Terahertz Technology

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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. Finally, I will give a brief description of an active metamaterial device capable of efficient real-time control and manipulation of THz radiation. The device consists of an array of gold electric resonator elements (the metamaterial) fabricated on a semiconductor substrate. The metamaterial array and substrate together effectively form a Schottky diode, which enables modulation of THz transmission by 50 per cent, an order of magnitude improvement over existing devices.

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.

One can find the details of the historic achievements and fundamental principles of THz research in many reviews[1–3]. 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. THz technology is now growing rapidly in many independent fields.

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 meta-material based THz generating devices based on Schottky barrier diode (SBD) designs are showing a lot of promise.

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 and $LiNbO_3$, 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)[4], 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 plasma[5], which emits THz radiation; that is, the source is

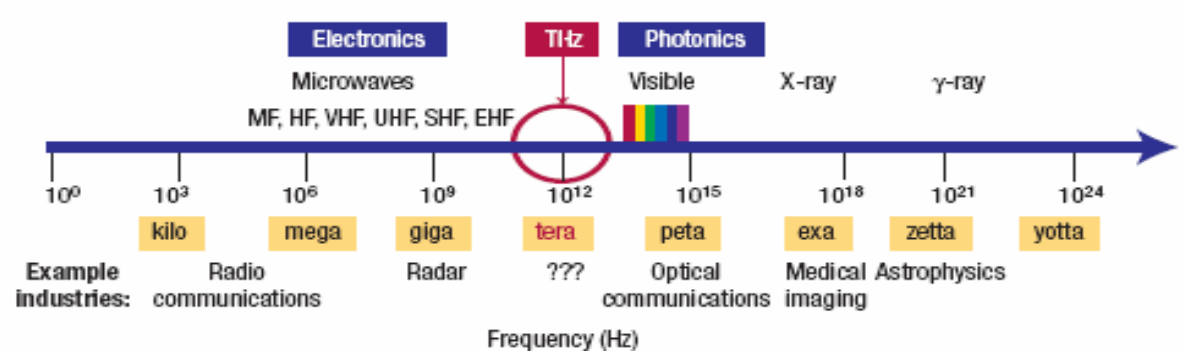

Figure 1: A schematic showing the THz region within the electromagnetic spectrum. Although there is no strict definition of what qualify as THz waves it seems reasonable to consider the region between 100 GHz and 30 THz..

controlled by a distant, focused, laser beam.

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 μW have been achieved[6] at 100 GHz and 1 THz, respectively, using LDs operating at 1.55 μm. Examples of current applications include sub-THz wireless communication and photonic local oscillators. Many researchers have also studied other sources 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 antenna[7]. 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 fabrication[8].

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 research. The principle of THz-TDS, as depicted in Fig. 2a, 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. 2b, one is from the surface of a p-InAs wafer, which has been reported as a strong THz emitter, the other waveform is from a DAST crystal. Their Fourier-transformed spectra extend to 4 and 8 THz respectively (Fig. 2c). A 10-fs-laser allows the components of waves exceeding a frequency of 100 THz to be detected either by electro–optic sampling or a photoconductive switch.In the case of transmission spectroscopy, a specimen is placed in the THz beam, and the change in the 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 well.

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

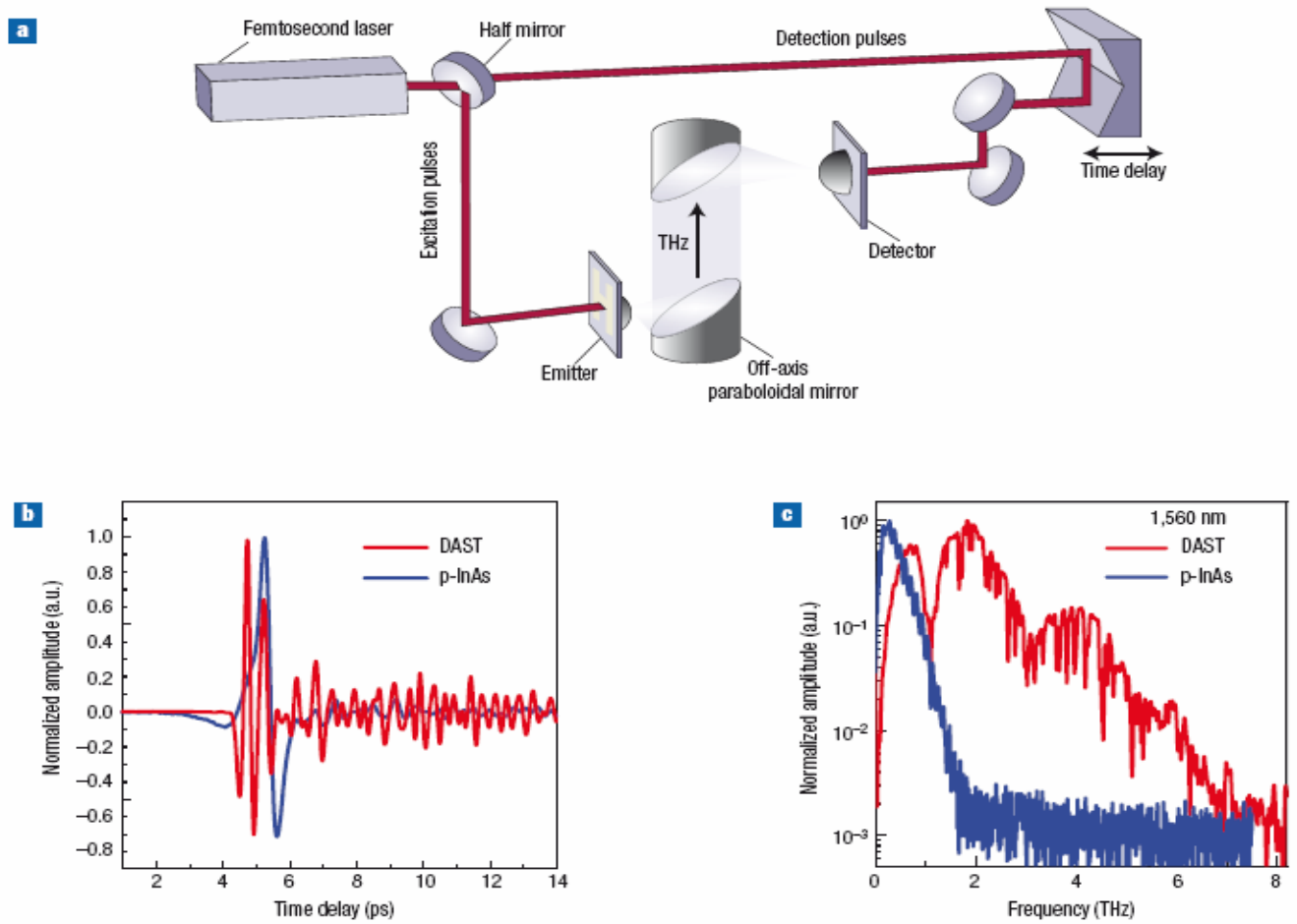

Figure 2: Typical set-up for THz-TDS. a, Schematic of THz-wave generation and a detection system in the time domain using a femtosecond laser. The emitters are typically made from a GaAs photoconductive switch, semiconductors (InAs, ZnTe, GaSe) and nonlinear crystals (DAST, GaP). The detectors are often a GaAs photoconductive switch or electro–optic crystals (ZnTe, GaSe, GaAs, DAST). b, Examples of THz pulses emitted from p-InAs and DAST and detected by LT-GaAs photoconductive antenna. A femtosecond fibre laser was used as an optical source with a wavelength of 1,560 nm. 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.

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.

SEMICONDUCTOR TERAHERTZ GENERATION

To realize the full potential of terahertz radiation, more sophisticated techniques for its generation, manipulation and detection are required. In a recent Nature issue, Chen et al[13] have come up with a unique THz generating device based on a metamaterial. They report the development of an efficient, electrically driven modulator for terahertz signals that functions at room temperature. This work builds on exciting developments in the field of metamaterials. These are materials engineered to have electromagnetic responses that are impossible in naturally occurring materials, such as a negative refractive index. The refractive index of a material, n, is a measure of the speed of light in the material, and is given by $n=(\mu\varepsilon)^{1/2}$, where μ is the material's 'permeability' to magnetic fields, and ε its 'permittivity' to electric fields. All naturally occurring materials have positive μ; transparent materials have positive ε, too. In these normal materials, therefore, the refractive index is a real and positive number. In 1968, a Soviet physicist showed that a hypothetical material with negative ε and μ would also have a real refractive index, meaning that light waves could propagate through the material, but would behave as though its refractive index were negative. This material would have unusual and potentially valuable properties. A flat slab of negative-index material, for example, would focus light in much the same way as a curved slab of ordinary material (a lens),

but with a smaller focal spot.

Although negative-index materials do not violate any laws of physics, the absence of a medium with negative μ confined the idea to the realm of speculation. But in the late 1990s, scientists found that, by assembling a collection of appropriately designed metallic structures, a material can be fabricated that has both negative ε and negative μ for incident electromagnetic radiation of a particular frequency. Furthermore, if the metal structures are each much smaller than the wavelength of the incident radiation, the radiation interacts with them not individually, but collectively, according to their average properties. These are the engineered materials now known as metamaterials. Engineering a material with negative ε was easy: this equates to opacity, a property of all metals for incident radiation below a certain frequency. It was necessary to show only that a discrete set of thin metallic structures could mimic this property of the bulk metal. The more difficult task was achieving a negative μ. It turned out that this could be done using a pair of concentric metallic rings with gaps that prevent current from circulating. Because these rings are both capacitors (they store electric charge) and inductors (they induce magnetic fields that self-sustain any current flowing through them), the presence of gaps leads to a resonant response, with charge accumulating alternately on one side of the gap and then the other, sloshing back and forth through the rings rather as a mass vibrates back and forth on a spring. At frequencies near the characteristic frequency of this resonant electron flow, ε and μ can vary dramatically as a function of frequency. Indeed, either one can become negative if the resonance is strong enough.

The development of the split-ring-resonator concept was significant not only because it permits a negative refractive index, but more generally because it represents a new technique for 'designing' the optical response of a medium. The first experimental demonstration of a negative index, along with nearly all research into metamaterials until now, was performed in the microwave regime. This region encompasses gigahertz frequencies below the terahertz regime, with wavelengths of several millimetres or longer. It was almost immediately recognized, however, that the approach could be extended into the shorter-wavelength, terahertz regime simply by shrinking the size of the individual metallic components so that they remained smaller than the incident radiation's wavelength. At 1 THz, this is 300 μm, so the fabrication of a negative-index medium requires the technically challenging construction of three-dimensional objects with micrometre-scale features. Two-dimensional patterns on that scale, on the other hand, can be easily generated using conventional photolithography, and these patterns can be designed to exhibit a strong resonance in either ε or μ at any frequency of interest. Chen et al.1 use the split-ring-resonator concept as the basis for a metamaterial that provides a resonant response in ε — although not a negative refractive index — in the terahertz range. Furthermore, they have shown that this resonance can be externally controlled, and therefore can be exploited as a modulator for controlling the transmission of terahertz electromagnetic radiation.

The principle of this device's operation is simple and elegant (Fig. 3). An array of sub-wavelength metallic ring resonators is deposited on top of a thin, lightly doped semiconductor layer and illuminated with a beam of terahertz radiation. The electrons in the semiconductor substrate effectively shortcircuit the gap in the split rings, driving the capacitance of the rings to zero and damping their normal resonant response. But when a negative voltage is applied to the metal structures, the electrons in the substrate beneath are repelled away from the gap. As electrons become depleted in the gap, current can no longer flow effectively and the gap behaves as a capacitor, storing electric charge. In this case, the resonance of the ring structure re-emerges, which gives rise to a pronounced change in the optical properties of the array at frequencies near its resonant frequency. The authors' results are impressive. At the design frequency, the on–off transmission ratio of this device is about 0.5 — more than ten times better than state-of-the-art, electrically operated modulators in this frequency range. The new design is simpler to fabricate, and the modulator works at room temperature. This excellent performance comes from the exquisite sensitivity of a metamaterial's response to the precise properties of its resonant substructures. The ability to electrically switch the properties of a metamaterial by fabricating it on a semiconductor substrate provides a new method for active control of terahertz devices. Naturally, challenges remain. Most obviously, larger on–off transmission ratios will be required for many applications. The modulation speed, which is only a few kilohertz, must be increased significantly. The authors point out that both of these difficulties can be addressed by optimizing both the pattern of the metal structures and the properties of the substrate. The properties of the device are also dependent on the direction of the electricfield vector (the polarization) of the incident radiation: the resonant behaviour of the split rings relies on this electric field driving current across the gaps, all of which are oriented in one particular direction. Designs of future devices may seek to eliminate or alternatively exploit this polarization sensitivity. Finally, one can imagine a structure for which not only the transmitted intensity, but also the resonant frequency, is externally controllable.

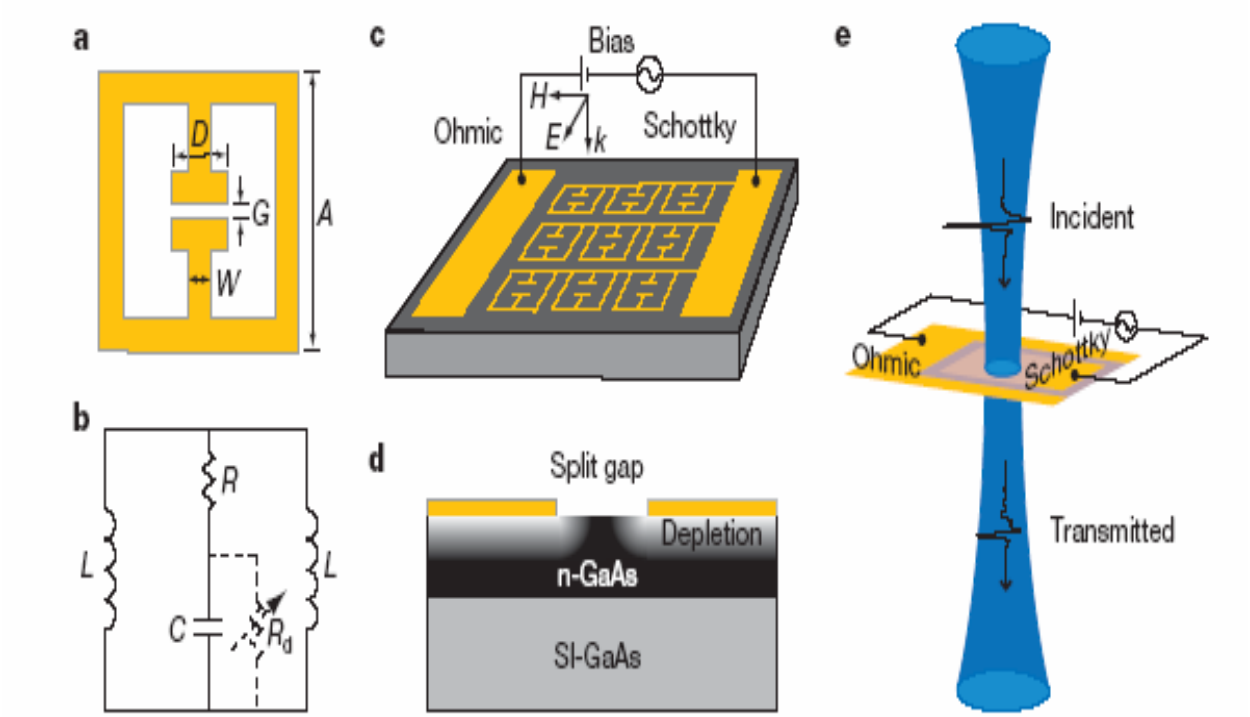

Figure 3: Experimental design of the active THz metamaterial device. a, Geometry and dimensions of the THz metamaterial switch/modulator: A536 mm, G52 mm, D510 mm andW54 mm. b, An equivalent circuit of the metamaterial element, where the dashed variable resistor corresponds to loss due to the substrate free carrier absorption within the split gap. c, The metamaterial elements are patterned with a period of 50 mmto form a planar array of 535mm2. These elements are connected together with metal wires to serve as a metallic (Schottky) gate. A voltage bias applied between the Schottky and ohmic contacts controls the substrate charge carrier density near the split gaps, tuning the strength of the resonance. Orientation of the incident THz wave is indicated and the polarization of the electric field, E, magnetic field,H, and wave vector, k, are shown. d, Diagram of the substrate and the depletion region near the split gap, where the grey scale indicates the free charge carrier density. e, Experimental configuration for THz transmission measurements through a fabricated device. The black curves show the measured time-domain waveforms of the incident and transmitted THz pulses when a reverse gate voltage bias of 16V is applied to the device and the THz electric field is polarized perpendicular to the connecting wires.

SUMMARY

Industrial semiconductor applications require speedy, cost-effective systems like the one Chen and his colleagues developed. 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.

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