

Cutting-edge terahertz technology

Research into terahertz technology is now receiving increasing attention around the world, and devices exploiting this waveband are set to become increasingly important in a very diverse range of applications. Here, an overview of the status of the technology, its uses and its future prospects are presented.

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Terahertz (THz) radiation, which lies in the frequency gap between the infrared and microwaves, typically referred to as the frequencies from 100 GHz to 30 THz, has long been studied in fields such as astronomy and analytical science. However, recent technological innovation in photonics and nanotechnology is now enabling THz research to be applied in many more sectors. Today, THz technology is finding use in an increasingly wide variety of applications: information and communications technology (ICT); biology and medical sciences; non-destructive evaluation; homeland security; quality control of food and agricultural products; global environmental monitoring; and ultrafast computing among others.

There have been numerous recent breakthroughs in the field, which have pushed THz research into the centre stage. Milestones include the development of THz time-domain spectroscopy (THz-TDS), THz imaging, and high-power THz generation by means of nonlinear effects. These techniques are often far superior to conventional tools for analysing a wide variety of materials.

Photonics has led the way to the realization of many important THz devices such as the development of the quantum cascade laser (QCL) and the uni-travelling-carrier photodiode (UTC-PD), for example. The QCL provides a powerful continuous-wave (c.w.) THz source, and the UTC-PD uses a photomixing technique to produce sub-THz waves for wireless communication.

In addition, continual advances in the performance of high-frequency electronics have also benefited terahertz technology. State-of-the-art semiconductor and superconductor logic circuits are already operating at frequencies greater than 100 GHz (0.1 THz). At the same time, recently developed solid-state electronic devices such as resonant tunnelling diodes and THz single-photon detectors, as well as conventional electronic devices, such as Schottky barrier diodes (SBDs), continue to move into the THz range.

THz technology is now growing rapidly in many independent fields. Readers can find the details of the historic achievements and fundamental principles of THz research in many reviews^{1–7}. Here, the focus is on describing the important progress of THz technology — in particular, THz sources, detectors, systems and application-oriented achievements — and a discussion of the future prospects.

TERAHERTZ SOURCES

Figure 1 summarizes THz-emission power as a function of frequency. There are three major approaches for developing

THz sources. The first is optical THz generation, which has spearheaded THz research for the past few decades. The second is the recently developed THz-QCL, which is still being refined. The third uses solid-state electronic devices, which are already well established at low frequencies.

Optical generation of THz radiation using lasers, either pulsed or c.w., falls into two general categories. The first involves generating an ultrafast photocurrent in a photoconductive switch or semiconductor using electric-field carrier acceleration or the photo-Dember effect. In the second category, THz waves are generated by nonlinear optical effects such as optical rectification (limited to femtosecond laser excitation), difference-frequency generation (DFG) or optical parametric oscillation. The current nonlinear media receiving attention are GaAs, GaSe, GaP, ZnTe, CdTe, DAST (diethylaminosulfur tetrafluoride) and LiNbO₃, although research to find more effective materials continues.

Femtosecond lasers are used mainly for THz-TDS whereas other lasers are used for frequency-domain spectroscopy (FDS) and imaging systems. Figure 2 gives an example of a THz source, an injection-seeded THz-wave parametric generator (IS-TPG)⁸, which can produce a peak power of as much as 1 W, a linewidth of less than 100 MHz, and tunable frequencies from 0.7 to 3.0 THz. Enhancing the output power, shrinking the size of systems and enabling high-speed frequency sweep and data acquisition are among the current objectives for future sources. Another intriguing optical THz generation method, ambient air-plasma generation, is drawing considerable attention at present, particularly with respect to security applications. Here, an intense pulsed laser induces an air plasma⁹, which emits THz radiation; that is, the source is remotely controlled by a distant, focused, laser beam.

Recent advances in nanotechnology have also led to the development of semiconductor-based THz sources: the THz-QCL. The first QCL was developed in 1994¹⁰ and had a lasing frequency of about 70 THz, which, after much research, was followed by a demonstration¹¹ at 4.4 THz in 2002. The THz waves are emitted by means of electron relaxation between subbands of quantum wells; for example, between several few-nm-thick GaAs layers separated by Al_xGa_{1-x}As barriers, whose emission blocks are serially connected to generate THz waves. The three main operational methods are referred to as ‘bound-to-continuum’¹², ‘interlaced’¹³, and ‘resonant phonon’¹⁴. These differ in the mechanism by which the electrons scatter after the THz-photon emission from the population inversion. The c.w. emission power is in the tens of milliwatts as depicted in Fig. 1b. At present, lasing frequencies as low as 1.59 THz (Q. Hu, private communication) have been achieved in a resonant-phonon-assisted THz-QCL, (see Fig. 3) and 1.39 THz when a magnetic field is applied¹⁵. The current research objectives are to reduce the threshold currents and lasing

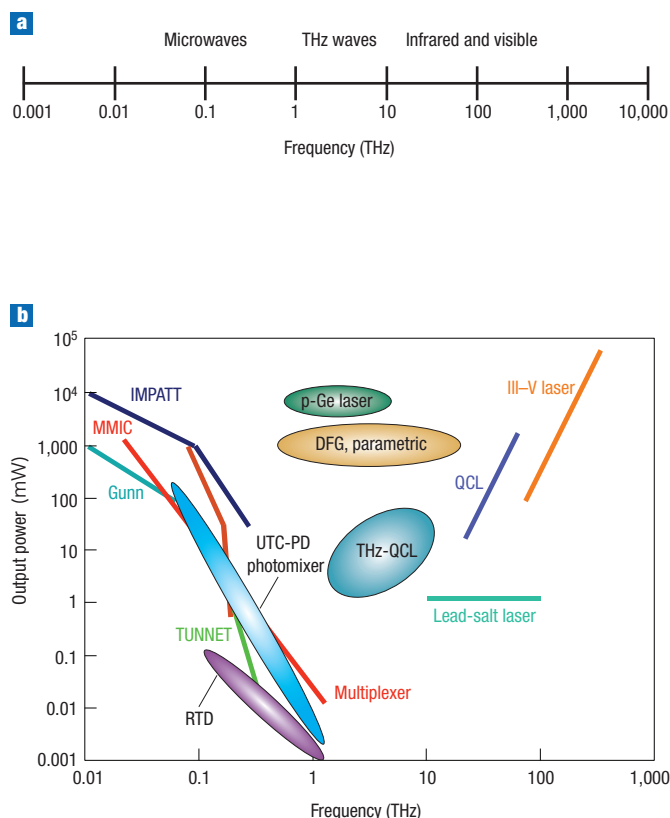


Figure 1 Welcome to the terahertz region. **a**, A schematic showing the THz region within the electromagnetic spectrum. Although there is no strict definition of what qualify as THz waves it seems reasonable to consider the region between 100 GHz and 30 THz. **b**, THz-emission power as a function of frequency. Solid lines are for the conventional THz sources; IMPATT diode stands for impact ionization avalanche transit-time diode, MMIC stands for microwave monolithic integrated circuit, TUNNET stands for tunnel injection transit time and the multiplexer is an SBD frequency multiplier. Ovals denote recent THz sources. The values of the last two are indicated by peak power; others are by c.w. power.

frequencies, increase the operational temperatures and the range of tunable frequencies and to obtain higher-quality beam modes. To achieve these goals new designs of structures, gratings and waveguides are being studied intensively.

Solid-state electronic devices have now entered the low frequency end of the THz regime. Among them, the UTC-PD, which produces high-quality sub-THz waves by means of photomixing, is one of the more promising devices. The THz waves in a UTC-PD are generated by the optical beat of the light from two different wavelength laser diodes (LDs) with the emission frequency being defined by the difference between the two wavelengths. The emission is typically tunable up to 1.5 THz. Maximum c.w. output powers of 20 mW and 10 μ W have been achieved¹⁶ at 100 GHz and 1 THz, respectively, using LDs operating at 1.55 μ m. Examples of current applications include sub-THz wireless communication and photonic local oscillators.

Many researchers have also studied other sources^{17,18}, such as resonant tunnelling diodes (RTDs), THz plasma-wave photomixers, and Bloch oscillators. Recently, an RTD was used to successfully demonstrate emission over 1 THz, made by coupling

the third harmonic of the fundamental 342 GHz oscillation with a slot antenna¹⁹. Conventional SBD multiplexers have also been used in astronomy as a local oscillator at sub-THz frequencies. The whisker contact SBD has now been almost totally replaced by planar diodes, which are built using advanced semiconductor technology, such as air-bridge contact fabrication²⁰.

Large facilities for generating high-power THz beams, such as the free-electron laser²¹ are also important for fundamental science. Among them, the p-germanium laser, which can emit a peak power of 10 W in the frequency range from 1 to 4 THz, is particularly useful as a spectroscopy source²².

DETECTORS

THz detectors for time-domain systems were intensively studied in the 1990s, and now GaAs grown at low temperature is often used as a photoconductive antenna. Alternatively, electro-optic sampling techniques are available for ultrawideband time-domain detection. One can measure over 100 THz using a 10-fs-laser and a thin nonlinear crystal such as GaSe (ref. 23). The time-domain method is explained below. DTGS (deuterated triglycine sulphate) crystals, bolometers, SBDs and SIS (superconductor-insulator-superconductor) junctions are widely used as conventional THz detectors^{24–26}, and their performance has improved steadily. Further, a THz single-photon detector has been developed using a single-electron transistor²⁷.

SPECTROSCOPY AND IMAGING

Since the early 1990s, the introduction of mode-locked femtosecond lasers has significantly expanded the use of time-domain spectroscopy for material research²⁸. The principle of THz-TDS, as depicted in Fig. 4a, starts with a femtosecond laser producing an optical-pulse train. Each pulse separates into two paths. One reaches the THz emitter, such as a photoconductive antenna, semiconductor wafer or nonlinear crystal, where the optical pulses are transformed into ultrashort electromagnetic pulses. These then propagate in free space, and are focused onto an ultrafast detector, such as a low-temperature-grown GaAs photoconductive switch or an electro-optic crystal. The other part of the pulse is also delivered onto the detector after passing through a time-delay stage.

The detector measures the electric-field amplitude of the electromagnetic waves. Examples are shown in Fig. 4b, one is from the surface of a p-InAs wafer²⁹, which has been reported as a strong THz emitter, the other waveform is from a DAST crystal³⁰. Their Fourier-transformed spectra extend to 4 and 8 THz respectively (Fig. 4c). A 10-fs-laser allows the components of waves exceeding a frequency of 100 THz to be detected either by electro-optic sampling²³ or a photoconductive switch³¹.

In the case of transmission spectroscopy, a specimen is placed in the THz beam, and the change in the waveform is measured. Generally, the amplitude decreases and the waveform is delayed in the time domain. Comparison of the waveforms with and without the sample enables the complex refractive index of the material to be estimated, which gives various parameters, such as the dielectric constant, conductivity and surface impedance. The strong advantage of TDS is the elimination of the uncertainty associated with the determination of the phase from a Kramers-Kronig analysis. A THz-FDS can be built in a similar way to conventional spectrometers, such as a Martin-Puplett interferometer, by using a high-power THz source, or, for some spectroscopic applications, a simple transmission configuration works well³².

THz imaging^{33–38} also has many practical applications. THz waves are transmitted through many materials that block light, and give much higher imaging resolution than microwaves. The

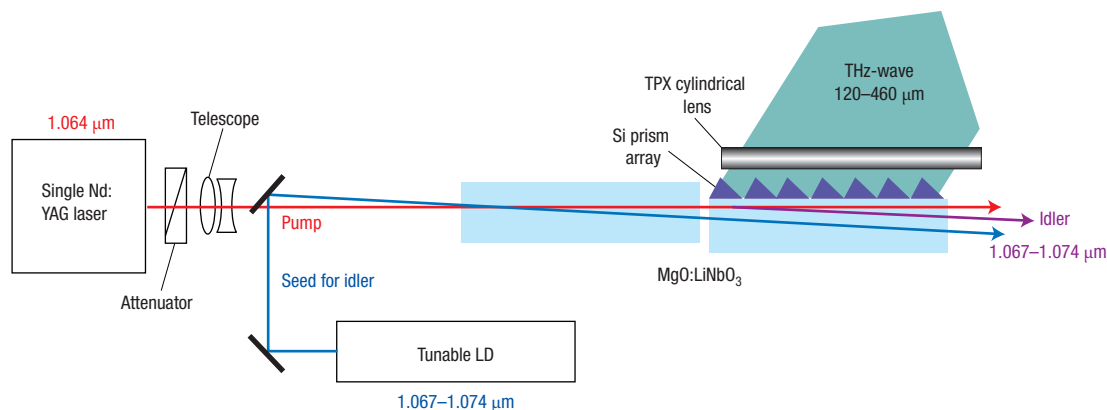


Figure 2 Typical design of a solid-state source of tunable THz waves based on an injection-seeded THz-wave parametric generator (IS-TPG). The pump laser was a single longitudinal mode Q-switched Nd:YAG laser (1.064 μm), and the seed for the idler was a c.w. Yb-fibre laser (1.070 μm) or tunable laser diode (1.067–1.074 μm). Generated THz waves in LiNbO₃ are coupled with a silicon prism array and emit into free space through a TPX (poly-methyl-1-pentene) cylindrical lens.

THz beam can be focused using mirrors or lenses, and the images are obtained by scanning the beam. The imaging resolution is defined by the beam diameter at the THz wavelength. Higher-frequency components give better imaging resolution, but it is still not sufficient for nanoscale applications. A wide variety of methods have been attempted to overcome this limitation. Scanning near-field microscopy, with a modulated THz field, is one of the potential imaging systems from which nanometre-scale resolution is expected^{39,40}.

A laser THz-emission microscope (LTEM) is a promising tool^{41,42} for visualizing the dynamic response of materials and devices. Various materials can emit THz radiation through carrier generation. As the spatial resolution is defined by the laser beam diameter, submicrometre resolution is easily obtained, and can be improved using near-field measurements. Applications for LTEM have included investigation of supercurrent distribution, ferroelectric domains, and microprocessors. Furthermore, a scanning probe-type LTEM has recently been developed⁴³.

Various types of passive THz camera are also under development using photoconductor arrays, bolometers, SBDs with photonic crystals⁴⁴, superconducting tunnel junctions²⁶, for example. There are advantages and disadvantages to all of them, with much room for improvement and further development.

THZ APPLICATIONS

The principle applications for THz technology are divided into two categories: sensing and communications. Terahertz TDS and FDS are advanced analytical technological methods applicable to various materials. Using these tools provides unprecedented sensing capabilities for many research fields including biology, pharmacy, medical science, industrial non-destructive evaluation, material science, environment monitoring, security, astronomy and basic science. There are numerous examples^{45–47} in every field: DNA chips, skin-cancer diagnosis, large-scale integrated (LSI) circuit testing, explosives inspection and many others.

Information and communications technology also benefits from THz technology where it is used for a wide range of applications, such as wireless communication, high-speed data processing and satellite communication. The synergy of these research areas will generate a wealth of applications in,

for example, biometrics — the development of recognition techniques based on unique human physical or behavioural traits — using a THz camera, massive sensor networks and selective communication.

BIOLOGICAL, MEDICAL AND PHARMACEUTICAL SCIENCES

Since being established in the early 1990s, THz-TDS has been applied to many materials^{48–51}, including biomolecules, medicines, cancer tissue, DNA, proteins and bacteria. One frequently asked question is how is the information provided by THz spectroscopy different from infrared spectroscopy? One striking example is the ability to observe, with THz spectroscopy, intermolecular vibrations⁵² in some chemicals and organic molecules where the intramolecular mode appears in the infrared region. It is expected that intermolecular vibration studies will elucidate the dynamics of large biomolecules, and thus increase knowledge of the human body.

Another application is the classifying of polymorphs in medicine⁵³. Figure 5 shows THz-absorption spectra of barbital (a hypnotic drug), which changes its form on heat treatment⁵⁴. One can easily recognize the clear differences in the TDS spectra, whereas in the Fourier-transformed far-infrared (FT-FIR) data they can hardly be distinguished.

The study of proteins, DNA and other biomolecules and various cancers is of grave importance. Although, at present, difficulties are anticipated in practical applications, it has been reported that hybridized and denatured DNA can be distinguished, so that research can progress towards the development of label-free DNA chips. These and other similar biomolecules are also now being studied.

There have been several studies on the diagnosis of cancer using THz spectroscopy and imaging⁴⁶. The absorption of THz waves is sensitive to polar molecules, such as water, and unusual reflections from cancer tissue, which has different hydration levels from normal tissue, can be detected. Skin cancer is visualized by the reflection of THz-TDS at a lateral and vertical resolution of about 350 μm and 40 μm , respectively and a penetration depth of about a millimetre can be realized. As the THz transmittance of ice is much higher than that of water, cancer cells can also be detected in frozen tissue.

One of the major hurdles for biomedical applications lies in the poor THz transmittance of polar liquids, which makes it difficult to extract information about solute molecules.

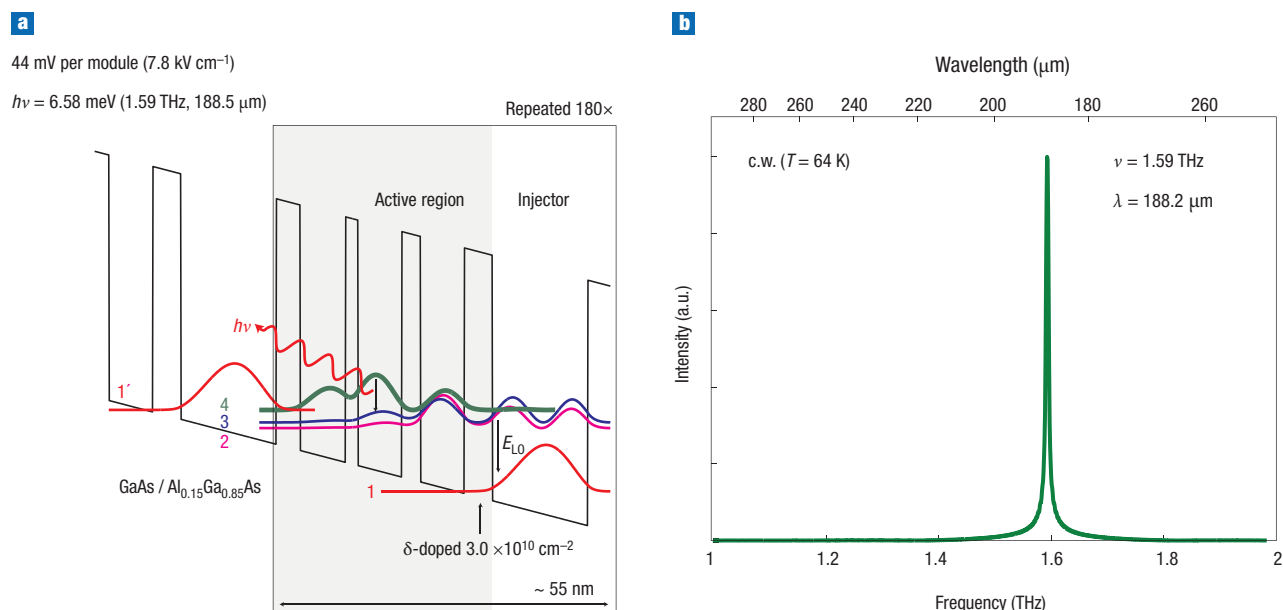


Figure 3 Semiconductor source of THz waves based on a QCL design. **a**, Conduction band profile of a GaAs–AlGaAs quantum-well-based QCL. Terahertz waves are generated in the active region by electron relaxation from band 4 (green) to band 3 (blue), followed by the relaxation from band 3 to band 1 (red) by means of longitudinal-optical (LO) phonon mode scattering. h is Planck's constant and ν is the frequency. **b**, c.w.-emission spectrum above threshold at a temperature of 64 K. The emission frequency corresponds to 1.59 THz, which is the shortest QCL lasing frequency at present.

One breakthrough that has been discovered and developed is THz time-domain attenuated total reflection spectroscopy (TD-ATR)⁵⁵. A Dove prism is inserted into the THz beam, which generates travelling evanescent waves on the prism surface. The change in the reflection and phase due to the interaction between the THz waves and the sample placed near the prism are evaluated by comparing the TDS signals with and without samples. One can then study the dynamics of the solute molecules as a function of characteristics such as hydration⁵⁶. The hydrated water molecules are bound to the surface of the biomolecules with a relaxation time limited to of the order of 10^{-7} s, as opposed to several picoseconds in bulk water. The evaluation of the dielectric constant at THz frequencies enables us to estimate the hydration number, which indicates that TD-ATR is an important technique for biomedical applications.

SEMICONDUCTOR AND OTHER INDUSTRIAL APPLICATIONS

There are numerous examples^{57–60} of material evaluations, many of which could lead to new industrial applications, including inspection of silicon solar cells, nanocomposites, polymer films and dielectric films. Terahertz technology will reach even greater prominence if it can be developed for use in the semiconductor industry. Terahertz TDS is already capable of evaluating various semiconductor wafer properties^{61,62}, such as mobility, conductivity, carrier density and plasma oscillations. The imaging ability is a particularly strong attribute; for example, one can visualize the doping level of ion-implanted silicon wafers.

In the semiconductor industry, fault analysis is one of the most important issues in the development of the sophisticated next-generation LSI circuit. LTEM might provide a breakthrough technology for localizing the fault point. Figure 6 shows an example of the examination of metal-oxide-semiconductor field-effect transistors (MOSFETs)⁴⁷. Three of them, indicated by

circles, were intentionally damaged using a focused ion beam, and the comparison with a normal MOSFET (b) in the THz-emission image (c) clearly shows the differences, indicating defects in the damaged MOSFETs.

Terahertz imaging has also been used, as the best non-destructive evaluation method now available, to inspect the foam insulation used for the space shuttle. As it can detect defects in the heat-insulation panels, such as voids⁶³, it has been adopted as the routine inspection method. The distinct features of THz waves, such as their sensitivity to water, could be used to control food and agricultural products, for example damage to fruit can be evaluated and the water content in vegetables monitored.

SECURITY

Every explosive and narcotic has a distinct signature in its THz spectra, making THz spectroscopy valuable for security applications. These signatures allow the identification of many chemicals through their transmission spectra. In particular, it is possible to distinguish illegal drugs and explosives from benign compounds. As waves below 3.0 THz can generally pass through envelopes, materials can be identified using THz multispectral images and component spatial-pattern analysis without having to open the mail⁶⁴ (Fig. 7a).

Terahertz QCLs can also provide a real-time THz-imaging tool. Figure 7b shows a demonstration of fingerprint imaging from a polyethylene wedge. The distance between the grooves in the print is about 500 μm . This technique can also be used to read a letter in an envelope. More real-time monitoring examples can be found at ref. 37.

The development of a focal-plane array for a THz camera has also been of great technological importance. A THz camera can image objects through fog and smoke, regardless of the background illumination. For instance, a passive sub-THz camera made up

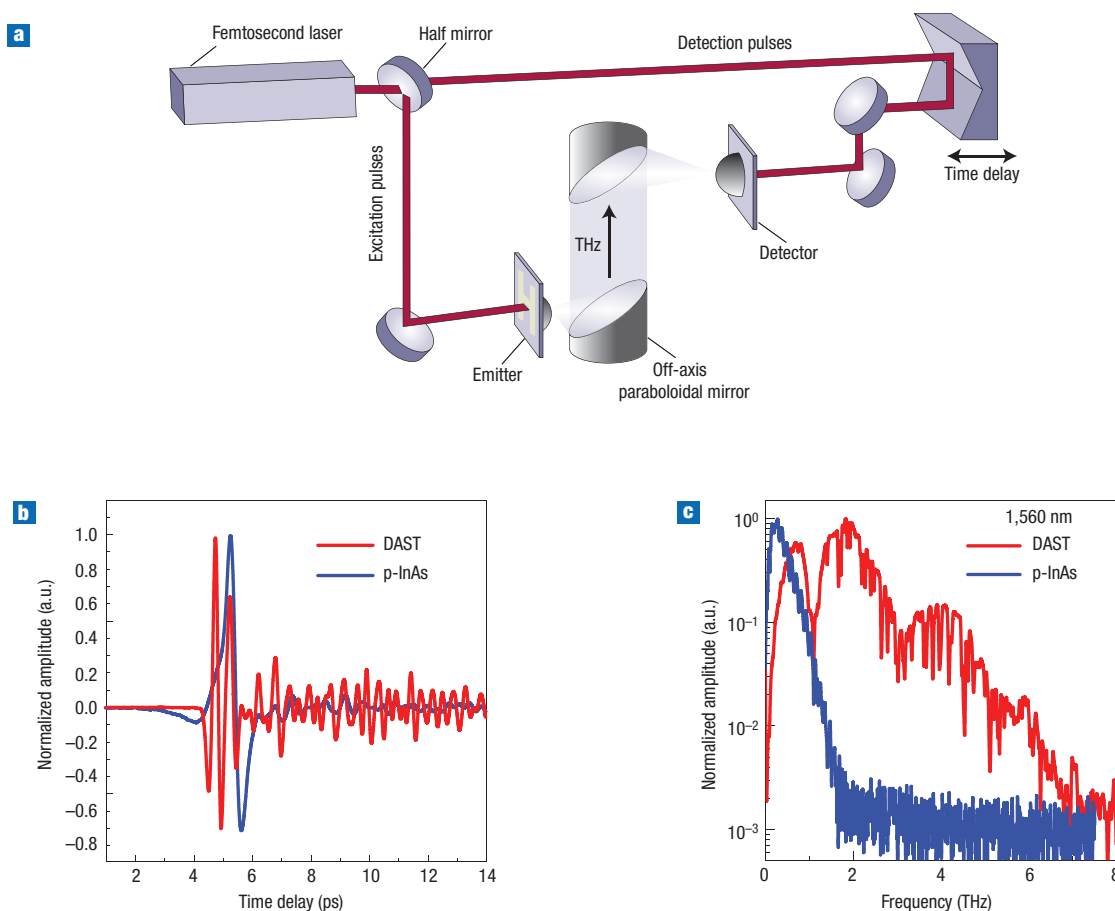


Figure 4 Typical set-up for THz-TDS. **a**, Schematic of THz-wave generation and a detection system in the time domain using a femtosecond laser. The emitters are typically made from a GaAs photoconductive switch, semiconductors (InAs, ZnTe, GaSe) and nonlinear crystals (DAST, GaP). The detectors are often a GaAs photoconductive switch or electro-optic crystals (ZnTe, GaSe, GaAs, DAST). **b**, Examples of THz pulses emitted from p-InAs (ref. 91) and DAST (ref. 92) and detected by LT-GaAs photoconductive antenna. A femtosecond fibre laser was used as an optical source with a wavelength of 1,560 nm (ref. 93). **c**, Corresponding Fourier-transformed spectra on a logarithmic scale in the frequency domain. The absorption dip at 1.1 THz in the DAST spectrum is attributable to the phonon resonance of the anion and cation.

of an SBD array with a silicon photonic-bandgap crystal and a heterodyne detection method operating at a frequency of about 500 GHz is now ready for use in airport security. An active THz camera would suit even more applications, including biometrics.

Some security applications may require remote detection over a significant distance. As THz waves are sensitive to the environment, active sensing performs poorly in this role. Recently, remote-controlled THz generation using an air plasma has started to garner attention. An intense femtosecond laser beam can be focused near the object to generate an ambient plasma, which produces THz waves, and the reflection from the target is detected in a similar way to THz-TDS⁶⁵.

Hazardous-gas detection using THz sensing is also expected to become more common. For instance, a new detection technique for detecting gases, such as carbon monoxide, is required at fire sites where infrared gas detection is sometimes blocked, for example by concrete walls.

INFORMATION AND COMMUNICATION TECHNOLOGY

There is a large potential market for THz applications within the ICT sector. Information flow in modern society has burgeoned rapidly, and the carrier frequency of the signal has increased

on a continual basis. Fibre-linked optical communication is successfully growing, realizing data rates exceeding a terabyte per second, whereas the data rate of wireless communication remains relatively poor. The realization of THz-ICT would be of great benefit here by enabling high-performance wireless connections for applications such as: communication in rural areas; communication between buildings during disasters; high-vision data delivery for telemedicine and outdoor entertainment; hot spots for movies; and even instant data transmission between Formula 1 cars and support crews.

The breakthrough of sub-THz-wave generation by UTC-PDs is now helping realize such possibilities. Already 120-GHz-band millimetre-wave wireless links have been developed and are undergoing field tests; these operate at over 10 Gbit s⁻¹ (ref. 66) — fast enough to download a typical movie in seconds. In the near future, the carrier frequency will be doubled, and 40 Gbit s⁻¹ will be achieved. Higher frequencies still could be useful for indoor wireless communication.

The development of various basic circuits for THz-ICT is also progressing rapidly. Integrated single-flux-quantum circuits have realized an 8-bit shift register, which is operative at 120 GHz (ref. 67). All-optical switching by means of InGaAs–AlAs–AlAsSb-coupled

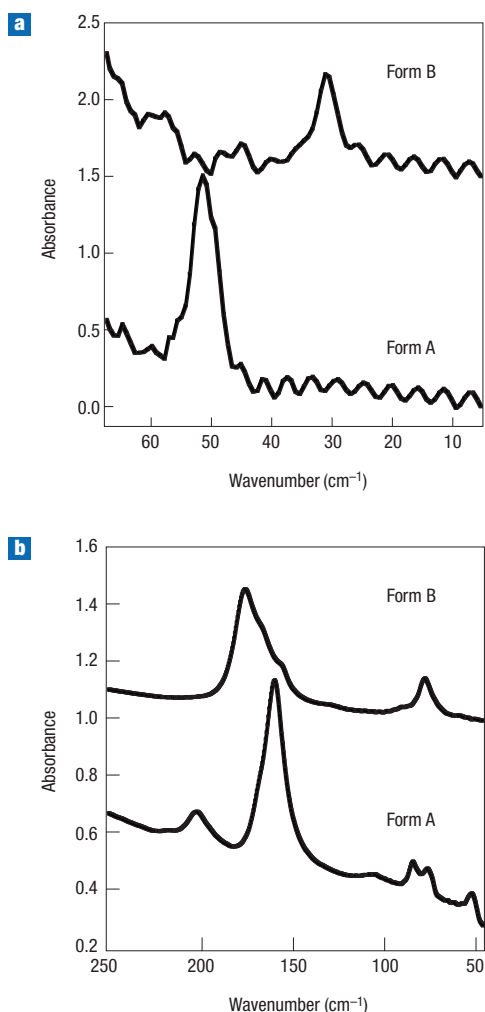


Figure 5 THz-absorption spectra of barbitol. **a**, THz-TDS. **b**, FT-FIR. The polymorph sample (form B) was obtained by heating original barbitol (form A) at 160 °C for 30 minutes.

quantum wells has been proven to operate at a frequency of 1 THz (ref. 68). Other, more conventional, approaches using high-electron-mobility transistors (HEMTs) and heterojunction bipolar transistors (HBTs) continue to progress⁶⁹.

Although it is important to develop elements such as THz mirrors, modulators and waveguides, activity in this area is still limited. Recently, omnidirectional mirrors have been made from polypropylene and high-resistivity silicon⁷⁰ and approaches for modulating the THz waves are also being developed⁷¹. Such components for real THz-ICT applications are expected to attract further research.

The delivery of THz waves is important for both ICT and sensing applications. There are many approaches, including plastic fibre and polycarbonate waveguides. Interestingly, bare metal can transport THz pulses along its surface with virtually no dispersion and low attenuation⁷²; this is explained in Sommerfeld's description of an electromagnetic wave propagating along the surface of a cylindrical conductor. This flexibility allows us to make components such as beam splitters. Recently, special photoconductive antennas with radial symmetry have been

developed to enhance the coupling coefficient of the THz waves to cylindrical-wire waveguides⁷³.

EARTH AND SPACE SCIENCE

THz technology is now important in the environmental monitoring of our Earth. The Earth Observing System Microwave Limb Sounder (EOS-MLS), onboard NASA's Aura satellite, was launched in July 2004. It has been monitoring atmospheric chemical species (OH, HO₂, H₂O, O₃, HCl, ClO, HOCl, BrO, HNO₃, N₂O, CO, HCN, CH₃CN, volcanic SO₂), cloud and ice as well as making temperature and other measurements⁷⁴. A heterodyne radiometer measures the thermal emission at frequencies of around 118, 190, 240 and 640 GHz and 2.5 THz. The major objectives are to obtain information about ozone chemistry to better understand global warming, to quantify aspects of how the atmospheric composition affects climate and to study aspects of pollution in the upper troposphere.

An international astronomy facility, the Atacama Large Millimetre Array (ALMA) is now under construction on a 5,000-m-high plateau near the Atacama Desert in Northern Chile. ALMA is a gigantic array of 64 12-m-high precision antennas and 16 super-high precision antennas, equivalent to an antenna 14 km in diameter at maximum. It will detect electromagnetic waves passing through atmospheric windows between 30 and 950 GHz. The monitoring could help probe the invisible dark universe, including newborn galaxies as far as 13 billion light years away, the birth of a new solar system, or extraterrestrial organic molecules.

The infrared astronomical satellite AKARI was launched on February 2006. It has a 68.5-cm telescope cooled to 6 K, and monitors the wavelength range from 1.7 to 180 μm (refs 75,76). Its principle objectives are to obtain information to help understand the formation and evolution of galaxies, and to investigate the formation processes of stars and planetary systems. AKARI is equipped with two instruments: the Far-Infrared Surveyor (FIS) for far-infrared observations and an infrared camera (IRC) for near and mid-infrared observations. The IRC and FIS cover the wavelengths from 1.7 to 14.1 μm and from 50 to 180 μm, respectively. Fresh THz images of galaxies and nebula are available in ref. 77.

BASIC SCIENCE

Because THz waves have energies between a few meV and a hundred meV, THz spectroscopy has been used, along with optical index analysis, to probe the low-energy carrier dynamics in various electronic materials, such as superconductors⁷⁸. Furthermore, THz emission itself can be used for spectroscopic study because various electronic materials emit THz waves through the ultrafast modulation of photo-excited carriers. A variety of materials, such as high-T_c (critical temperature) superconductors, manganites, ferromagnetics and multiferroics have been examined using THz-emission spectroscopy^{79–82}. These activities indicate that THz-TDS is establishing a strong presence in material science.

The most distinguishing advantage of THz-TDS is that the dynamic behaviour of photo-excited carriers can be traced with a time resolution as fast as, or better than, 10 femtoseconds, which is shorter than the electron–electron scattering time in typical semiconductors⁸³. The temporal dielectric function in semiconductors just after photo-excitation can be evaluated by means of pump and probe THz-TDS. For instance, the change in the dielectric spectra unveils the build-up process of an electron–hole plasma in solids, which typically occurs within 100 fs. These kinds of measurements will open new areas of ultrafast science, such as the dynamic diagnosis of chemical and biological reactions and, possibly, transient quantum physics.

Terahertz pulses also provide an opportunity to study the nature of light. Scale-model experimentation provides a platform

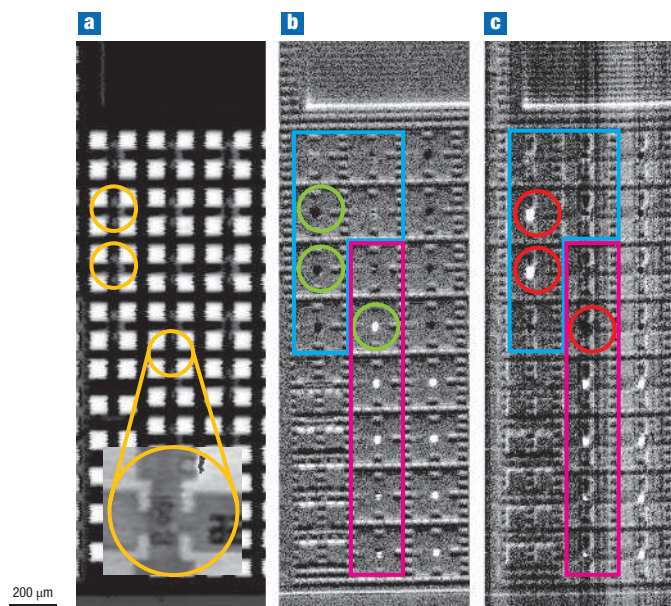


Figure 6 MOSFET damage detection by LTEM. **a**, Laser-reflection image of a series of MOSFETs. Three MOSFETs as indicated by yellow circles have interrupted connection lines cut by a focused ion beam. One MOSFET is shown magnified in the large yellow circle. **b,c**, LTEM images of the normal and damaged sample, respectively. The negative and positive amplitude of the THz waves, when the delay time is fixed at the time which gives maximal intensity, are denoted by black and white respectively. The blue and red boxes indicate p- and n-type respectively.

to study the behaviour of light at longer wavelengths. Examples include the study of multiple diffraction and propagation in random media^{84,85} and the group-velocity anomaly of propagating light. The development of electromagnetic metamaterials in the THz-frequency range is also drawing considerable attention^{86–88}.

Other THz devices can be applied to exploring solid-state science. Scanning THz single-photon counters image the THz emission from quantum Hall electron systems to study local dynamics⁸⁹ and THz-QCLs are available for the spectroscopic study of the cyclotron resonance in semiconductors⁹⁰. These applications are still in the early stages of research. Terahertz technology promises a rich fund of new science in the near future.

PROSPECTS AND STRATEGY

Figure 8 presents a roadmap for some specific applications. Outdoor wireless communication should soon be available at a rate of 40 Gbit s⁻¹ without any difficulties, and may increase to 100 Gbit s⁻¹. The performance of indoor use, which is technically easier than outdoor use, would strongly depend on the application and its market. One can detect hazardous materials and narcotics, but it will take some time to develop a speedy, cost-effective system. The high-quality THz camera required for biometrics is already under development. Food and agricultural applications are definitely in need of a low-cost system and this may be realized using the parametric THz system. It will be necessary to determine which materials can be evaluated by THz waves in biomedical applications and this research should focus on theoretical studies such as intermolecular interactions. Special tools for THz sensing, such as DNA chips, are also needed. Industrial semiconductor applications require speedy, cost-effective systems and, in addition, the resolution of the

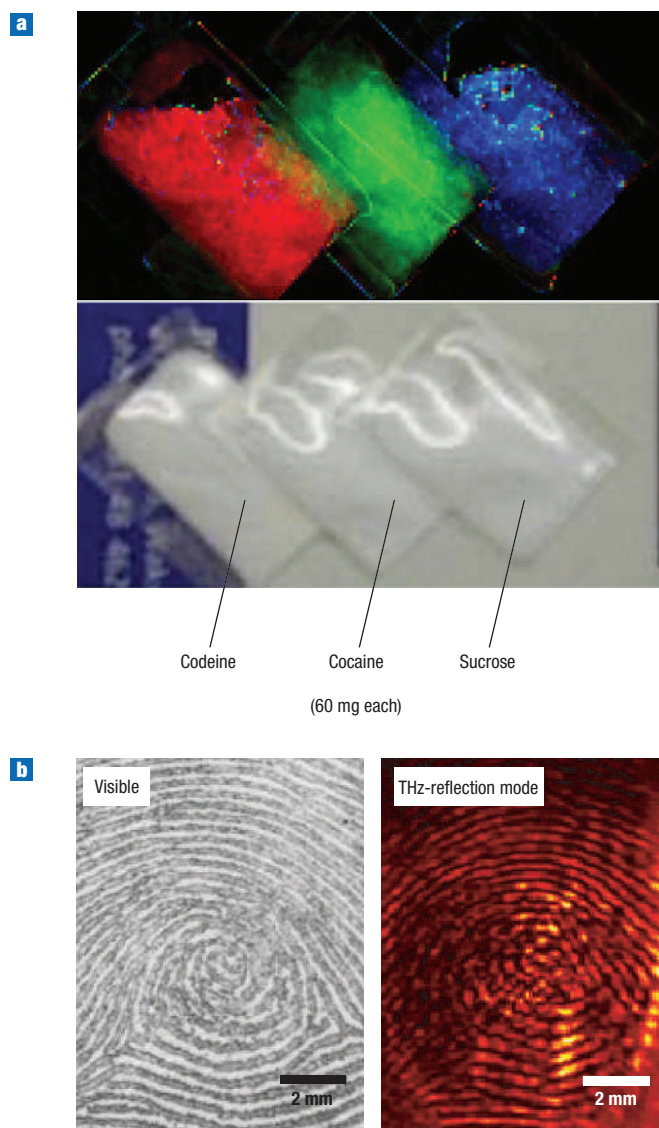


Figure 7 Terahertz narcotic detection **a**, THz image (upper) and photograph (lower) of specimens under inspection. Three kinds of powder (codeine, cocaine and sucrose) are hidden in the envelope and can be distinguished using THz-TDS by their own THz signatures. Image courtesy of Kodo Kawase, RIKEN. **b**, Visible frequency thumb print and real-time THz reflection mode image of the print. The real-time THz images can be obtained by a 4.3-THz QCL and a 320 × 240 microbolometer focal-plane array at an acquisition rate of 20-frames per second.

LTEM must be improved for LSI inspection. THz-QCL will be available for gas sensing, which would lead to the observation of air pollution.

Activities and efforts geared towards the implementation of THz applications are unbounded. For instance, THz sensor networks, weatherproof traffic and road-monitoring systems, satellite communication to keep information confidential (THz waves cannot pass through the astrosphere) and many other medical, food, agricultural and industrial applications are important potential targets.

In order to realize such applications, it is obvious that we need higher-power THz sources, more sensitive THz sensors, and more functional devices and materials. Among the more critical

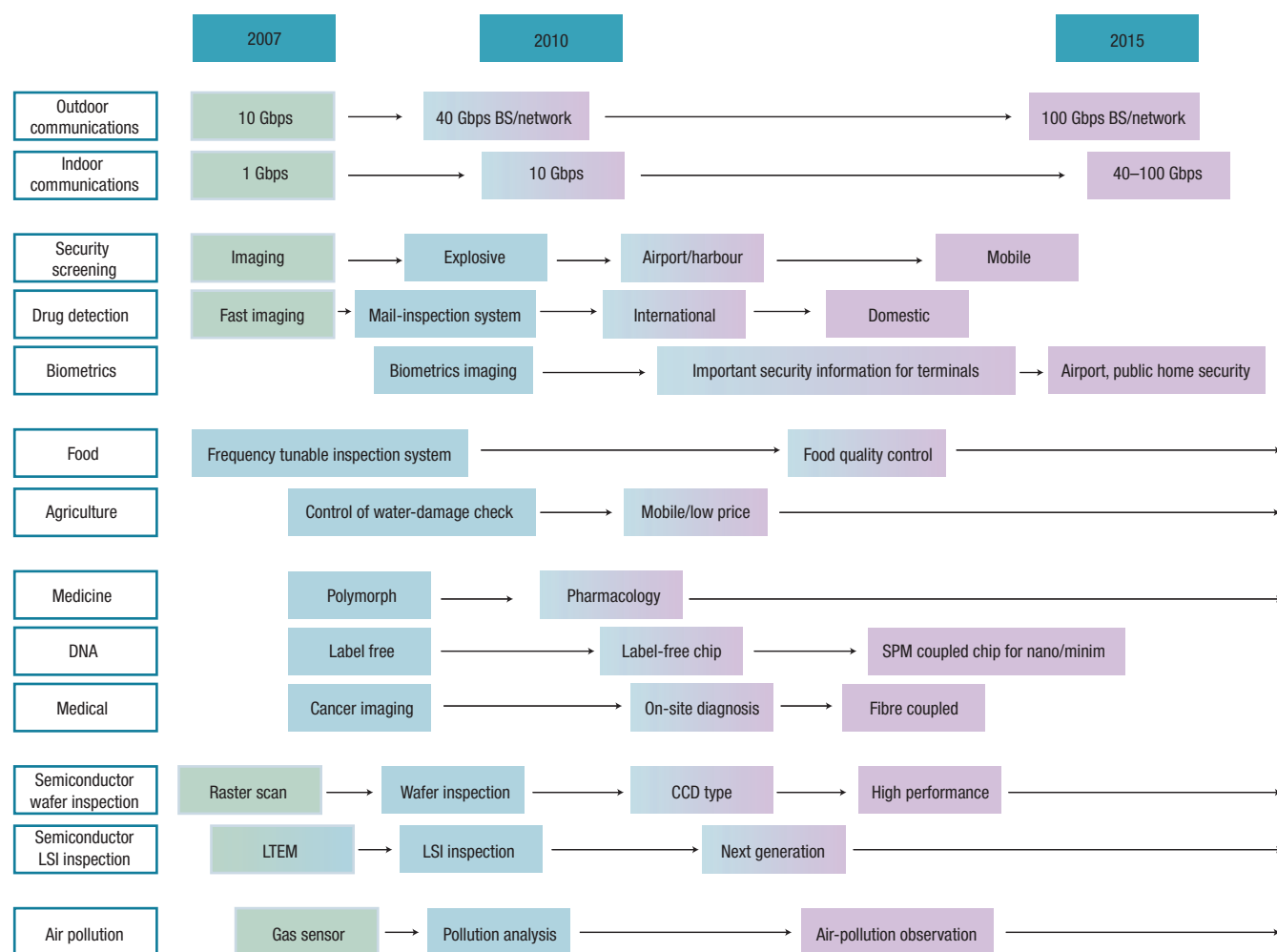


Figure 8 Expected roadmap for some THz applications. BS/network stands for broadcast station, fixed wireless-access network, storage station; SPM stands for scanning probe microscopy; and nano/minim stands for nanoscale and/or ultratrace amounts of DNA.

objectives is the creation of an extended database for various materials in the THz frequency range. Other essential issues to be solved include the development of a THz measurement system, THz standards and electromagnetic compatibility. Although we have a long task-list to conquer this frontier, it seems to be within reach. We can foresee a historic breakthrough for science and technology through THz research. It is also noteworthy that THz research is built on many areas of science and the coordination of a range disciplines is giving birth to a new science.

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