Physicists and industrialists are turning to terahertz radiation to provide cheaper, safer and more versatile ways of producing detailed images

Terahertz imaging comes into view

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IMAGING technology is becoming increasingly prevalent in our society. X-ray scanners are routinely used to examine luggage at airports, for example, and most hospitals are equipped with ultrasound scanners and magnetic resonance imaging machines. There is also a wealth of other less well known applications throughout industry. For instance, X-rays are used for package inspection, while the defects or voids in materials on production lines are often probed using microwaves or ultrasound.

In spite of their considerable success, X-rays, magnetic resonance imaging and ultrasound all have shortcomings (see table on page 37). Many clinicians and non-medical users feel that fundamentally different physical principles are needed to provide safer and more cost-effective imaging techniques. And physicists are turning to other regions of the electromagnetic spectrum to address these issues.

Indeed, a cursory examination reveals that conventional imaging techniques only use the extreme ends of the electromagnetic spectrum: photons with energies greater than 30 keV for X-rays, and around 0.4 μeV for magnetic resonance imaging. The radiation between these extremes falls largely into the visible, infrared and millimetre or microwave regions.

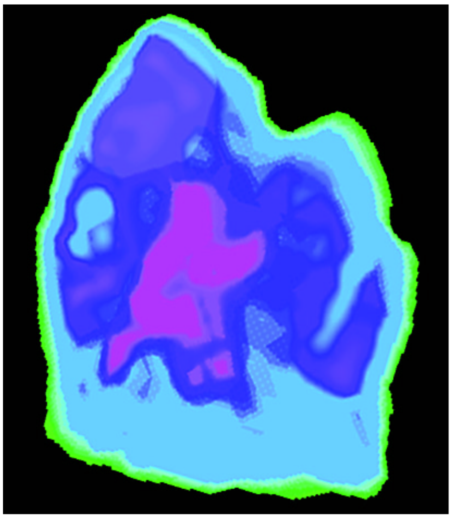


Image of a human tooth formed from terahertz radiation. The data can be manipulated to provide different terahertz images, each containing different diagnostic information

The challenge for imaging

The visible and near-infrared regions of the spectrum have been studied extensively for over a decade using a variety of laser-based techniques such as fluorescence imaging and optical coherence tomography. Medical imaging, in particular, has benefited greatly from advances in these areas (see French in further reading).

However, the Rayleigh scattering of light – from tissue and many inorganic materials – has traditionally hindered the development of optical-based techniques. This scattering attenuates the light and blurs the image. Although recent advances have sought to redress these effects, scattering remains a considerable obstacle in most biomedical applications.

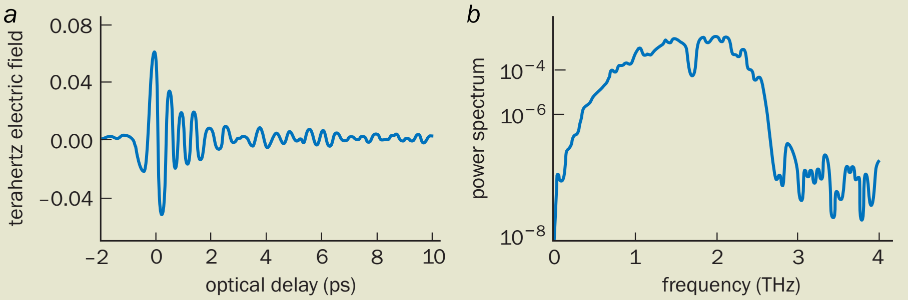
As the probability of Rayleigh scattering is inversely proportional to the fourth power of the wavelength, λ, we expect the quality of an image to improve rapidly as we increase the wavelength. For example, the level of scattering should be reduced by a factor of 10^{12} if we use waves with $\lambda = 1$ mm rather than near-infrared light with $\lambda = 800$ nm. This means we could, in principle, obtain sharper images at greater depths if we increase the wavelength of light used.

Microwave imaging in the 0.3–30 cm wavelength range is a well established technique that has been developed for almost two decades. Its potential was spotted early, and a variety of imaging techniques has since been demonstrated. One of the most intriguing methods is known as "video-pulse detection", a technique that was borrowed, in part, from radar technology.

In video-pulse detection, a sequence of microwave pulses is injected into a particular point on an object. The transmitted or reflected portion of each pulse is then detected after a time delay. By varying the length of this delay, a 3-D image of the internal structure can be discerned. The object may be translated through the beam or the beam may be scanned across the object to build up an image at various points. By using pulses, which are made up of a wide range of frequencies, frequency-domain as well as time-domain images may be obtained.

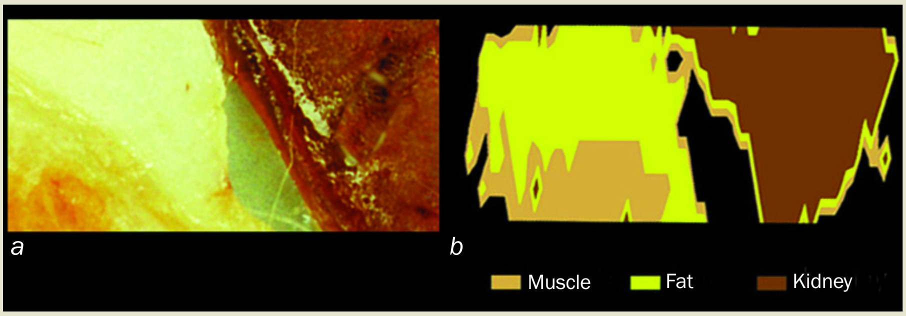
However, conventional radiation sources produce microwaves with wavelengths between a few millimetres and tens of centimetres. Such relatively long wavelengths limit the spatial resolution of the objects that can be discerned to around 5 mm, thereby precluding the use of microwaves in many applications. What was really needed was a bright source of radiation at intermediate wavelengths: in other words, the wavelength had to be sufficiently small to provide good resolution, yet large enough to prevent serious losses by Rayleigh scattering. Physicists looked to the so-called terahertz gap in the electromagnetic spectrum – the region between 300 GHz and 20 THz in frequency (i.e. 15 μm–1 mm in wavelength) – but for many years no coherent source of radiation or coherent means of detection were available.

1 Terahertz pulses



(*a*) A typical terahertz waveform in the time domain. The "ringing" after the main pulse is due to absorption in the atmosphere and propagation effects in the zinc-telluride emitter and detector crystals. (*b*) The transmission as a function of frequency can be obtained by applying a Fourier transform to the time-domain data. This spectrum represents the frequency bandwidth of the system and can be used to collect spectroscopic data.

2 Fleshing out the details



(*a*) A visible image of a sample of pork. (*b*) A terahertz-pulse image of the same piece of pork. The absorption spectrum at each pixel highlights the regions of muscle and fat in greater detail. The food-processing industry could use the technique to determine the fat content of packaged food.

Generating terahertz radiation

A major breakthrough came in the 1980s when David Auston and co-workers at Columbia University in New York demonstrated that "photoconductive emitters" could be used to generate coherent picosecond (10^{-12} s) pulses at terahertz frequencies. When a photoconductive emitter is illuminated with a subpicosecond pulse of visible or near-infrared light, electron–hole pairs are created in a semiconducting layer within the device. These charge carriers are then accelerated by a bias voltage. The resulting transient photocurrent is proportional to this acceleration and radiates at terahertz frequencies.

Another way of converting picosecond and femtosecond (10^{-15} s) pulses of visible light into terahertz radiation is based on the generation of difference-frequency radiation. This effect arises from the second-order susceptibility $\chi^{(2)}$ of a crystal. The susceptibility, $\chi = P/\varepsilon_0 E$, measures the degree of polarization, P, caused when an electric field, E, is applied to a dielectric material (ε_0 is the permittivity of a vacuum). Higher-order terms, such as $\chi^{(2)}$, denote the nonlinear response of the materials and are important for the high electric fields found in laser pulses.

Ultrafast pulses with a temporal width of ~70 fs comprise a large number of different frequency waves and have a frequency bandwidth in excess of 10 THz. Using an ultrafast visible pulse to excite a crystal that has a large second-order susceptibility, such as zinc telluride, produces a time-varying polarization of the electron cloud inside the crystal. We can think of the oscillating electron cloud with electric polarization, P, vibrating at the various frequencies (say ω_1 and ω_2) that correspond to those that make up the incident pulse of visible light. The electron cloud then re-radiates at terahertz frequencies, $\omega_{\mathrm{THz}} = \omega_1 - \omega_2$, as a result of the beats that form between the various frequency components. The pulse of terahertz electromagnetic radiation contains a broad range of frequencies, from zero up to the bandwidth of the visible radiation.

Both the photoconductive and the difference-frequency generation (DFG) sources produce average powers that range from several nanowatts to tens of microwatts. The pulse energies are typically in the femtojoule to nanojoule range. These figures are modest compared with other conventional sources of terahertz light, such as free-electron lasers and molecular-gas lasers. The advantages of photoconductive and DFG sources, however, is that they are smaller, cheaper and more stable – all important factors for research and commercial applications.

Detecting terahertz radiation

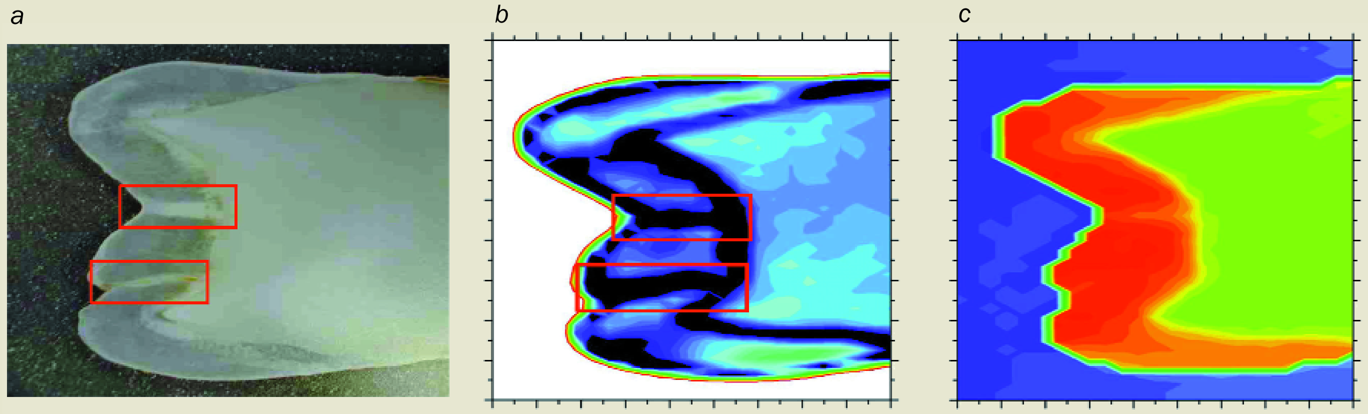
The biggest advantage of photoconductive and DFG generators is the fact that they can be readily married to "coherent" detectors operating at room temperature. The coherent nature of these detectors means that they provide both phase and amplitude information about the pulse, and can reject noise due to background radiation.

The detection mechanisms rely on what is essentially the inverse of the generation mechanism, photoconductive detection and free-space electro-optic sampling (EOS). EOS uses an electro-optical effect known as the AC Pockels effect. A terahertz pulse incident on an electro-optical medium – such as zinc telluride – alters the refractive index perpendicular to the optical axis of the crystal. This "birefringence" is proportional to the amplitude of the terahertz electric field, E_{THz}, because the birefringence of the crystal changes instantaneously.

The terahertz pulses can be accurately probed on short timescales. This is straightforward to achieve by passing a small portion of the visible beam through the electro-optical medium, which becomes elliptically polarized. The degree of elliptical polarization of the pulse is readily measured using inexpensive and commercially available optical components and photodetectors.

Due to the instantaneous response of the electro-optical material, in principle EOS has an extremely high frequency bandwidth and allows a direct measurement of the amplitude, phase and spatial distribution of E_{THz}. Attowatt (10^{-18} W) noise levels are theoretically possible and stem from the coherent nature of the technique. By directly measuring E_{THz} at different time intervals, we can eliminate any back-

3 Detecting tooth decay



Panchromatic transmission and time-of-flight images provide different types of information about teeth. (*a*) A visible image of a section through a human tooth. The lesions caused by caries are highlighted by the boxes. (*b*) A terahertz absorption image of the tooth decay in the enamel. The black regions are areas of high absorption. (*c*) A terahertz image also reveals the enamel and dentine layers. The image was formed from time-of-flight data, where the red and green areas represent the longest and shortest delays, respectively. The timing information gives a large contrast because there is a large difference in the refractive indices of the two types of tissue ($n = 3.0$ for enamel and $n = 2.6$ for dentine).

The pros and cons of imaging techniques

Imaging technique	Advantages	Disadvantages
Ultrasound	Low cost, safe	Lack of chemical specificity
X-rays	High penetration depth, low cost	Ionizing radiation, lack of chemical specificity
Magnetic resonance imaging	High sensitivity, deep penetration	High cost, lack of sensitivity in thin tissue

ground-radiation contribution and hence achieve low levels of noise. In contrast, conventional detection techniques rely principally on liquid-helium-cooled bolometers, which measure only the intensity of the radiation and do not provide any phase information. The sensitivity of these detectors is also limited by background noise.

The photoconductive and EOS detection techniques are much more versatile than their conventional counterparts. By measuring the time it takes a terahertz pulse to travel through a medium, we can determine both its thickness and refractive index. Moreover, we can apply a Fourier transform to this timing information to extract transmission information as a function of frequency (figure 1). Indeed since the late 1980s terahertz pulses have been used in spectroscopic studies of semiconductors, gases, liquids and DNA.

Imaging with terahertz pulses

The spectral response of many organic and inorganic materials to low-frequency terahertz light is dominated by the dielectric response of the materials. This is akin to the interactions that prevail in the microwave and millimetre-wave regions of the spectrum. At high frequencies, however, the response is dominated by specific intra- or inter-molecular vibrations and rotations, similar to those that occur with infrared radiation in infrared spectroscopy. Imaging has been successfully demonstrated in both the microwave/millimetre-wave and infrared regions. In view of the known spectral capabilities of terahertz pulses, terahertz-pulse imaging is an important extension of these proven methods.

In 1995 Martin Nuss and co-workers at AT&T in the US became the first to demonstrate terahertz-pulse imaging. They used terahertz pulses to look through the packaging of a semiconductor chip to see the detailed metal tracks inside, and to determine the water content of tree leaves. The technique was extended to produce a 3-D map of the dielectric interfaces inside a ballpoint pen and floppy disk, together with a impressive map of the temperature gradient across a flame. Meanwhile, Xi-Cheng Zhang and co-workers at the Rensselaer Polytechnic Institute in New York produced equally impressive images of terahertz emitters and ladybirds! Indeed, terahertz-pulse imaging holds enormous promise for a wide variety of applications.

The most straightforward ways to produce a terahertz pulse image are by translating an object through the beam or by scanning the beam across it. This allows us to make a variety of *in situ* measurements in various applications. Alternatively, we can eliminate the need for either the sample or the source being moved by using a charge-coupled device (CCD) camera, which effectively takes a terahertz snapshot of the object. Furthermore, each pixel contains information in both the time and frequency domains.

One of the main advantages of terahertz light is that a variety of common materials are transparent or semi-transparent in this frequency range. These include certain plastics, paper, cardboard and semiconductors, together with animal and human tissue. The list is not exhaustive, and indeed completing it is one of the pressing issues for the commercialization of terahertz-pulse imaging. At the Toshiba Research Laboratory in Cambridge, we have developed terahertz systems for imaging in a variety of non-medical areas. We have also successfully applied this technology for the first time to the imaging and diagnosis of diseased human tissue.

Of course, X-rays, MRI and ultrasound can also penetrate deep within the human body and inside many inanimate objects. These traditional methods have provided detailed images, which represent many years of effort by the imaging community. Currently terahertz-pulse imaging cannot compete head-to-head with these mature technologies because it is at an early stage of development. Applications of terahertz imaging have therefore focused initially on specific areas where terahertz pulses have unique capabilities.

In this respect, a major advantage of terahertz imaging is its diagnostic capabilities. For example, we can use the spectral information from terahertz pulses to distinguish between different types of soft tissue – such as muscle, fat and kidney – because each has a characteristic "fingerprint" (figure 2). In addition, some types of diseased tissue have different absorption features compared with healthy tissue.

Similar fingerprints are able to characterize many other substances. In the petroleum industry, for example, terahertz imaging could be used to identify kerosene (i.e. aircraft fuel) and measure its water content.

The power of terahertz imaging

One of the most significant advantages of terahertz imaging is its sheer versatility compared with other imaging techniques. This versatility derives from the number of contrast mechanisms available for constructing an image (see box on page 39). At the Toshiba Research Laboratory, we have produced 2-D "panchromatic" images using terahertz radiation that demonstrate the wide variety of potential medical and industrial applications of the technique.

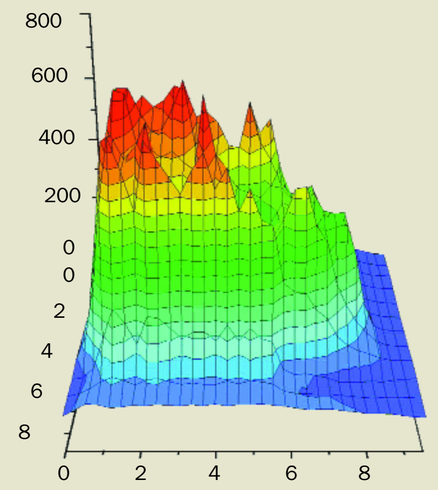
One of the most promising medical applications we have identified is dental imaging. Currently dentists try to identify if a patient has tooth decay using visual inspection or X-ray radiography, but this is difficult using either of these techniques. Terahertz-pulse imaging could detect the early stages of tooth decay. This early detection is of considerable importance, since it may be possible for a dentist to treat the decay without drilling, and perhaps even reverse the decay process.

In the most common form of tooth decay, called caries, the enamel or dentine is destroyed by acid in the mouth. This acid permeates the enamel coating surrounding the tooth and forms microscopic lesions that may eventually reach the dentine layer. These lesions can extend through the tooth without showing any visible signs at the enamel surface, thus making caries difficult to detect.

The disadvantage of visual inspection is that it cannot identify the earliest stages of tooth decay in many cases. Moreover, it is not quantitative and does not supply any appreciable diagnostic information. For example, the probability of detecting primary caries – the initial attack on a previously healthy tooth – is less than 40% using X-rays, and less than 20% for the decay associated with a filling.

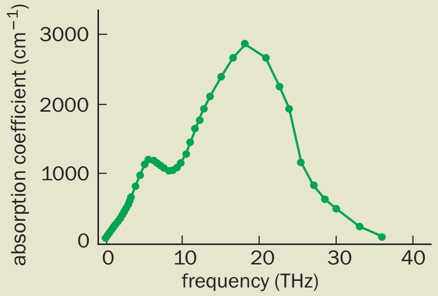
Panchromatic terahertz-pulse imaging may provide a means of detecting the early stages of caries (figure 3). Since lesions and cavities reduce the mineral content of the enamel and dentine, caries appears as regions of higher absorption in a panchromatic transmission image (figure 3*b*). Furthermore, the mineral content of enamel and dentine differs significantly, leading to a large difference in the index of refraction for the two types of tissue. The enamel and dentine layers can therefore be identified readily from the time-of-flight information (figure 3*c*). This example is a powerful illustration of how the different parameters that characterize a single terahertz data set can be manipulated to give different images, each containing different diagnostic information. These multiple-contrast mechanisms lead to enhanced sensitivity and selectivity in disease detection. Terahertz-pulse imaging could be extended to other dental applications, such as identifying periodontal disease – which affects the tissue surrounding the teeth – and assessing the condition of the soft tooth pulp.

4 Monitoring the softness of skin



A time-of-flight image of a section of pig skin reveals variations in the skin's thickness. We can construct the quasi 3-D image by plotting the time-of-flight at each pixel.

5 Watery signature



Water has two strong and broad absorption bands in the terahertz frequency range, at 6 THz and 19.5 THz. The absorption is particularly acute at this higher-frequency end of the spectrum.

Surface maps and water

Another powerful, yet relatively simple, application of terahertz-pulse imaging is to 2-D tomography – a scanning technique that allows us to reconstruct the dielectric layers buried within a solid structure. One of the earliest examples of 2-D tomography was demonstrated by Jon Young and co-workers at Ohio State University in the US using video-pulsed microwaves. More recently, Daniel Mittleman and colleagues at Rice University in the US constructed tomographic images using terahertz light.

Reconstructing the simplest of surfaces can have enormous commercial benefits in previously intractable problems. For example, forthcoming guidelines in the European Union and the US will stipulate that cosmetics companies must test the effectiveness of certain anti-aging products to justify any claims. Can the product reduce the number and depth of wrinkles in the skin? What are the chemical and structural effects of the agent on the skin? Terahertz-pulse imaging seems well suited to assessing the changes in the thickness and tomography of the skin, and can, in principle, measure any differences to within an accuracy of 1 μm or better (figure 4).

Terahertz imaging can also measure the absorption spectrum at each pixel, which could then be used to assess the effects of a reagent on the water content of the skin. Indeed, one of the strengths – and incidentally one of the weaknesses – of terahertz radiation is its sensitivity to water (figure 5).

In a typical terahertz-imaging system, the 100 nW pulses can penetrate 2–3 mm of moist dermal tissue. Similar penetration depths are possible using visible and near-infrared light.

However, the penetration depth for terahertz radiation can be considerably improved by increasing the power of the pulses and by tailoring the frequency for a specific application. Further advances in semiconductor engineering will improve the efficiency with which the visible light can be converted into terahertz radiation. These advances – combined with the use of more compact, affordable and powerful lasers – will lead to substantial gains in terahertz power, and thus in penetration depth.

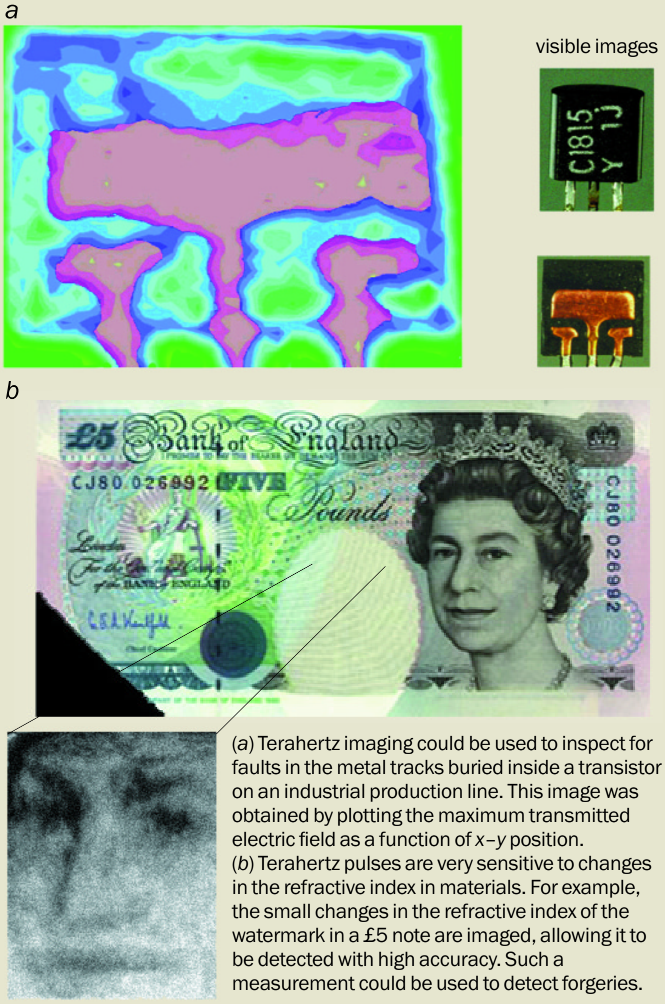
Currently, most terahertz pulses are produced in the 0.3–

The versatility of terahertz imaging

For every pixel measured we can form a variety of different images

- **Panchromatic-absorption image**. This is constructed by measuring the absorption coefficient, $\alpha(\omega)$, over the entire frequency bandwidth of the terahertz pulse. $\alpha(\omega)$ is determined by measuring the change in the amplitude of either the transmitted or reflected terahertz radiation.
- **Monochromatic-absorption image**. The absorption coefficient can also be measured at a fixed frequency or over a limited frequency range covered by the terahertz pulse.
- **Time-of-flight image**. The thickness of the object can be determined by measuring the time delay, D, for the radiation to travel through the object compared with free space. The thickness, t, is then calculated according to the simple relation $t = (n - 1)/Dc$, where n is the refractive index of the portion of the object sampled by the pulse and c is the speed of light.
- **Refractive-index image**. The average refractive index, at either a fixed frequency or over a range of frequencies, can be calculated from a portion of an object with uniform thickness using the simple relation above.

6 Non-medical applications



(*a*) Terahertz imaging could be used to inspect for faults in the metal tracks buried inside a transistor on an industrial production line. This image was obtained by plotting the maximum transmitted electric field as a function of x–y position.
(*b*) Terahertz pulses are very sensitive to changes in the refractive index in materials. For example, the small changes in the refractive index of the watermark in a £5 note are imaged, allowing it to be detected with high accuracy. Such a measurement could be used to detect forgeries.

2.7 THz frequency range, where the water absorption is strong. For applications in which water absorption is undesirable, we would benefit greatly by changing this frequency range. Given our current bandwidth – which peaks near 2.0 THz – we can still form reasonable images using terahertz light that has penetrated through 335 μm of water. But by shifting the central frequency of the pulse down to 0.3 THz, we would be able to construct images through approximately 1 mm of water.

Electro-optic sampling techniques have been developed to extend the frequency range of a single terahertz pulse from 100 GHz to 70 THz, a sizeable portion of the electromagnetic spectrum. Combining such techniques with higher powers may provide a route to imaging much deeper inside the body.

It is worth noting that the ability to determine hydration levels and form images is required in a wide range of disparate applications. Terahertz imaging may also be used to diagnose burns and detect tumours due to the variations of water and other substances. And in non-medical applications, measuring the water content in products is potentially lucrative. In the food-processing industry, in particular, there are requirements to determine the fat and water content in packaged foods. Another diverse application includes producing detailed images of watermarks to detect forgeries (figure 6).

Safety and cost

Terahertz imaging has a number of other attractions compared with conventional imaging techniques. It is believed to be a safe and non-invasive alternative to techniques such as X-rays. This is because terahertz radiation is non-ionizing and interacts primarily with the low-frequency vibrational and rotational states of molecules, resulting in small modifications of nuclear motion that are not usually accompanied by changes in the electronic state.

Moreover, the average power levels used in terahertz-pulse imaging are low, typically in the nanowatt to microwatt range. These power levels are unlikely to increase significantly as the brightness or electric field rises, mainly because short (<200 fs) terahertz pulses are used. As such, it is unlikely that significant tissue heating and detrimental thermal effects will be encountered. Indeed, work is planned on irradiating DNA samples to ensure that there are no unexpected non-thermal effects.

Another attractive feature of terahertz-imaging systems is their cost, currently estimated to be between £100 000 and £300 000 depending on the capability. This compares very favourably with the price of MRI systems – which typically cost several million pounds, and have similar capabilities and safety advantages in some applications – and is comparable with many diagnostic ultrasound systems.

Approximately 85% of the price of terahertz systems is wrapped up in the ultrafast visible laser. However, the price of ultrafast lasers has fallen in the past few years as the systems become more compact, reliable and user-friendly. All of these factors will contribute to the commercial acceptance of terahertz imaging and diagnostics.

Future outlook

So how successful is terahertz technology likely to be? The answer, at least in commercial terms, depends critically on establishing a so-called killer application. Such an application is one in which terahertz radiation provides a safer, cheaper alternative to other imaging methods, and is so versatile and sensitive that it leaves other techniques in the pale. Another aspect of the killer application is that it is financially lucrative.

There are two areas, however, that may play the deciding role in determining the killer application of terahertz-pulse imaging. One is the penetration depth of the radiation, which will dictate in part what items can be imaged and/or diagnosed. Because there is little opportunity now (or in the near future) to supplant X-rays and magnetic resonance imaging to view deep inside the body, terahertz imaging should concentrate on those applications that it alone can address. Our work has uncovered a wealth of areas, particularly in the medical field, that could be addressed using technology that is currently available, or will be in the near future. These include dental and dermatological imaging, and endoscopic imaging inside the body. For non-medical applications, spectroscopic examination of biofluids together with imaging of semiconductors, processed foods and a variety of other materials for quality assessment and control are important and viable areas.

The second important point for commercial focus is price. The development of alternative systems of coherent terahertz radiation, both in terms of bright sources and sensitive detectors, would dramatically increase the number of markets for the technology. Different types of solid-state lasers and optical techniques may eliminate the relatively expensive pulsed visible laser in the near future, and will reduce cost by a factor of 5 or 10, putting terahertz technology within the grasp of many mass markets.

Physicists and engineers developed the technologies associated with X-ray, magnetic resonance imaging, ultrasound and other conventional imaging techniques, and have been responsible for their success in dramatically enhancing our quality of life. In the same way, terahertz imaging was originally developed by physicists as a research tool and is now a viable imaging and diagnostic technique. The principle commercial concerns that limit the wider proliferation of this technology – the penetration depth and the cost – require additional innovation from physicists, at a very fundamental level in some cases. If the past history of imaging technology is anything to go by, physicists will rise to the challenge.

Further reading

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