymers such as polyethylene and polyester have low attenuation.

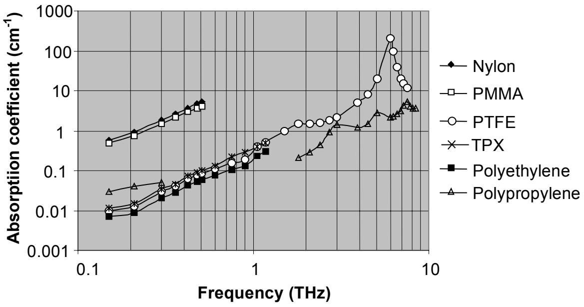

Figure 6: THz absorption of polymers

At frequencies below 1THz, absorption coefficients are much less than 1cm^{-1} for polyethylene and polystyrene [27] as shown in Fig. 6, and in the region of 1-10cm^{-1} for clothing materials such as nylon. Clothing and thin camouflage materials are therefore likely to be highly transmitting in this range.

Armoured vehicles and aircraft are frequently fitted with antireflection materials to reduce their microwave and IR crossections. Microwave AR materials contain absorbing matrices embedded in plastics to give high absorption at the operating frequency, but are likely to have comparatively low THz absorption. One of the authors [28] has performed measurements on a range of such materials, and has investigated the possibility of using the THz beam to view the internal structure for manufacturing process control.

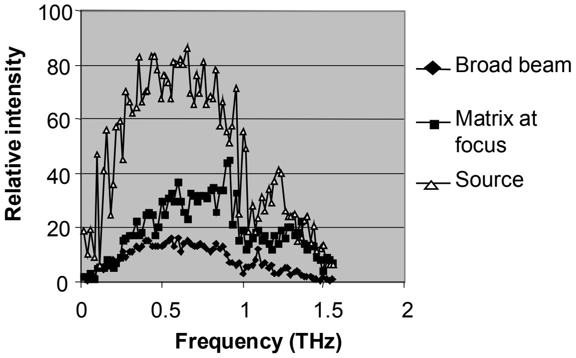

Figure 7: THz transmission through X-band AR material containing embedded dipoles.

Using a fast-pulse measurement system similar to that described in section 2, the results shown in figure 7 were obtained for a thin plastic sheet containing embedded dipoles. For a focused beam, the transmission in between dipoles was 20-30% up to the maximum available frequency of about 1.5THz, but the loss was greater when the dipoles were illuminated by a broad beam, indicating significant scattering. The technique can therefore be used to indicate the position and perhaps orientation of embedded dipoles. AR absorbing materials generally are likely to have significant transmission over at least part of the THz range, giving reflections from the target structure underneath.

War gas and bio-agent sensing

Complex organic molecules such as war gases have a rotational absorption spectrum at THz frequencies. High resolution spectroscopy can identify gases at the parts per billion level in the laboratory where individual lines are resolved at low pressure. At atmospheric pressure individual lines overlap due to pressure broadening, but the overall spectrum envelope can still be used to characterise individual gases. The spectra of the war gases Sarin and Soman at atmospheric pressure is shown in figure 8 [29].

Much of the prominent spectral detail is located in the 0.25-0.3THz range where long transmission paths can be obtained in the atmosphere at sea level. Pulsed, narrow-band tuneable sources with sufficient energy could therefore be used as an atmospheric probe for war gases, to plot their spatial extent and movement. Substantial pulse energy would be needed to obtain sufficient signal directly from backscatter using atmospheric aerosols, but RPVs with retroreflectors could be deployed to enhance the signal from relatively weak sources.

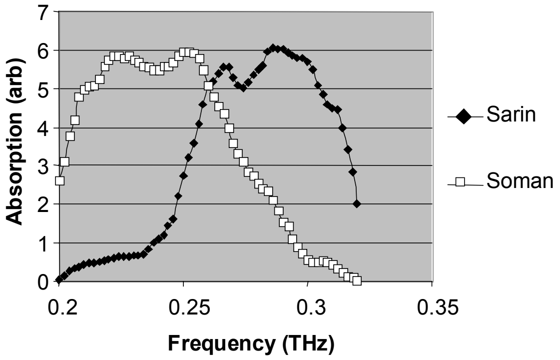

Figure 8: Absorption spectra of the war gases Sarin and Soman at atmospheric pressure [5,29]

Biological-warfare agents such as anthrax have characteristic phonon resonances in the THz range which could be used in a similar manner to identify them and plot their dispersion in the atmosphere. Spectral absorption measurements done on similar bacterial spores coated on glass slide show a complex group of phonon resonances associated with the bacillus structure as shown in figure 9 [6,30]. In contrast to molecular spectra of war gases, bacterial spectra are related to internal structure, so are unlikely to be influenced by ambient conditions. If sufficient THz power is available, backscatter from bio-agents could provide a convenient means for plotting wind-driven movements at sufficient range to enable personnel to get out of the path, or put on protective clothing.

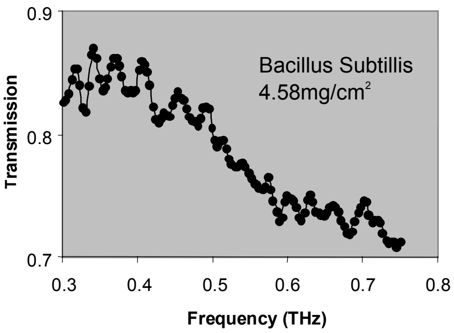

Figure 9: Resonance absorption spectra of Bacillus Subtillis spores coated on a glass slide. [6,30]

Conclusions

Imaging by terahertz radiation has the advantage of high spatial resolution in 3-dimensions, although the maximum range is limited at ground level by atmospheric absorption. At frequencies of 1THz or less it has the ability to penetrate clothing and camouflage materials to detect hidden weapons or personnel, so has applications to security imaging as well as short-range battlefield uses. A major feature is its ability to detect chemical structure from detailed absorption data that gives terahertz techniques a unique ability to discriminate between targets on the basis of composition, and to provide remote sensing of war gases and biological warfare agents. Provided that the many source technologies currently being developed can provide sufficient power, long-range air and space sensing capabilities superior to other EMRS techniques could emerge.

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