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# Analysis of system trade-offs for terahertz imaging

S. Mickan[a,*], D. Abbott[a], J. Munch[b], X.-C. Zhang[c], T. van Doorn[d]

[a]*Centre for Biomedical Engineering, The University of Adelaide, Adelaide 5005, Australia*
[b]*Department of Physics, The University of Adelaide, Adelaide 5005, Australia*
[c]*Department of Physics, Rensselaer Polytechnic Institute, Troy, NY 12180, USA*
[d]*Department of Medical Physics, Cancer Centre, Royal Adelaide Hospital, Adelaide 5000, Australia*

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## Abstract

In this paper we analyse the trade-offs for a terahertz imaging system and discuss implementation of a terahertz micro antenna array for imaging. We also describe applications of terahertz imaging and improvements in the signal processing. © 2000 Elsevier Science Ltd. All rights reserved.

*Keywords*: Terahertz; T-ray imaging; Optoelectronics; Wavelets

## 1. Introduction

The rapidly developing field of terahertz (or T-ray) imaging promises to provide a non-invasive method of identifying the composition of various objects. Biomedical diagnostics, semiconductor device diagnostics, trace gas analysis, moisture analysis for agriculture, quality control of packaged goods, inspection of artwork, inter-satellite communications and tissue burn reflectometry are among a growing number of potential terahertz applications [1–4]. To realise this potential, further development of terahertz systems is needed.

In our set-up, picosecond pulses of terahertz radiation are produced via *optical rectification*, using a GaAs crystal. A coherent detection method is used, whereby both amplitude and phase of the terahertz beam are measured, providing an exact terahertz signature of the material under observation [1]. Current terahertz systems remain too slow for many real-time applications and the need for high speed image processing is evident [5–7]. We discuss enhanced processing based on wavelet transforms, which are computationally inexpensive for pulsed waveforms [8].

## 2. Properties of far infrared radiation

As shown in Fig. 1, terahertz radiation lies on the boundary of electronics (millimetre waves) and photonics (the infrared). The terahertz spectrum encompasses the wavelengths running from 3 mm to 15 μm [9], which overlaps with the far infrared (20 mm to 50 μm [10]). The terahertz frequency band has remained less utilised and developed than the adjacent fields of the mid-infrared or millimetre waves. The rarity of terahertz radiation technologies can be largely explained by the lack of good radiative sources and recent research has been driven by the development of new terahertz sources. One of the limits of terahertz in imaging is the resolution, which is 0.3 mm for a frequency of 1 THz. This can be improved by operating at higher frequencies or by working in the optical near field [11].

Terahertz radiation interacts strongly with polar molecules, a prime example being water. Water molecules absorb terahertz waves, on the one hand limiting penetration of the radiation in moist substances, and on the other hand making it readily detectable even in very low concentrations. It can be used for detecting low concentrations of polar gases, conceivably for pollution control. However, terahertz radiation will penetrate non-polar substances such as fats, cardboard, cloth and plastic with little attenuation.

Molecules have dense and distinctive absorption spectra in the far infrared, which leads to an interest in terahertz spectroscopy [12–16]. Recent terahertz spectroscopy has made use of terahertz pulse emitters. The broad Fourier spectrum in a pulsed waveform enables many spectral lines to be discerned simultaneously. In principle, it is possible to calculate the absorption and refractive index spectra of a transmitted or reflected pulse and thus determine the

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[*] Corresponding author. Tel.: + 61-8-8303-5277; fax: + 61-8-8303-4360.

*E-mail address:* spmickan@eleceng.adelaide.edu.au (S. Mickan).

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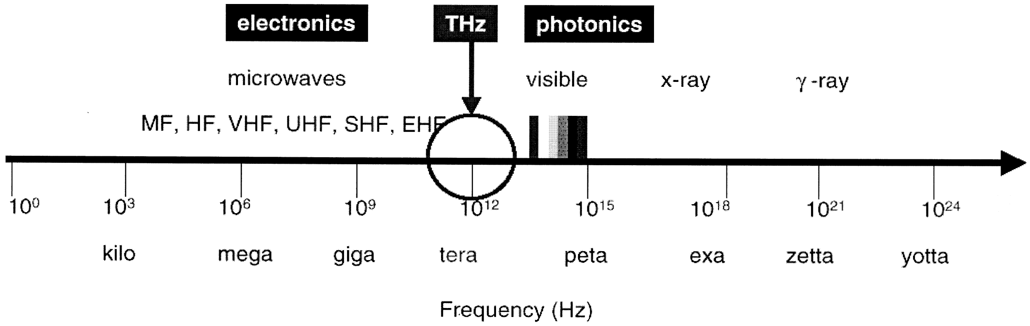

Fig. 1. Terahertz lies between gigahertz radio frequencies and mid-infrared light on the electromagnetic spectrum.

molecules that are present in the terahertz beam path. In practice, the attenuation is often too severe for a signal to be transmitted, meaning only thin samples or surface molecules can be analysed. To understand the current limitations of terahertz radiation, it is necessary to consider the detectors and emitters that are available.

## 3. Terahertz emitters and detectors

The following section describes methods used to generate terahertz radiation, including lasers, non-linear optics and electronics. These produce radiation of different wavelength ranges, either pulsed or continuous wave (cw), with varying degrees of success.

### 3.1. Photonic sources

The first difficulty in creating a terahertz source is finding a suitable radiative transition, because rotational and vibrational energy levels of large molecules are difficult to use in a laser [17]. Terahertz lasers have been built with a p-Germanium oscillator, but these are unsatisfactory since they offer no cw operation and operate only at 2 K [18]. Current research focuses on photomixing [19,20] and on

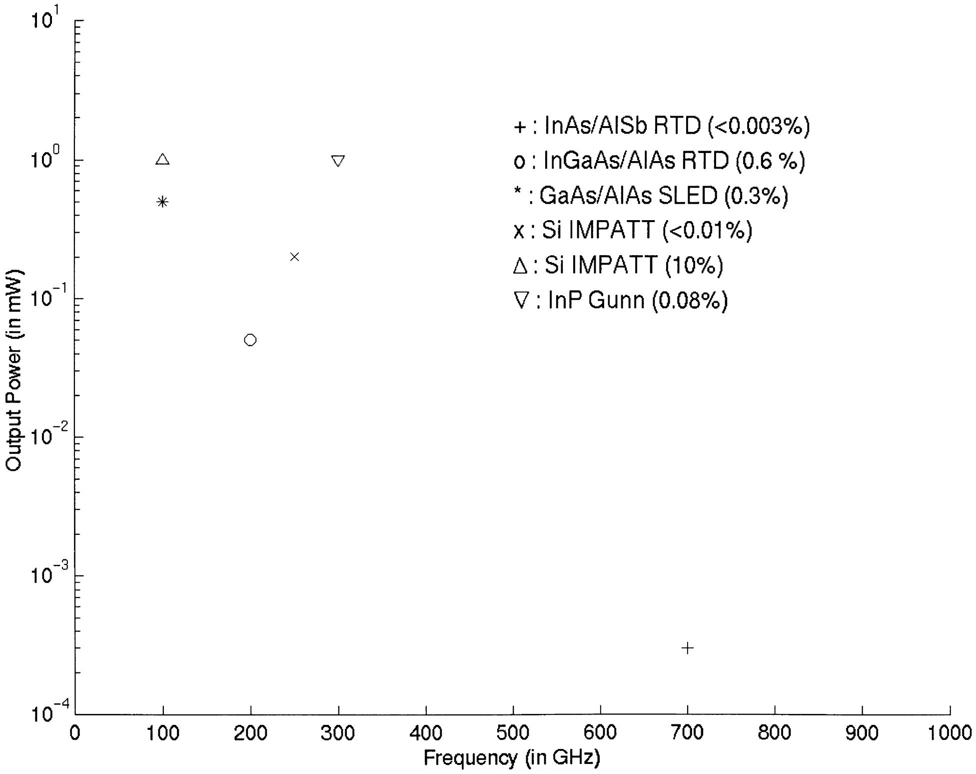

Fig. 2. State-of-the-art results for electronic sources of terahertz [29]. This plot shows that even the best electronic devices are limited to sub-terahertz frequencies and low powers. The devices include resonant-tunnelling diodes (RTDs), a superlattice electronic device (SLED), impact avalanche transit-time (IMPATT) diodes and a frequency doubling Gunn diode. The efficiency of each device is shown in brackets.

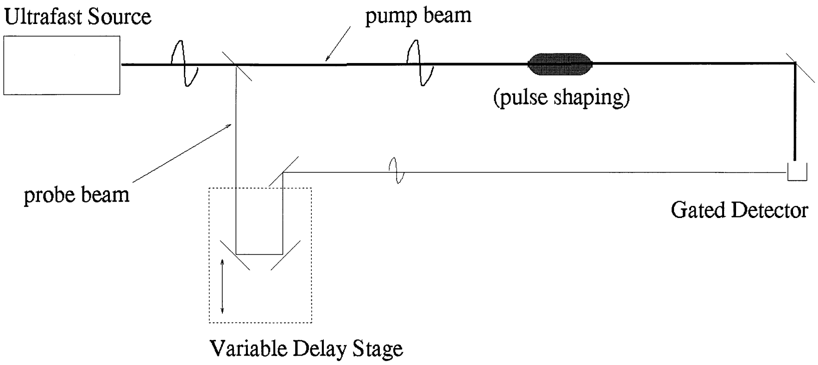

Fig. 3. Pump-probe detection: Gated detection with an ultrafast laser pulse.

transitions in semiconductor materials, using quantum wells [21–25], quantum dots [26], superlattices [27] and unipolar lasers [28]. Lastly, the free-electron laser (FEL) is capable of emitting in the far infrared, but current requirements for terahertz do not justify the complexity and expense of a FEL except for experimental use.

### 3.2. Electronics sources

The frequency of electronic sources has increased steadily for many years, from MHz to the GHz regime. Current research centres on applications of electronic local oscillators for terahertz radio astronomy, remote sensing, atmospheric imaging and ultra broadband intersatellite communication [29]. However, state-of-the art ultrafast electronic sources remain limited to frequencies in the hundreds of gigahertz and sub-milliwatt powers. For imaging purposes, this would severely limit both resolution and penetration depth. Fig. 2 shows the output power and operating frequency characteristics of the most promising high-speed electronic devices. Although these devices are suited to low power continuous-wave operation, other technologies are required for high speed, room-temperature imaging and spectroscopic applications.

### 3.3. Detection

Detecting terahertz signals is difficult because blackbody radiation at room temperatures is strong at terahertz frequencies. This can be overcome by using a helium-cooled bolometer, which is desensitised to ambient temperature and registers only the heating effect of the terahertz radiation. The bolometer is an incoherent detector, registering only incident amplitude. Using a *pump–probe* configuration, on the other hand, allows for a far greater sensitivity and full coherent signal acquisition [30]. The pump–probe technique is used in pulsed terahertz systems, which include those based on *photoconductive antennae*, *optical rectification* emitters and electro-optic detectors. These techniques are described below. The pump–probe set-up shown in Fig. 3 demonstrates how two ultrafast pulses can be delayed relative to each other in time. The gated detector operates only when illuminated by the probe pulse. The time resolution depends on the duration of the laser pulse and the cut-off speed of the detector.

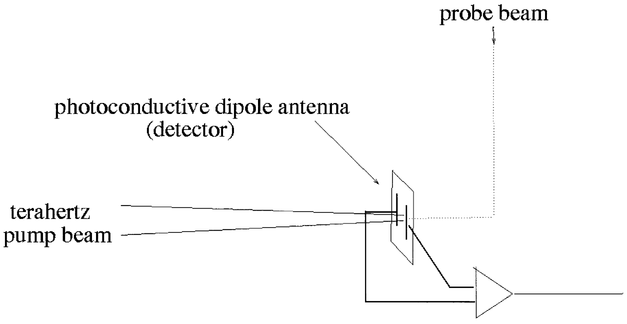

Fig. 4. Terahertz detection set-up using a photoconductive dipole antenna (PDA).

### 3.4. All optical generation and detection

The photoconductive dipole antenna (PDA) was first described, in the early 1980s, by Auston et al. [31] and rapidly grew in popularity among high-speed laser research groups around the world. The PDA is typically a dipole antenna drawn on a semiconductor substrate, which radiates when a laser pulse enables a photocurrent pulse to flow across the biased semiconductor gap [32]. Although simple to construct, a PDA requires an ultrafast laser to activate, and femtosecond lasers are expensive. On the other hand, femtosecond gating enables the use of PDA detectors in the high-resolution pump–probe configuration. The PDA is activated by ultrashort laser pulses and emits terahertz pulses of picosecond duration. PDA emitters can have high powers, although they are limited by the maximum surface current flow. The energy radiated from a PDA depends both on the energy of the laser pulse and the bias that powers the current cascade. PDAs can also be used for detection, as shown in Fig. 4. The main problem with PDAs is their bandwidth limitation. The bandwidth of PDA detection has a high frequency limit determined by the speed of the photocurrent response [33]. The resolution of terahertz pulse radiation

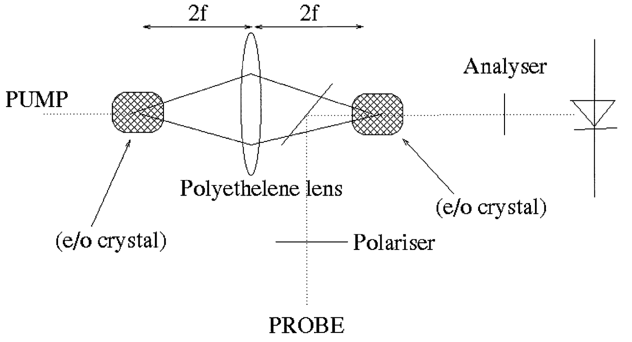

Fig. 5. Terahertz pump–fs probe system with crossed polarisers (electro-optic sampling) [62].

is poor at low terahertz frequencies; PDAs emit over a spectral range from about 100 GHz to 1 THz, peaking at about 500 GHz. For pulsed terahertz applications, the PDA is powerful and sensitive, but lacks a short wavelength for higher resolution.

The other primary pulsed terahertz technique is the *free-space electro-optic sampling* (FSEOS) method, a technique based on emission by optical rectification and detection by electro-optic sampling [34]. Optical rectification is a process first observed in the 1960s that describes how a pulse at optical frequencies can be down-shifted by degenerate difference frequency generation inside a non-linear crystal [35]. In FSEOS, an ultrafast pulse with 800 nm centre wavelength is directed into a non-linear crystal, which subsequently emits a pulse with terahertz centre frequency. In contrast to PDA emission, the power of the terahertz pulse is derived entirely from the incident laser pulse, so FSEOS typically has lower power. For example, the most efficient dipole configuration emits an average of 3 μW of terahertz for 20 mW of excitation [36], whereas only 30 nW is typically generated from 175 mW of excitation with optical rectification [37]. The advantage of FSEOS lies in its bandwidth, which is limited not by the speed of the photocurrent pulse as in a PDA, but by the non-linear characteristics of the emitter crystal [32]. Terahertz pulses with wavelengths extending down to 7 μm have been generated [37]. The higher frequencies of emitted terahertz in FSEOS are detected using electro-optic sampling, a technique reliant on the electro-optic, or Pockels effect [38]. This detection scheme is shown in Fig. 5. Electro-optic sampling operates by writing the terahertz waveform into the polarisation of an electro-optic crystal and then reading it with a second femtosecond pulse, that is, the probe pulse in a typical pump–probe configuration. The electro-optic effect is extremely fast but very weak compared to photoconductive sampling. An electro-optic crystal can be used to detect up to 50 THz [37], but the signal becomes increasingly disguised by background laser noise [33]. FSEOS benefits from the temporal resolution and coherent detection of the pump–probe method, and its lack of power is offset by its improved resolution.

## 4. Applications of terahertz pulses

Far infrared radiation is rarely produced at really high powers and is thus considered primarily for observation rather than physical manipulation. Observation with terahertz has involved spectroscopy, range finding, tomography and microscopy. Terahertz spectroscopy is valuable for distinguishing molecules and studying intermolecular interactions, while tomography relates to imaging through successive layers of a material. Microscopy with terahertz is realised by working in the near-field terahertz radiation pattern, thus overcoming the far-field wavelength limitation on resolution.

### *4.1. Spectroscopy*

As in any spectroscopic system, terahertz spectroscopy is based on observing changes in the terahertz spectrum after transmission through or reflection from a material. The most common terahertz spectroscopy system is terahertz time-domain spectroscopy (THz-TDS) [7]. THz-TDS relies on PDA detection and emission technology. In its most simplistic form, the Fourier spectrum of a free-space terahertz pulse is first characterised, then compared to the spectrum of a pulse that has passed through some sample. The difference between the two spectra reveals the sample's molecular absorption lines. THz-TDS has been used to measure the refractive index of dielectrics [39], thin films [13], semiconductors [40], liquids and superconductors. It has also featured in studying the dielectric properties of polar liquids [41], in recognising gases and gas mixtures [42], in observing the rotational absorption spectra of hot water vapour in flames [43] and in classifying terahertz material parameters [11]. Spectroscopy in the far infrared is particularly interesting because one can study the dynamics of chemical reactions, which is very important in understanding how chemical and biological systems operate and interact [44].

THz-TDS is advantageous because a wide spectral range can be probed with the one pulse, so there is no need for frequency sweeping as in a cw system. FSEOS has a broader bandwidth and operates at shorter wavelengths. This may be important for discerning particular spectral lines at frequencies higher than 1 THz.

An important variation on transmission spectroscopy is reflection spectroscopy. Both techniques are very similar, however there are two important differences to note. The first relates to penetration depth, because terahertz radiation is easily blocked by large amounts of material, especially if it contains water. Femto-joule terahertz pulses of 0.3–2.7 THz are blocked by three millimeters of moist dermal tissue [9]. The second important point of reflection spectroscopy is consideration of the phase. Unlike the transmission geometry, the path length will change depending on the placement of the sample, so phase information has to be referenced to a known surface or a carefully measured distance.

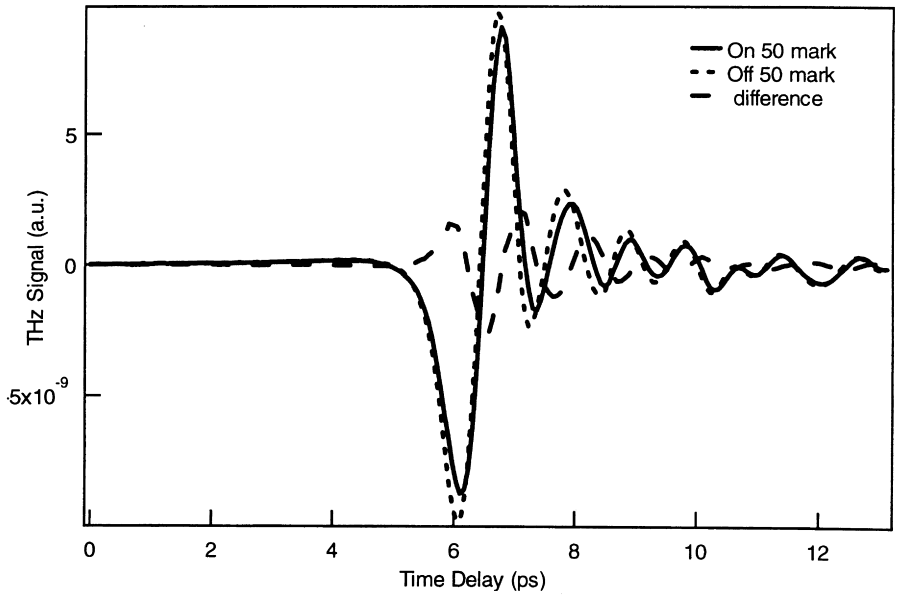

Fig. 6. Two terahertz pulse waveforms after transmission through an Australian $50 plastic note. The solid line is through the lettering ($50) and the dotted line is through the surrounding plastic. The dashed line shows the difference between the two waveforms.

### 4.2. Ranging and tomography

Two obvious modalities for pulsed radiation are ranging and tomography, both of which rely on a reflective geometry. The basic elements of ranging involve measuring the time of flight of the terahertz pulses and thus calculating the distance and shape of objects. For example, the radar profiles of large objects can be characterised using scale models and terahertz pulses [45]. Tomography is a similar application, looking at the flight time of pulse reflections from subsequent boundaries inside an object. Thus the internal structure of, for example, a computer floppy disc can be observed non-invasively [6]. In a second step, tomography could be combined with spectroscopic analysis to reveal the

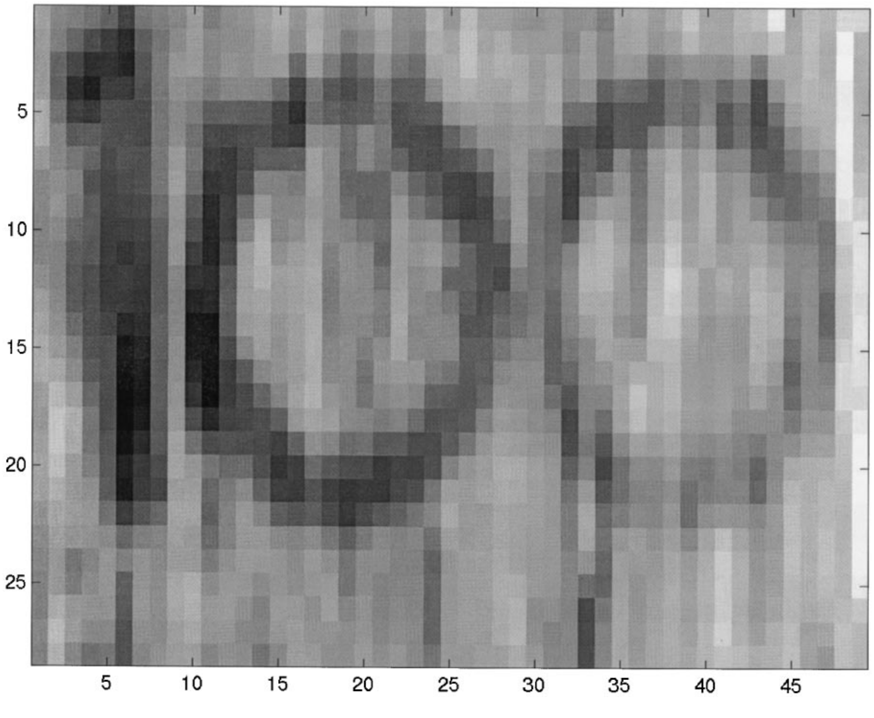

Fig. 7. Terahertz transmission image of an Australian $100 bank note. The terahertz absorption of the ink used to write the numeral is greater than that of the surrounding plastic, so the digits appear darker.

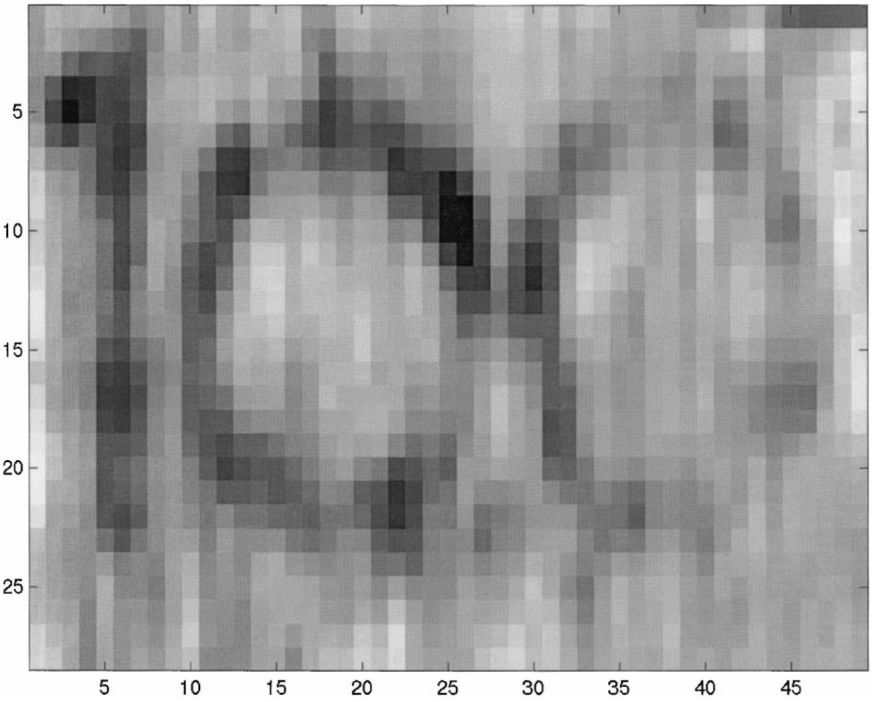

Fig. 8. The same bank note at in Fig. 7, but inside a paper envelope. The numeral still appears because paper has little effect on terahertz radiation.

structure and composition of certain objects. This requires intensive signal processing to deal with large amounts of data efficiently.

### 4.3. Microscopy

Near-field terahertz microscopy first developed from a desire for better resolution, and can be used to demonstrate some important properties of light and ultrafast phenomena [46]. Near-field microscopy has enabled imaging at spatial resolutions better than the diffraction limit, down to a quarter wavelength [47]. The near field is created with a tapered near-field tip, similar to those of scanning optical microscopes. The tip is held in contact with the sample and scanned in two dimensions to generate images.

## 5. Terahertz pulse imaging

Imaging in the far infrared was a natural extension of spectroscopic analysis and initially involved building up a two-dimensional image from an array of spectroscopic measurements [48]. Terahertz imaging has been performed using both PDAs and FSEOS by a number of groups and has also been implemented with a CCD camera, which obviates scanning the sample between pixel [1,4,49]. The aim is to speed up acquisition of a terahertz image so real-time processes can be observed. The future of terahertz imaging lies with inexpensive, robust systems that produce images swiftly and efficiently.

### 5.1. Scanning imaging

Terahertz images can be created by scanning an object pixel by pixel, as in Figs. 6 and 7 [48]. Fig. 7 shows part of an Australian banknote where the ink of the numeral ‘100’ absorbs terahertz radiation more than the surrounding plastic. Fig. 8 shows the same banknote inside an envelope. Covering the banknote with a paper envelope does not block the terahertz radiation, as it would visible light, thus the numeral remains visible.

A typical terahertz imaging system requires three motorised stages; two for xy scanning the sample in the terahertz beam and the third for the pump–probe delay. For full spectroscopic information at each pixel, the delay stage must scan for each pixel, which is slow. An alternative is to choose a delay that corresponds to a pulse peak and take an image of the terahertz amplitude transmitted at that delay. However, this second method discards useful information about the distortion of the pulse and is prone to errors; it is insensitive to large phase shifts and laser jitter. Clearly, an ideal terahertz image would contain not only amplitude attenuation information, but also a complete spectroscopic analysis at terahertz frequencies, thus enabling different materials to be classified across the sample. This requires burdensome signal processing and is very slow, but not intractable and is a target area for our research.

### 5.2. Parallel processing: CCD camera

The slowness of two-dimensional imaging can be avoided

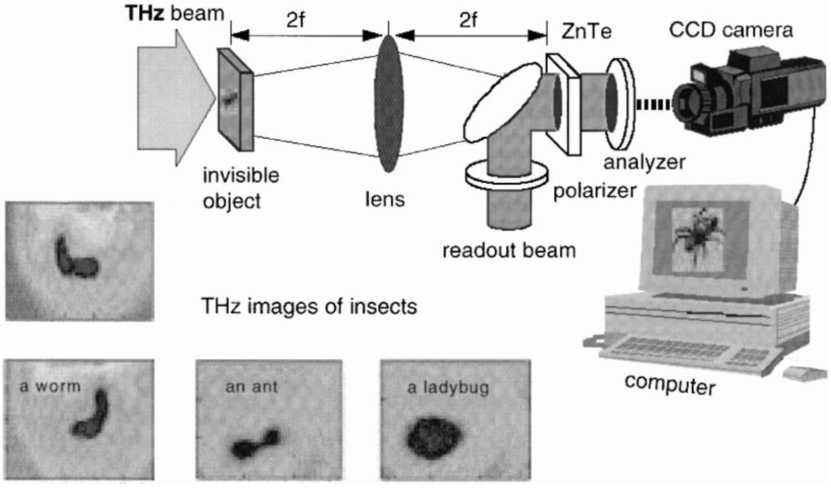

Fig. 9. A system for terahertz imaging with FSEOS and a CCD camera. The images shown are of insects imaged with terahertz.

by using an imaging array, rather than mechanically scanning each pixel individually. With electro-optic sampling, it is easy to replace the balanced photodiodes with a CCD camera and image the entire terahertz radiation plane [4]. There is, however, a trade-off between the signal-to-noise ratio and the size of the area being imaged, since the energy of the pulse is being spread over an array of detectors. Fig. 9 shows a system for terahertz imaging with a CCD camera, accompanied by two-dimensional terahertz images of insects. An important disadvantage of CCD imaging is the loss of the lock-in amplifier, which normally provides cancellation of the $1/f$ laser noise. No group has reported using a CCD with lock-in detection.

### 5.3. Parallel processing: antenna array

The benefit of two-dimensional parallel processing has not been realised with photoconductive antennae. An array of PDAs would be far less sensitive to laser noise than a CCD based on electro-optic detection, and laser noise dominates an electro-optic system [33]. Fig. 10 shows an array of PDAs, each typically sized between five and 50 μm, depending on the desired emission characteristics [50]. Such structures would be easy to implement using existing lithographic technology. The resolution of an image detected by an array of these dimensions would be limited by the far-field wavelength of the radiation rather than the detector size. At a centre frequency of 1 THz, typical for a photoconductive antenna, the far-field spatial resolution is about 300 μm.

The extension of a single PDA into a one-dimensional array has been reported for beam steering of terahertz beams [51]. This used 64 electrodes, each 20 μm wide, spaced by 150 μm centre-to-centre, deposited on a semi-insulating GaAs substrate. There is still room for routing in such a layout. An extension of a PDA array would involve replacing the simple dipole antennae with more efficient horn antennae. Various photoconducting antennae have already been reported in tapered slotline, stripline and spiral antenna

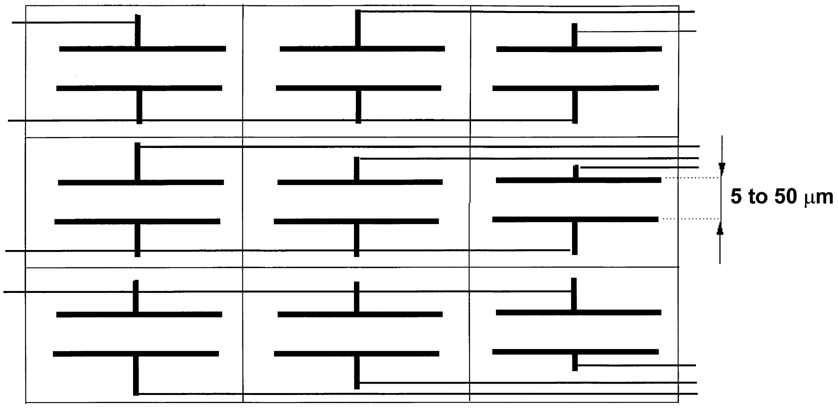

Fig. 10. A layout of an array of PDAs used for two-dimensional detection. The electric field is detected at each pixel in the array. The strip lines are metal on a GaAs substrate.

Table 1
Comparison of pulsed terahertz techniques

| Electro-Optic | | Photoconductive Antenna | |
|---|---|---|---|
| Emitter | Detector | Emitter | Detector |
| Lower power<br>Higher frequencies | Lower efficiency<br>Higher frequencies<br>Easy to align<br>CCD imaging | Higher power<br>Lower frequencies | Higher efficiency<br>Lower frequencies<br>Less equipment<br>Array imaging |

configurations [52–56]. Constructing an array of small three-dimensional structures in a 50 μm will require micromachining technology.

## 6. Terahertz system trade-offs

The essential system trade-offs for a pulsed terahertz system are summarised in Table 1. The electro-optic system is characterised by low power and low efficiency generation and detection, whereas PDAs generate higher power. PDAs are, however, limited in frequency by their terahertz generation mechanism. This effect is slower than the electro-optic effect used both to generate and detect terahertz in FSEOS. In the critical consideration of bandwidth, electro-optic techniques can achieve frequencies up to 50 THz [37], whereas photoconductive switches are limited to a few terahertz.

Apart from the trade-off between terahertz power and bandwidth, two other issues contribute to selecting a terahertz system. The first has to do with supporting equipment, specifically lock-in amplifiers and regenerative laser amplification, and the second relates to two-dimensional imaging.

Although electro-optic generation has a greater bandwidth than photoconductive switching, the power in the terahertz pulse derives entirely from the incident laser pulse power. In a PDA emitter, the output power scales both by incident pulse power and by bias voltage. The energy of an ultrafast laser pulse can be increased using a regenerative amplifier in addition to the ultrafast laser oscillator. Electro-optic detection is a weak effect and very sensitive to optical noise. To eliminate the noise it is necessary to

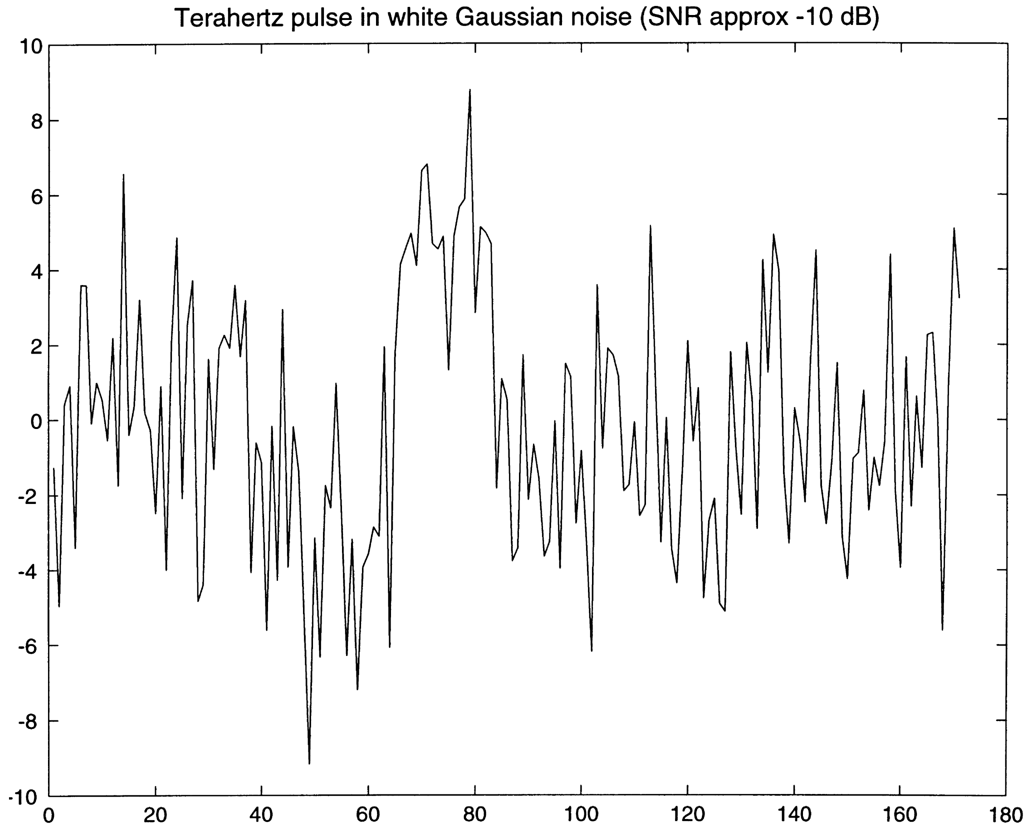

Fig. 11. Plot of a real terahertz pulse buried in zero-mean white Gaussian noise at a signal-to-noise ratio (SNR) of approximately −10 dB.

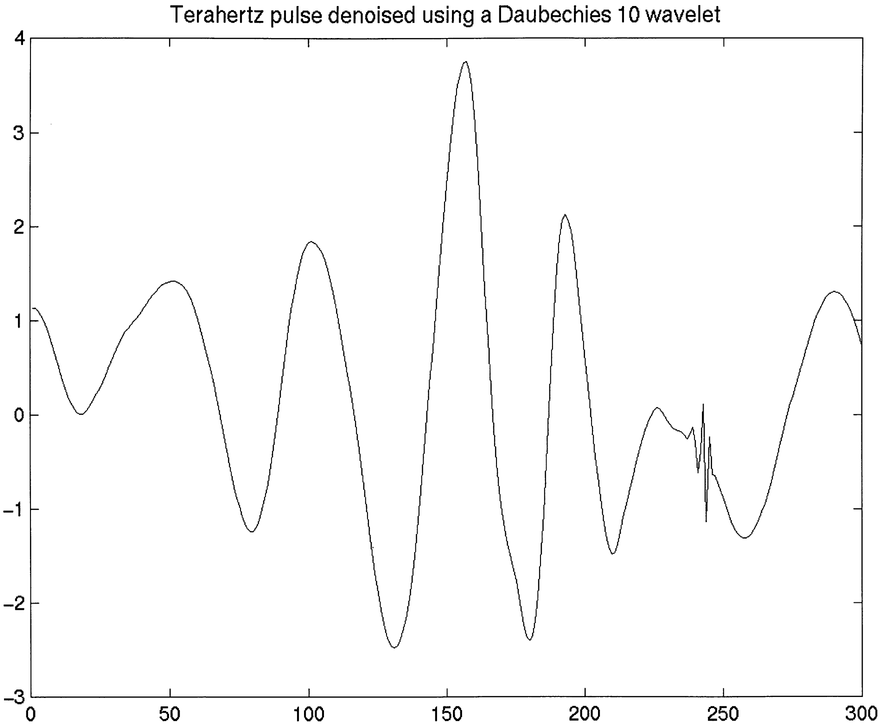

Fig. 12. Plot of the noisy terahertz pulse from Fig. 11 after being de-noised using a wavelet thresholding. The typical pulsed nature of a sampled terahertz waveform is revealed. A number of spurious oscillations are produced by the wavelet de-noising process.

use a lock-in amplification technique [57]. Regenerative and lock-in amplifiers are large and expensive, limiting the development of a portable and cheap terahertz system.

As shown in Table 1, electro-optic detection permits parallel imaging with a CCD camera. This takes advantage of the increased bandwidth associated with electro-optic detection but optical noise cannot be eliminated. It would be beneficial to have an array of photoconductive switches. This would take advantage of the increased speed of parallel processing and the insensitivity to laser noise of the photoconductive switch. Implementation of a two-dimensional array of photoconductive antennae was discussed in Section 5.3.

## 7. Signal processing for terahertz pulses

### 7.1. Wavelet image processing

The development of a robust and efficient terahertz imaging system requires efficient signal analysis and information processing algorithms. Apart from detection and system interfaces, it is vital to take incoming terahertz waveforms or images, enhance salient features and present the information for storage and interpretation. Currently most operational terahertz imaging systems are pulsed, so the idea of processing based on wavelets appears practical [3]. Wavelet analysis extends the concept of Fourier decomposition to a more complicated time and scale (‘frequency’) decomposition. In wavelet analysis, a signal is decomposed into an array of pulse-shaped *wavelets*, so that the time domain and spectral domain of a signal can be studied simultaneously, much like the short-time Fourier transform (Gabor transform) [58]. The basic premise of wavelet analysis is to construct the signal from the scaled wavelets instead of from infinite sinusoidal functions, as used in Fourier analysis. When applied to pulsed systems, like pulsed terahertz imaging, the wavelet function fits far more closely to the shape of the actual signal than any sinusoid would and thus correlation coefficients are higher than for Fourier transforms. Higher coefficients mean better noise thresholding and faster signal detection. In fact, it has been shown that wavelets have near optimal noise reduction properties for a wide range of signals [59]. Fig. 11 depicts a noisy pulsed waveform. It consists of a real sampled terahertz pulse with the addition of simulated zero-mean white Gaussian noise at a signal-to-noise ratio of about $-10$ dB. Fig. 12 demonstrates the effectiveness of wavelet de-noising on this pulsed waveform; the fast oscillations are removed and the pulsed nature of the terahertz is revealed.

Image processing must not only be effective, it must also be fast. One of the primary features of the *discrete wavelet transform* (DWT) algorithm is its speed. Compared to the Fast Fourier Transform, which has complexity of order *O(NlogN)*, the DWT is far quicker with complexity order *O*(*N*) [5]. This can make a phenomenal difference to the time required to de-noise and analyse signal data. The central trade-off in wavelet analysis comes between

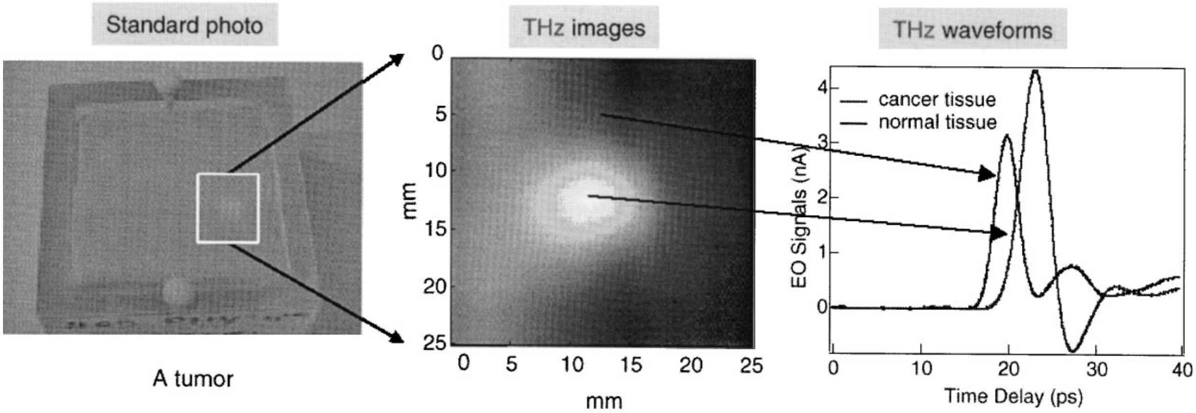

Fig. 13. Terahertz image of a breast phantom (wax) with fibres embedded to simulate cancerous growths. The cancerous tissue can be determined from the difference in terahertz transmission waveforms.

performance and speed. Although the DWT is fast, better and more flexible performance can be achieved by introducing some redundancy by using an *over-complete wavelet transform* (OCWT). The OCWT provides better noise robustness, allows for non-uniform sampling and allows adjustment of its bandwidth [60]. The trade-off with the OCWT is performance against speed. Algorithm speed can be sacrificed for better noise suppression.

### *7.2. Imaging applications*

Finding applications for terahertz imaging systems remains an important investigative pursuit as the field continues to mature [17]. Medical imaging is a fertile field for terahertz imaging because, unlike X-rays, they are not harmful to tissue. An example of medical imaging is shown in Fig. 13, in which a terahertz image of a breast cancer phantom clearly shows where simulated cancers are. Although terahertz do not penetrate far into the body, it would be possible to project terahertz endoscopically, as in optical coherence tomography [61].

## 8. Conclusions and future directions

The field of terahertz imaging is rapidly maturing to a point where practical commercial terahertz systems are realisable. Based on femtosecond lasers, terahertz pulse imaging offers scope for wide-ranging analysis in the terahertz spectrum, once important system issues have been resolved and signal processing optimised. For the first time we demonstrate results based on terahertz imaging of plastic banknotes. This may find application in the identification and counting of currency.

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## References

[1] D.M. Mittleman, R.H. Jacobson, M.C. Nuss, T-ray imaging, IEEE Journal of Selected Topics in Quantum Electronics 2 (3) (1996) 679–692.

[2] D.M. Mittleman, M. Gupta, R. Neelamani, R.G. Baraniuk, J.V. Rudd, M. Koch, Recent advances in terahertz imaging, Applied Physics B: Lasers and Optics 68 (6) (1999) 1085–1094.

[3] M. May, T-rays spell sharper, safer images, New Scientist 154 (2083) (1997) 22.

[4] D.A.R.P. Agency, Electronics technology office: solicitations: Baa 99-15. Internet (World Wide Web), 1998. http://www.darpa.mil/ETO/Solicitations/BAA99-15/S/Section1.html.

[5] S. Hunsche, D.M. Mittleman, M. Koch, M.C. Nuss, New dimensions in T-ray imaging, IEICE Transactions on Electronics E81-C (2) (1998) 269–276.

[6] D.M. Mittleman, R. Neelamani, R.G. Baraniuk, M.C. Nuss, Applications of terahertz imaging, in: Nonlinear Optics ‘98: Materials, Fundamentals and Applications Topical Meeting, IEEE, Princeville, HI, 1998, pp. 294–296.

[7] Q. Wu, T.D. Hewitt, X.-C. Zhang, Two-dimensional electro-optic imaging of terahertz beams, Applied Physics Letters 69 (8) (1996) 1026–1028.

[8] C.S. Burrus, R.A. Gopinath, H. Gou, Introduction to Wavelets and Wavelet Transforms: A Primer, Prentice-Hall, Englewood Cliffs, NJ, 1998.

[9] D.D. Arnone, C.M. Ciesla, A. Corchia, S. Egusa, M. Pepper, J.M. Chamberlain, C. Bezant, E.H. Linfield, R. Clothier, N. Khammo, Applications of terahertz (THz) technology to medical imaging, in: Proceedings of SPIE-Conference on Terahertz Spectroscopy and Applications, vol. 3828, SPIE, Munich, Germany, 1999, pp. 209–219.

[10] V.G. Dmitriev, G.G. Gurzadyan, D.N. Nikogosyan, Handbook of Nonlinear Optical Crystals, Springer Series in Optical Sciences, 3rd ed., 64, Springer, Berlin, 1999.

[11] D.M. Mittleman, S. Hunsche, L. Boivin, M.C. Nuss, T-ray tomography, Optics Letters 22 (12) (1997) 904–906.

[12] M.V. Exter, C. Fattinger, D. Grischkowsky, Terahertz time-domain spectroscopy of water vapour, Optics Letters 14 (20) (1989) 1128–1130.

[13] M.C. Nuss, Chemistry is right for T-rays, IEEE Circuits and Devices 12 (2) (1996) 25–30.

[14] L. Duvillaret, F. Garet, J.-L Coutaz, A reliable method for extraction of material parameters in terahertz time-domain spectroscopy, IEEE Journal of Selected Topics in Quantum Electronics 2 (3) (1996) 739–746.

[15] G. Gallot, D. Grischkowsky, Terahertz time-domain spectroscopy (THz-TDS) with electro-optic sampling, in Conference on Lasers and Electro-Optics ‘99, IEEE LEOS OSA, Optical Society of America, Baltimore, MD, 1999, pp. 492–493.

[16] M. Li, G.C. Cho, T.-M. Lu, X.-C. Zhang, S.-Q. Wang, J.T. Kennedy, Time-domain dielectric constant measurement of thin film in GHz-THz frequency range near Brewster angle, Applied Physics Letters 74 (15) (1999) 2113–2115.

[17] B. Lax, Applications of far infrared lasers, in: A. Mooradian, T. Jaeger, P. Stokseth (Eds.), Tunable Lasers and Applications, Springer Series in Optical Sciences, 3, Springer, Berlin, 1976, pp. 340–347.

[18] T. Klaassen, N. Hovenier, T. Wenckebach, A. Murajov, S. Pavlov, V.N. Shastin, Pulsed and mode-locked p-Ge terahertz laser: wavelength dependent properties, in: Proceedings of SPIE—Conference on Terahertz Spectroscopy and Applications, vol. 3828, SPIE, Munich, Germany, 1999, pp. 58–67.

[19] P. Gu, M. Tani, M. Hyoho, K. Sakai, T. Hidaka, Generation of cw-terahertz radiation using a two-longitudinal-mode laser diode, Japanese Journal of Applied Physics 37 (8B) (1998) L976–L978.

[20] S. Verghese, K.A. McIntosh, S. Calawa, W.F. Dinatale, E.K. Duerr, K.A. Molvar, Generation and detection of coherent terahertz waves using two photomixers, Applied Physics Letters 73 (26) (1998) 3824–3826.

[21] P.C.M. Planken, M.C. Nuss, I. Brener, K.W. Goossen, Terahertz emission in single quantum wells after coherent optical excitation of light hole and heavy hole excitons, Physical Review Letters 69 (26) (1992) 3800–3803.

[22] A.J. Sengers, L. Tsang, Valance-band mixing and continuum excitons in the excitonic model for coherent terahertz radiation form quantum wells, Journal of the Optical Society of America B: Optical Physics 14 (5) (1997) 1057–1065.

[23] M.S.C. Luo, S.L. Chuang, P.C.M. Planken, I. Brener, H.G. Roskos, M.C. Nuss, Generation of terahertz electromagnetic pulses from quantum-well structures, IEEE Journal of Quantum Electronics 30 (6) (1994) 1478–1488.

[24] C. Chansungsan, Coherent terahertz radiative dynamics of excitons from ultrafast optical excitation of single semiconductor quantum wells, Journal of the Optical Society of America B: Optical Physics 13 (12) (1996) 2792–2800.

[25] A.N. Korotkov, D.V. Averin, K.K. Likharev, Tasers: Possible dc pumped terahertz lasers using interwell transitions in semiconductor heterostructures, Applied Physics Letters 65 (15) (1994) 1865–1967.

[26] V.A. Kovarsckii, Squeezed states of long-lived terahertz vibrations in quantum dots, JETP Letters 65 (2) (1997) 215–216.

[27] C. Waschke, H.G. Roskos, R. Schwedler, K. Leo, H. Kurz, K. Kohler, Coherent submillimeter-wave emission from Bloch oscillations in a semiconductor superlattice, Physical Review Letters 70 (21) (1993) 3319–3322.

[28] C.Y.L. Cheung, et al., bandwidth optimization for unipolar intersubband semiconductor lasers, IEEE Proceedings Optoelectronics 144 (1) (1997) 44–47.

[29] H. Eisele, Two-terminal devices as fundamental solid-state terahertz oscillators, in: Proceedings of SPIE - Conference on Terahertz Spectroscopy and Applications, vol. 3828, SPIE, Munich, Germany, 1999, pp. 70–80.

[30] J.A. Valdmanis, G. Mourou, C.W. Gabel, Picosecond electro-optic sampling system, Applied Physics Letters 41 (3) (1982) 211–212.

[31] D.H. Auston, K.P. Cheung, P.R. Smith, Picosecond photoconducting Herzian dipoles, Applied Physics Letters 45 (3) (1984) 284–286.

[32] D.H. Auston, in: W. Kaiser (Ed.), Ultrafast optoelectronics, in Ultrashort Laser Pulses and Applications, Topics in Applied Physics, 60, Springer, Berlin, 1988, pp. 183–233 (chap. 5).

[33] Y. Cai, I. Brener, J. Lopata, J. Wynn, L. Pfeiffer, J.B. Stark, Q. Wu, X.-C. Zhang, J. Federici, Coherent terahertz radiation detection: Direct comparison between free-space electro-optic sampling and antenna detection, Applied Physics Letters 73 (4) (1998) 444–446.

[34] Q. Wu, X.-C. Zhang, Free-space electro-optic sampling of mid-infrared pulses, Applied Physics Letters 71 (10) (1997) 1285–1286.

[35] M. Bass, P.A. Franken, J.F. Ward, G. Weinreich, Optical rectification, Physical Review Letters 9 (11) (1962) 446–448.

[36] Y. Cai, I. Brener, J. Lopata, J. Wynn, L. Pfeiffer, J. Federici, Design and performance of singular electric field terahertz photoconducting antennas, Applied Physics Letters 71 (15) (1997) 2076–2078.

[37] A. Bonvalet, M. Joffre, J.-L. Martin, A. Migus, Generation of ultrabroadband femtosecond pulses in the mid-infrared by optical rectification of 15 fs light pulses at 100 MHz repetition rate, Applied Physics Letters 67 (20) (1995) 2907–2909.

[38] Q. Wu, X.-C. Zhang, Design and characterization of travelling-wave electro-optic terahertz sensors, IEEE Journal of Selected Topics in Quantum Electronics 2 (3) (1996) 693–700.

[39] D. Grischkowsky, S. Keiding, M.V. Exter, C. Fattinger, Far-infrared time-domain spectroscopy with terahertz beams of dielectrics and semiconductors, Journal of the Optical Society of America B: Optical Physics 7 (10) (1990) 2006–2015.

[40] D.M. Mittleman, J. Cunningham, M.C. Nuss, M. Geva, Noncontact semiconductor wafer characterization with the terahertz Hall effect, Applied Physics Letters 71 (1) (1997) 16–18.

[41] J.T. Kindt, C.A. Schumuttenmaer, Far-infrared dielectric properties of polar liquids probed by femtosecond terahertz pulse spectroscopy, Journal of Physical Chemistry 100 (1996) 10373–10379.

[42] R.H. Jacobsen, D.M. Mittleman, M.C. Nuss, Chemical recognition of gases and gas mixtures with terahertz waves, Optics Letters 21 (24) (1996) 2011–2013.

[43] R.A. Cheville, D. Grischkowsky, Observation of pure rotational absorption spectra in the band of hot HO in flames, Optics Letters 23 (7) (1998) 531–533.

[44] B.N. Flanders, D.C. Arnett, N.F. Scherer, Optical pump–terahertz probe spectroscopy utilizing a cavity-dumped oscillator-driven terahertz spectrometer, IEEE Journal of Selected Topics in Quantum Electronics 4 (2) (1998) 353–359.

[45] R.A. Cheville, D. Grischkowsky, Time-domain terahertz impulse ranging studies, Applied Physics Letters 67 (14) (1995) 1960–1962.

[46] K. Wynne, J.C. Carey, J. Zawadzka, D.A. Jaroszynski, Superluminal propagation of terahertz pulses in sub-wavelength structures, in: Conference on Lasers and Electro-Optics ‘99, IEEE LEOS OSA, Baltimore, MD, 1999, p. 397.

[47] S. Hunsche, M. Koch, I. Brener, M.C. Nuss, Terahertz near-field imaging, Optics Communications 150 (1998) 22–26.

[48] B.B. Hu, M.C. Nuss, Imaging with terahertz waves, Optics Letters 20 (16) (1995) 1716–1718.

[49] X.-C. Zhang, Ultrafast electro-optic field sensor and its image applications, in: M. Nuss, J. Bowers (Eds.), OSA TOPS on Ultrafast Electronics and Optoelectronics, vol. 13, OSA, 1997.

[50] I. Brener et al., Design and performance of singular electric-field terahertz emitters and detectors, in Conference on Lasers and Electro-Optics ‘97, IEEE LEOS OSA, Baltimore, MD, 1997, p. 66.

[51] N.M. Froberg, Terahertz radiation from a photoconducting antenna array, IEEE Journal of Quantum Electronics 28 (10) (1992) 2291–2301.

[52] A.P. DeFonzo, C.R. Lutz, Optoelectronic transmission and reception of ultrashort electrical pulses, Applied Physics Letters 51 (4) (1987) 212–214.

[53] R. Heidemann, T. Pfeiffer, D. Jager, Optoelectronically pulsed slotline antennas, Electronics Letters 19 (1983) 316–317.

[54] Y. Pastol, G. Arjavalingham, J.-M. Halbout, G.V. Kopscay, Characterisation of an optoelectronically pulsed broadband micro-wave antenna, Electronics Letters 24 (1988) 1318–1319.

[55] Y. Pastol, G. Arjavalingham, J.-M. Halbout, Characterisation of an

optoelectronically pulsed equiangular spiral antenna, Electronics Letters 26 (1990) 133–134.

[56] D.R. Dykaar, B.I. Greene, J.F. Federici, A.F. Levi, L.N. Pfeiffer, R.F. Kopf, Log-periodic antennas for pulsed terahertz radiation, Applied Physics Letters 59 (1991) 262–264.

[57] M.L. Meade, Lock-in Amplifiers: Principles and Applications, Numerical Measurement Series, 1, Peter Peregrinus, London, 1983.

[58] A. Graps, An introduction to wavelets, IEEE Computational Science and Engineering 2 (2) (1995) 50–61.

[59] D.L. Donoho, De-noising by soft thresholding, IEEE Transactions on Information Theory 41 (3) (1995) 613–627.

[60] A. Teolis, Computational Signal Processing with Wavelets, Birkhauser, Boston, MA, 1998.

[61] J.A. Izatt, A.M. Rollins, R. Ung-arunyawee, A. Chak, R.C. Wong, K. Kobayashi, M.V. Sivak, Real-time endoscopic optical coherence tomography in human patients, in: Conference on Lasers and Electro-Optics ‘99, IEEE LEOS OSA, Baltimore, MD, 1999, pp. 336–337.

[62] Q. Wu, M. Litz, X.-C. Zhang, Broadband detection capability of ZnTe electro-optic field detectors, Applied Physics Letters 68 (21) (1996) 2924–2926.