

Perspective: Terahertz science and technology

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Perspective: Terahertz science and technology

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The field of terahertz science and technology has been an active and thriving research area for several decades. However, the field has recently experienced an inflection point, as several exciting breakthroughs have enabled new opportunities for both fundamental and applied research. These events are reshaping the field, and will impact research directions for years to come. In this Perspective article, I discuss a few important examples: the development of methods to access nonlinear optical effects in the terahertz range; methods to probe nanoscale phenomena; and, the growing likelihood that terahertz technologies will be a critical player in future wireless networks. Here, a few examples of research in each of these areas are discussed, followed by some speculation about where these exciting breakthroughs may lead in the near future. *Published by AIP Publishing.* <https://doi.org/10.1063/1.5007683>

INTRODUCTION

In the last 30 years, the terahertz (THz) portion of the electromagnetic spectrum has become a focus of active research. This spectral range is often approximately defined by the lower limit of 100 GHz (roughly speaking, the frequency above which vector network analyzers become challenging and expensive) and the upper limit of 10 THz (roughly speaking, the lowest frequency available from a conventional lead salt laser diode). Although long recognized as a promising regime for both fundamental and applied physics, the field remained relatively small through the 1980s. Of course, there were many important and notable contributions during this period, of which it is possible to list only a few here. Gebbie and co-workers developed the electrical discharge-pumped THz gas laser¹ in the 1960s, followed shortly thereafter by the demonstration of optically pumped THz gas lasers.² Button and colleagues coupled far infrared sources to a magnet, pioneering THz magneto-optics.³ Shen and colleagues pioneered the generation of THz signals via nonlinear optics in the early 1970s.^{4,5} Several groups developed advanced techniques for infrared spectroscopy.^{6–8} A small but tightly knit community developed, with an annual conference and even a prize (the Kenneth J. Button Prize,⁹ initiated in 1990) for forefront research accomplishments in the field of long-wavelength science and technology. Nonetheless, the many technological challenges associated with both generation and detection of radiation in this range limited worldwide research efforts, and gradually inspired the widespread use of the phrase “terahertz gap.” This phrase referred to both the sensitivity of typical detectors¹⁰ and the power available from typical sources.¹¹ It was intended to capture the general notion that, while technological development had proceeded rapidly at both lower (microwave) and higher (infrared and optical) frequencies, thus dramatically lowering the barrier for accessing and using these frequencies, the THz range had

not experienced such rapid progress. As a result, the barrier to entry for new research groups remained high.

In the late 1980s, the field witnessed the invention of a new spectroscopic tool that would lead to a significant jump in activity. Several groups, notably Auston at Bell Labs and Grischkowsky at IBM, developed methods for using femto-second laser sources to both generate and detect freely propagating THz pulses.^{12–15} This proved to be an inflection point, as it dramatically lowered the barrier for new researchers, especially with the decreasing cost and complexity of commercial femtosecond laser systems. The number of groups employing terahertz time-domain spectroscopy (THz-TDS) grew from just a few in 1990 to several dozens by 2000. THz science began to spread more broadly into research areas outside of solid state physics, including the chemical^{16–18} and biological^{19,20} sciences. At the same time, new THz sources, such as THz quantum cascade lasers²¹ as well as integrated circuits based on silicon²² or III–V semiconductors,²³ began to emerge. Meanwhile, the use of THz-TDS to form images, first demonstrated²⁴ in 1995, inspired many to think more broadly about the applications of THz techniques outside of basic research, such as imaging^{25,26} and sensing.^{27,28}

In the intervening years, researchers in the THz field have continued to explore new physics and new applications.^{29–31} However, within just the last few years, THz research appears to have experienced a second inflection point, resulting from breakthrough developments on several fronts. Advances in techniques for generation and measurement have opened new realms of physics, for which terahertz techniques are ideally (and sometimes uniquely) suited. In addition, the number of companies participating in this technology space has grown substantially. The achievements of integrated THz sources and systems continue to accelerate, enabling many new applications. Numerous possibilities which were previously considered somewhat speculative, such as THz wireless communications, are now becoming increasingly realistic. In this Perspective article, I focus on a few of these recent developments, and on the implications for the future of the THz field.

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TERAHERTZ NONLINEAR OPTICS

There are many different ways to generate terahertz radiation. However, few of them are capable of generating the high peak intensities required for most nonlinear optics experiments. Time-domain sources, which usually rely on either photoconductive antennas¹³ or optical rectification in a nonlinear-medium,³² can produce very short pulses of terahertz radiation, but typically with very low pulse energy (e.g., perhaps 10 fJ per THz pulse). As a result, despite the sub-picosecond pulse duration, even a beam focused to the diffraction limit can typically achieve a peak intensity of only about 10^4 W/m² (corresponding to a peak electric field in the range of a few tens of V/cm). This is far below the threshold for driving nonlinear optical effects in any material. Other THz sources can produce higher average power—vacuum electronic sources such as gyrotrons can even reach into the megawatt range³³—but even in these cases, the achievable peak intensity is low because the pulse duration is long. With such systems, one can dump a lot of heat into a medium, but the realm of nonlinear optics remains largely out of reach. Conventional measurement techniques to elucidate dynamics in materials, such as pump-probe or hole-burning spectroscopy, cannot be performed with either low-power time-domain sources or high-power continuous-wave sources. As a result, for many years, THz experiments remained mostly stuck in the realm of perturbative or linear optics. At best, one could couple intense optical pulses with weak THz pulses to perform a time-resolved optical-pump, THz-probe measurement.³⁴ Here, a strong optical pulse induces a rapid change in the properties of a material. A controlled time delay later, a weak terahertz pulse probes the resulting photo-excited material. By measuring the terahertz pulse's interaction with the material as a function of time delay, dynamical information can be obtained. This technique, while powerful, still does not provide direct access to the fast dynamical processes associated with THz energy scales since the perturbation (the pump pulse photon energy) occurs far outside the THz spectral range. Early attempts to scale up the efficiency of THz generation, for example, by using large-aperture photoconductive³⁵ or electro-optic³⁶ emitters, were cumbersome and not easily scalable, and thus did not find widespread use. Other options require large user facilities, such as electron accelerators,³⁷ which are not readily accessible to most researchers.

This situation has changed very rapidly with the development of optimized techniques for THz pulse generation. Today, there are several such table-top techniques, two of which have been widely adopted by many labs around the world. The first of these is known as “tilted pulse-front generation,” first demonstrated by Nelson and co-workers.³⁸ This approach is conceptually similar to the traditional methods of THz generation via second-order nonlinear frequency conversion (optical rectification), but with an optimized non-collinear beam geometry to account for the very large difference between the phase velocity of the generated THz pulse and the group velocity of the near-infrared input laser pulse. The nonlinear medium is usually lithium niobate, which has a high second-order nonlinear coefficient but a large velocity

mismatch between the infrared and terahertz fields, necessitating a noncollinear geometry. If the pulse front of this incident wave is tilted at the appropriate angle with respect to its propagation direction, in order to match the angle of the THz wave front, then the conversion efficiency from optical to THz can be enhanced by orders of magnitude. Indeed, this and other similar nonlinear generation processes can even exceed the Manley-Rowe efficiency limit, as each incident near-infrared photon can produce more than one THz photon.³⁹ Using an amplified femtosecond laser, which now conventionally produce pulses with energy in the millijoule range, the generation of THz pulses with energy of a few microjoules is now typical in many laboratories, and even higher values are possible. This pulse energy corresponds to a peak THz electric field of hundreds of kV/cm at a diffraction-limited focus, which is easily large enough to access both $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities in many materials.³⁸

Almost concurrently with the development of the tilted-pulse-front approach, Zhang and co-workers described a second method for high-intensity THz pulse generation, which also makes use of amplified femtosecond lasers. This method, known broadly as THz air photonics,⁴⁰ involves focusing an intense femtosecond pulse, along with its second harmonic, in a gas (even in air at standard temperature and pressure). By carefully controlling the relative phase of the fundamental (e.g., 800 nm) and second harmonic (400 nm) waves, one can generate an asymmetric electric field pattern at the focus, and thereby induce strong second-order nonlinear effects including THz generation.⁴¹ This is not a phase-matched process, but since the nonlinear medium is a gas, one can scale the intensity of the input beam arbitrarily without concern about optically induced damage. Detection can also be accomplished using air as the nonlinear medium, via a process called air-biased coherent detection (ABCD).⁴² A strong (~ 500 V) DC bias is applied across the air region where the THz field interacts with the infrared femtosecond pulse, providing a built-in asymmetry to enable coherent (i.e., phase-sensitive) detection of the THz field via generated 2nd harmonic (400 nm) photons. THz air photonics spectrometers can provide both high peak intensity and remarkably smooth and broadband spectra of up to several tens of THz, traits which have proven to be very valuable for ultrabroadband spectroscopy.^{43–45}

Together, these two methods have initiated a wave of activity, opening up the new realm of THz nonlinear optics. Many examples of the power and potential of these new spectroscopic techniques have been discussed in the recent literature.^{46,47} Since the THz range of the spectrum is home to numerous fundamental excitations in solids, these breakthroughs offer the possibility to perform time-resolved nonlinear measurements that reveal new physics of many materials. For example, intense THz pulses can induce collective excitations in solids, such as charge density waves in high-temperature superconductors⁴⁸ or magnons in antiferromagnetic metal oxides.⁴⁹ Intense THz pulses can generate electron-hole pairs in semiconductors via impact ionization,⁵⁰ induce field emission from metals,^{51,52} and even cause irreversible material damage.⁵³ Other recent examples include terahertz-pump, terahertz-probe spectroscopy,^{54,55}

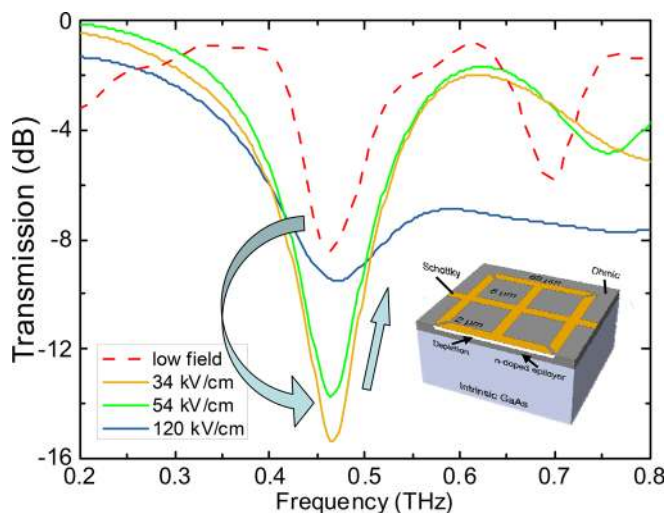


FIG. 1. The nonlinear transmission of a switchable terahertz metasurface. The inset shows a schematic of one unit cell of the metasurface, indicating the geometry of the split-ring resonator and the underlying substrate. The measured nonlinear transmission spectra exhibit an unusual non-monotonic variation with increasing THz field strength; the resonant transmission minimum first decreases, then increases, as the field strength increases. This is due to the interplay of competing nonlinear effects induced by the strong THz field.⁶⁷

and coherent spectroscopies such as THz photon echoes⁵⁶ and multi-dimensional THz spectroscopy.^{57–59} The generation of high-order harmonics, which underpins the field of attosecond spectroscopy and has previously been restricted solely to gas-phase targets, has now been extended to solid targets using intense THz sources.^{60,61} In structured or engineered materials such as metasurfaces, intense THz pulses can be used to control the properties through nonlinear interactions in the substrate.^{62–64} Interestingly, in switchable metasurfaces, where DC fields are used to control the linear optical transmission,^{65,66} an intense THz pulse can produce a peak field that is comparable to this externally applied DC field. This can lead to a fascinating interplay between competing effects of the two fields, a nonlinearity which has no obvious analog in conventional nonlinear optics (see Fig. 1).⁶⁷

One can envision many new experimental configurations, which will reveal new physics and new interactions. For example, the idea of coherent control using a properly shaped sequence of pulses, a long-standing goal in femtosecond science, may be more readily realized using terahertz pulses. It has been proposed that intense THz pulses can induce switching in ferroelectrics, by coupling directly to the relevant soft mode.⁶⁸ To study this and similar possibilities, new experimental configurations will be required, such as THz-pump, x-ray probe.⁶⁹ This will enable direct investigations of the role of THz vibrational modes in phase transitions in solids,⁷⁰ structural changes induced in liquids,⁷¹ or conformational changes in biomolecular systems or complexes.⁷² Another exciting proposal involves the use of THz pulses to induce field emission from metal tips. A THz-induced field emission source could be an extremely bright point-like source of photo-electrons,⁷³ the ideal tool for ultrafast electron diffraction experiments (see Fig. 2). Because the photo-generated electrons would be perfectly synchronized with the THz pulse used to create them, this pulse could also be used to compress and/or accelerate the electron bunch.⁷⁴ Other nonlinearities, familiar at optical frequencies, have yet to be investigated in the terahertz range. For instance, one may wonder if it is possible to observe either spatial or temporal soliton effects using terahertz pulses. What is the nature of solitons in the single-cycle regime, where the slowly varying envelope approximation fails? Intense THz pulses may provide the ideal tool for investigating unusual situations such as this.

It seems likely that the new techniques for high-intensity THz pulse generation will revolutionize THz science in much the same way that the development of femtosecond chirped-pulse amplification has revolutionized optics. Even more, high-intensity THz pulses offer access to a new regime of optical science, beyond just the novelty of the frequency range. Conventional methods for generating intense terahertz pulses offer a unique combination of features: a train of carrier-envelope-phase-stable pulses which can be detected coherently in the time domain (i.e., direct measurement of the electric field, not merely the intensity

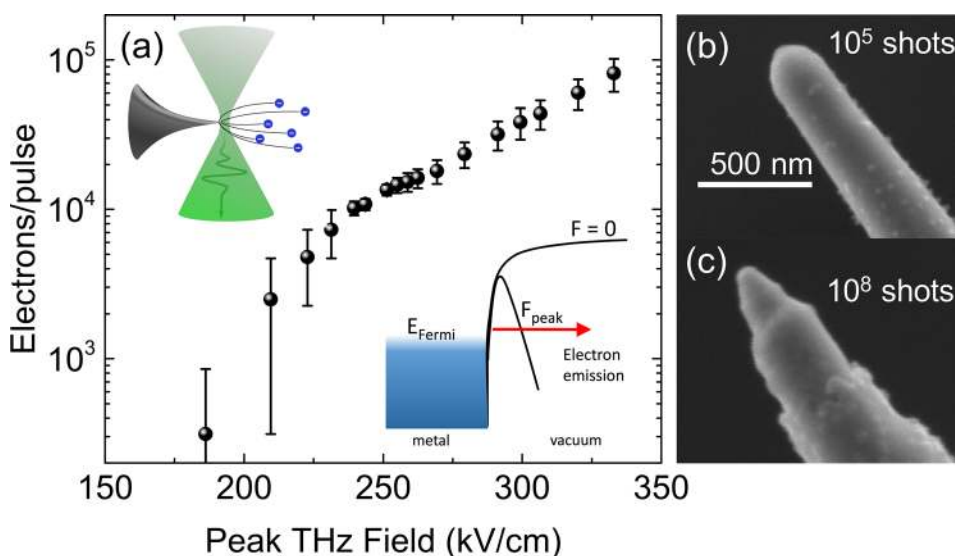


FIG. 2. (a) Number of electrons per pulse emitted from a tungsten nanotip for variable peak field strength of an incident single-cycle intense THz pulse. Inset (top left): Schematic of the field emission from a nanotip at the focus of the THz field. (bottom right) Sketch of the field emission process: the local field of the THz pulse bends the potential barrier, permitting tunneling directly from the Fermi surface of the metal. Electrons are subsequently accelerated by the same THz pulse. (b) and (c): SEM image of two tungsten nanotips illuminated by 10^5 and 10^8 intense THz pulses. A gradual reshaping of the tip can be seen, reducing the tip radius and improving the electron emission rate.¹⁷²

envelope), with a peak intensity high enough to induce non-linearity, and with the ability to influence or probe a sample using a synchronized pulse that is short compared to the intense field's cycle time. This unusual regime has been recognized as a frontier for novel nonlinear effects,^{61,75} going well beyond what can be accomplished in the visible and near-infrared.⁷⁶ Of course, the limits of achievable peak intensity in a single-cycle THz pulse are still not yet established. With higher pulse energy come even greater possibilities. Given the λ^2 scaling of the ponderomotive energy of free electrons, it is not unreasonable to speculate that much higher-order nonlinearities may be more readily accessible with ultra-intense single-cycle pulses.

TERAHERTZ NANOSCIENCE

Another exciting frontier in THz research lies in the area of nanoscience. For decades, many have recognized the challenge of coupling long-wavelength THz radiation to nanoscale phenomenon. The huge mismatch between the free-space wavelength and the size of the target renders this a thorny problem, even more so than the corresponding challenge in the optical regime. Yet, techniques borrowed from both the optical and microwave communities have recently begun to offer solutions.⁷⁷

As is well known from conventional optics, it is very difficult to focus a beam to a spot size that is much smaller than half the wavelength. As a result, most applications of terahertz imaging and sensing have been limited to those in which millimeter-scale resolution is acceptable.⁷⁸ There are, by now, numerous examples, most of which exploit the ability of terahertz radiation to penetrate through many dielectric materials, such as inspection of written materials^{79,80} or of artwork.^{81–83} One should expect the emergence of even more applications in areas such as non-destructive inspection and spectroscopic imaging, as the technology continues to mature.

Yet, there is a clear interest in imaging, sensing, and spectroscopy with better than millimeter resolution. Terahertz science lends itself remarkably well to a variety of methods for accessing the sub-wavelength regime. An illustrative example is laser terahertz emission microscopy. Here, an optical beam is used to generate terahertz radiation from the sample under study. By raster-scanning the optical spot (which can be small compared to the terahertz wavelength), one can form emission images with a resolution in the few-micron range, far better than conventional terahertz imaging.^{84–88} This technique has proven useful in a variety of applications involving non-contact characterization of surfaces and interfaces, such as the study of the surface potential at a Si/SiO₂ interface⁸⁹ and the characterization of surface defects in GaN.⁹⁰

The diffraction limit for terahertz imaging can also be overcome using near-field techniques that were initially developed for other frequencies. In the THz realm, the first attempt to apply conventional near-field methods for improved image resolution was through the use of a conical tapered aperture.⁹¹ In this case, the image resolution can be limited by the aperture size, not by the wavelength. This

THz measurement was similar in spirit to the common scanning near-field optical microscope (SNOM), except without the use of a dielectric waveguide to transport the radiation to the tapered aperture. It also suffers from similar limitations—the power transmitted through an aperture decreases very rapidly with the aperture diameter, so one quickly reaches a practical limit for the smallest useful aperture size. Even so, careful engineering of the aperture and coupled THz detector can push the achievable resolution for this general method into the few-micron range, corresponding to $\sim \lambda/100$.^{92,93} This approach has been used to make spatio-temporal maps of guided waves in waveguides⁹⁴ and to study sub-wavelength resonators.^{95,96} Figure 3 illustrates one example, in which a THz plasmonic resonance of a carbon microfiber (CMF) is imaged with $\sim 5 \mu\text{m}$ spatial resolution.

More recently, a different idea has come to the forefront, which can push the spatial resolution limit even farther. This technique, known as apertureless or scattering-type SNOM, was inspired by the pioneering work of Kawata,⁹⁷ Keilmann,⁹⁸ and Wickramasinghe,⁹⁹ which in turn built on similar ideas demonstrated in the microwave region of the spectrum using RF transmission lines.^{100,101} The essential idea is that the scattering of radiation from a tapered metal tip held close to a sample surface can contain spectroscopic information about the tiny region of the sample directly underneath the tip. Since the strength of the scattered field varies as a nonlinear function of the tip-sample separation, one can discriminate this small scattering contribution from the much larger background scattering by dithering the tip height and using lock-in detection.¹⁰² As a result, images can be formed by scanning the tip across the surface, with resolution determined by the radius of the tip. The scaling of the strength of the scattered field with decreasing tip radius is more favorable than that of aperture transmission, so much smaller regions of a sample can be investigated. These images can encode dielectric information about the sub-wavelength region, and can therefore indicate material properties or composition with nanometer resolution. Early demonstrations of this idea in the THz range readily achieved micron resolution,^{103,104} while highlighting the novel features of this configuration that become evident only in the situation where the field is detected coherently, as in a typical THz TDS measurement.¹⁰⁵ More recent work pushed the spatial resolution into the nanoscale range by using a smaller tip size,¹⁰⁶ and also demonstrated the extraction of dielectric information from the scattered radiation.¹⁰⁷

This general idea of using a sub-wavelength tip for improved resolution is very powerful, and can be adapted to a variety of terahertz techniques. Most simply, one need not have a sample surface present; a tip scattering approach can be used to map terahertz fields in free space with sub-wavelength resolution.¹⁰⁸ This scattering-probe approach has proven useful in imaging the sub-wavelength field confinement of terahertz fields at the ends of tapered waveguides.^{109,110} With a sufficiently sensitive detector, one can dispense with the illumination source, and instead simply detect the passive incoherent radiation emitted by a sample under study. This thermal noise imaging configuration has

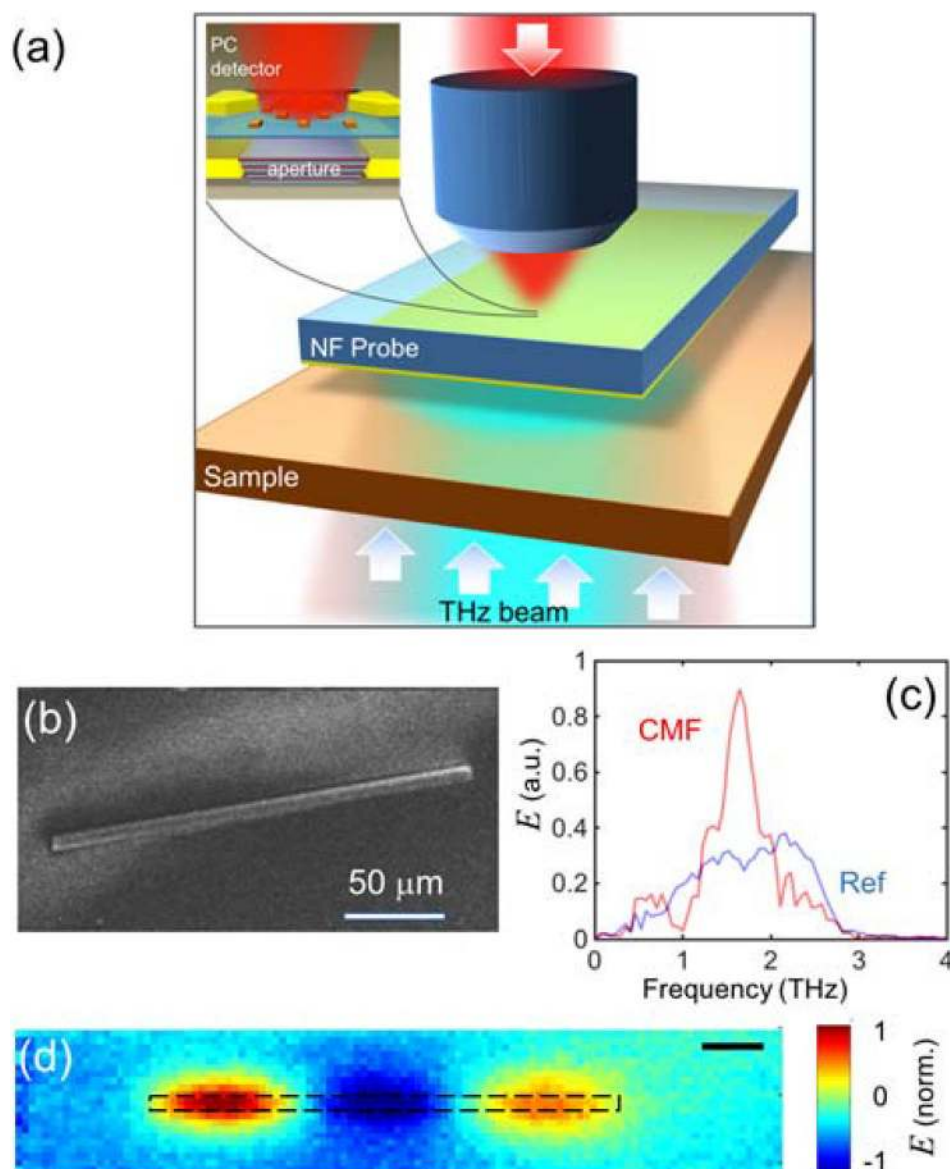


FIG. 3. (a) Sub-wavelength aperture THz near-field microscopy configuration employing a near-field probe with an integrated photoconducting (PC) detector.⁹³ The detector is built into the probe within 300 nm from the aperture as shown in the inset. (b) SEM micrograph of a carbon microfiber (CMF), which supports plasmonic resonances. The fiber is $\sim 7 \mu\text{m}$ in diameter and $207 \mu\text{m}$ long. (c) THz pulse spectrum (red) measured in the center of the fiber with a pronounced resonance at $\sim 1.8 \text{ THz}$, the spectrum of the incident pulse is shown (blue) as a reference. (d) Instantaneous field map detected by the near-field probe $\sim 1 \text{ ps}$ after the excitation of CMF by the THz pulse.⁹⁶ The fiber position is outlined by the dashed line, and the scale bar is $30 \mu\text{m}$.

proven to be extremely valuable in understanding current fluctuations on the nanoscale.^{111,112}

One can also combine the high spatial resolution of the tip with the high temporal resolution from short pulses, exploiting the picosecond duration of ultrafast terahertz pulses. For example, optical pump-terahertz probe measurements can be performed with nanoscale resolution,¹¹³ enabling the spatio-temporal mapping of photoexcitations in individual nanostructures. For different materials, one may envision tuning either the pump or the probe frequency in order to suit the situation; for example, recent work on a heterostructure of black phosphorus on SiO_2 required a femtosecond pump pulse at $1.5 \mu\text{m}$ (to drive interband excitations in the phosphorus without photoexciting the SiO_2) followed by a multi-terahertz probe pulse (to access the polariton excitations in the heterostructure).¹¹⁴

A different variation on the theme involves coupling the laser terahertz emission mechanism mentioned above to an AFM tip. In this case, the tip not only acts as a scattering site but also mediates a nonlinear optical interaction (optically induced THz generation) in the sample (see Fig. 4). This

situation is unusual because of the inherent tip-mediated nonlinearity, and also because the input (optical) and output (terahertz) beams are of such very different wavelength. The signal transduction mechanism is strongly influenced by this wavelength asymmetry, as seen, for example, in the spectral reshaping of the terahertz output due to antenna effects,¹¹⁵ which is quite different from that seen in the earlier tip-mediated terahertz imaging experiments.^{116,117}

One can now contemplate an enormous range of materials and techniques that are amenable to study using tip-based THz techniques. One intriguing possibility involves the use of liquid-state AFM, to probe molecules in solution via THz techniques. Consider a situation in which the AFM probe is immersed in a liquid, which is sitting atop a conductive substrate. If the probe tip is biased with respect to the substrate, it can induce alignment of solvated molecules in a nanoscale volume near the tip. Then, optical excitation of these aligned molecules should lead to a change in the aggregate dipole moment and therefore a THz emission signature, which would be sensitive to both the tip bias and its position. This would be a revolutionary new method for probing solvation

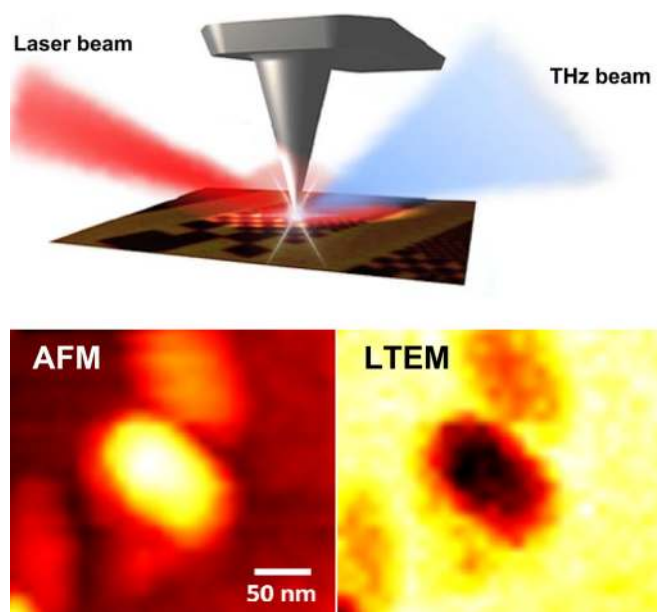


FIG. 4. Upper: A schematic of the experimental configuration for nanoscale laser terahertz emission microscopy, in which a femtosecond optical pulse is incident on a nanoscale tip held near a sample surface. The tip mediates the out-coupling of terahertz radiation to the far field, and therefore determines the spatial resolution of the measurement. Lower: Two images of a single gold nanoparticle on a bare semiconductor wafer. The left panel shows a conventional AFM (topography) image, while the right shows a terahertz emission image, formed using the emission from the underlying InAs substrate. The agreement between these two images demonstrates the ~ 20 nm resolution of the emission imaging technique.¹¹⁵

on the nanoscale, and could have extremely important implications, for example, in the study of the role of low-frequency modes in the structure and function of biomolecules in aqueous environments.

Another recent research development that is beginning to make an impact is the use of terahertz pulses in combination with scanning tunneling microscopy (STM), pioneered by Hegmann and co-workers in 2013.¹¹⁸ If an STM tip is illuminated with a terahertz pulse, then the electric field from that pulse can induce a tunneling current between the tip and the sample. The THz field therefore modulates the conventional STM tip current. In fact, a single-cycle THz pulse may be regarded as the fastest possible electrical bias pulse that can be applied to the junction of a scanning tunneling microscope (STM).¹¹⁹ This THz-induced tunnel current can provide a time-resolved method for studying electron density of states on an atomic length scale, revealing individual atomic¹²⁰ and molecular¹²¹ dynamics triggered by ultrashort THz pulses (or, potentially, by synchronized pulses at other wavelengths). The advent of time-resolved THz-STM now offers the promise of bringing THz techniques to the level of individual atoms.

Obviously, some of the most intriguing possibilities are to be found in the combination of high field, ultrashort pulse duration, and nanoscale resolution. One can envision driving a single nanostructure far out of equilibrium, by driving either the electronic or vibrational degrees of freedom with an intense THz pulse, and then probing the result with high spatial and temporal resolution. This general idea, applied either in one of the scattering SNOM configurations or with

THz STM, offers the possibility of answering questions that could not be addressed in any other way. There are, of course, many experimental challenges, and moreover the ultimate limits of temporal and spatial resolution remain unknown. It is clear, however, that this will be a fruitful avenue for future research.

TERAHERTZ SIGNAL PROCESSING

With the first demonstrations of terahertz imaging²⁴ came a flood of ideas for commercial applications. Some of these early ideas were promising (e.g., locating voids in the impact foam inside an automobile dashboard), while others were somewhat more outlandish (e.g., using THz spectroscopy to tell when a hamburger is fully cooked). Quite a few of these proposals were studied in preliminary laboratory-scale verification tests, including semiconductor wafer characterization,¹²² gas sensing,^{27,28,123} non-destructive evaluation of plastic components²⁵ and artwork,^{81–83} and non-contact burn diagnostics.^{26,124} Some of these ideas were realistic, and could have been immediately addressed, if the instrumentation had been sufficiently advanced to be moved outside of the research laboratory. However, it was several years before the first commercial portable THz time-domain

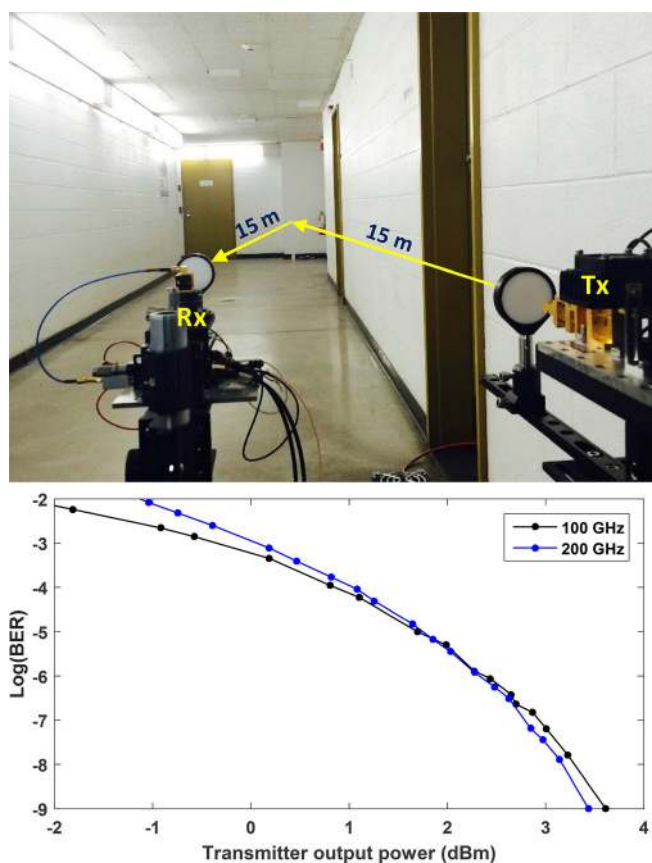


FIG. 5. Terahertz wireless links in an indoor environment, using a non-line of sight (NLOS) path, which incorporates a specular reflection from a painted cinderblock wall. The data rate is 1 Gb/s; results are shown for two different carrier frequencies. In both cases, an error-free data link ($\text{BER} < 10^{-9}$) is maintained with a transmitter output power of about 3.5 dBm (about 2.2 mW).¹⁴⁸ The possibility of a robust NLOS link above 100 GHz is something of a surprise, contrary to the conventional wisdom in the field.

system became available.¹²⁵ Subsequent development of these and other types of THz instruments gradually led to more robust and user-friendly systems, enabling a wider range of applications.⁷⁸

The last few years have seen a more rapid acceleration of this progress. This may be due to several different factors, such as increased competition leading to lower prices. However, one important factor could be the growing realization that one particular application will become crucially important in the near future—that is, wireless communication using terahertz carrier waves. This notion was discussed in the literature over 10 years ago,^{126,127} but it is only relatively recently that it has attracted significant attention from the broader research community. Now, the world awaits the highly anticipated roll-out of next-generation (5G) wireless technology, which will include a standard for millimeter-wave wireless links. This appears to justify the need for high bandwidth, even at the cost of higher directionality and shorter propagation range. Given the ongoing exponential growth of wireless traffic, this need does not seem likely to abate before the capacity of even this next generation of technology is saturated.

This realization has catalyzed a great deal of interest in frequency bands above 100 GHz for wireless communication. Researchers have pursued the development of components that could be useful for processing and manipulating these free-space THz signals. Early work on THz modulators^{128,129} has led to a flood of studies describing efforts to achieve high speed, low insertion loss, and high modulation depth.^{65,130–134} Researchers have also studied other signal processing components, including splitters,^{135,136} multiplexers,^{137,138} spatial light modulators,^{139,140} and filters.^{141,142} In recognition of the

fact that the use of directional beams for wireless links will require the ability to control their propagation angle, several groups are pursuing methods for electronically controlled beam steering.^{143–145} In anticipation that multi-path links would experience significant loss at higher frequencies, there have been attempts to design inexpensive dielectric coatings that could be used to create an indoor pico-cell environment with highly reflective walls at designed frequencies of interest.¹⁴⁶ While such engineered environments may prove valuable, high-gain antennas can also provide sufficient headroom in the link budget to compensate for losses, enabling multi-path links even with conventional painted cinderblock walls (see Fig. 5).^{147,148}

In parallel, another extremely significant development has involved the inevitable march of silicon and III–V technologies into the terahertz range. For example, within the last five years, InP heterojunction bipolar transistor technologies have demonstrated power amplifiers producing 200 mW at 210 GHz, amplification above 670 GHz, and transistors with $f_{\max} > 1$ THz.²³ Meanwhile, a conventional silicon CMOS process can now be used to create circuits that produce and radiate picosecond-scale pulses with spectral content extending beyond 1 THz.^{149,150} A collection of on-chip sources can act as a phased array, enabling beam steering and wavefront engineering.¹⁵¹ Since these circuits can contain on-chip antennas, one can even integrate a large number of subwavelength sensing elements close to the antenna, for broadband spectroscopic detection and sensing.¹⁵² Figure 6 illustrates examples of signal generation and detection using silicon-based circuitry. These advances will inevitably have a major impact on the architecture of many future THz technologies, including both imaging¹⁵³ and

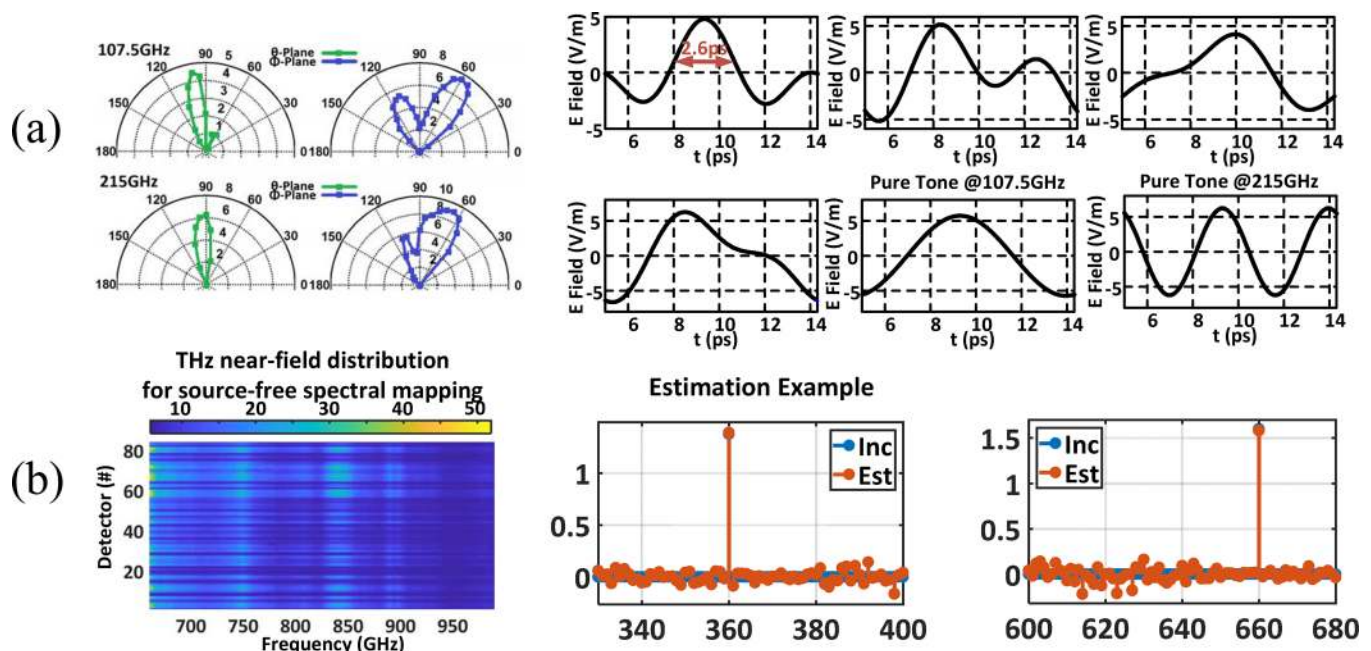


FIG. 6. THz signal generation and detection with on-chip radiating elements. (a) A single CMOS chip with 4-element radiating arrays capable of radiating reconfigurable time signatures and radiation patterns. The signals can be programmed electronically ranging from picosecond pulse trains (2.6 ps) to continuous wave tones.¹⁵⁰ (b) A source-free THz spectroscope in silicon extracting incident radiated THz field spectral information through real-time sensing of 2D impressed THz current distribution on an on-chip antenna.¹⁵² Massive sub-wavelength sensing and a multi-port architecture eliminate the need for complex sources, mixers, amplifiers and reduce the architecture to a single chip capable of THz detection from 0.04 to 0.99 THz with 10 MHz accuracy.

communication systems.¹⁵⁴ It is also possible that these extremely compact THz sources could replace conventional THz-TDS systems in some scientific applications. For example, there may be advantages to using a CMOS-based pulsed THz source instead of a laser-based source to perform s-SNOM measurements, perhaps associated with a higher modulation rate, or the ability to place this compact integrated source in close proximity (and with arbitrary orientation) to the AFM cantilever.

Alongside this growing activity in component development, numerous system demonstrations have established the feasibility of sending data via THz links. Various different combinations of data rate, carrier frequency, and propagation range have been demonstrated, using a variety of different technology platforms as the source and detector.¹⁵⁵ One of the earliest and most notable examples was the 120 GHz demonstration employed at the 2008 Olympic games for some Japanese television broadcasts.¹⁵⁶ Since then, numerous research teams have demonstrated increasing data rates and broadcast range.^{157–159} Meanwhile, theoretical efforts to understand the channel characteristics are also ramping up.¹⁶⁰

These steps, while impressive, are only the first efforts in the research needed to establish this technology platform. For instance, all of the system demonstrations described to date have been single-input, single-output (SISO) links, with fixed transmitter and receiver architectures (i.e., no mobility). This configuration would be suitable for certain applications, such as backhaul or for information transfer in data centers. Other envisioned applications will require multiple independent users and will need to incorporate mobility, among the key challenges for the field. Further, the demonstration of components can no longer rely on characterization with a conventional time-domain spectrometer, or a continuous-wave tunable source. It is now clear that a good understanding of the capabilities of any device will require realistic system demonstrations, in which the component under study is used to manipulate a THz data stream.^{138,161}

Such measurements provide crucial information that cannot readily be obtained using conventional characterization methods. A good example is illustrated in Fig. 7. This shows simulations of two beams (with two different frequencies) emerging from a leaky wave antenna, used in a demultiplexing configuration. Here, the diffractive spreading of each of the two output beams is large compared to the angular spacing between the carrier wave and the modulation sidebands; this suggests that the aperture of the detector should not be a significant factor in determining the quality of the data link (aside from trivial consideration of power collection efficiency). However, experiments have verified that even a small asymmetry in the detection of these sidebands can lead to a noticeable degradation in the bit error rate.¹³⁸ This result, although specific to this particular multiplexer configuration, reveals a general feature of any demultiplexing subsystem in which diffraction plays a role. It suggests an additional factor in the consideration of receiver design which will be relevant in any situation where highly directional signals are employed. Rather than seeing this as an obstacle, one may instead consider the potential advantages

that may be achieved by exploiting this frequency-dependent diffraction using an antenna array, such as in a multiple input, multiple output (MIMO) context.¹⁶²

CONCLUSION

In this article, I have attempted to touch on a few of the most exciting research frontiers in the terahertz field. It is, of course, impossible to do full justice to any of them. In addition, it is inevitable that some equally exciting areas have been neglected, simply due to space limitations. One prominent example is the emerging area of terahertz quantum optics, in which researchers have studied strong light-matter coupling in cavities,^{163,164} photon statistics of a terahertz laser,¹⁶⁵ and even directly measured vacuum fluctuations¹⁶⁶ and squeezed states of the vacuum.¹⁶⁷ This and other examples serve to prove the point: the field of terahertz science and technology is rich and vibrant, with impacts in many

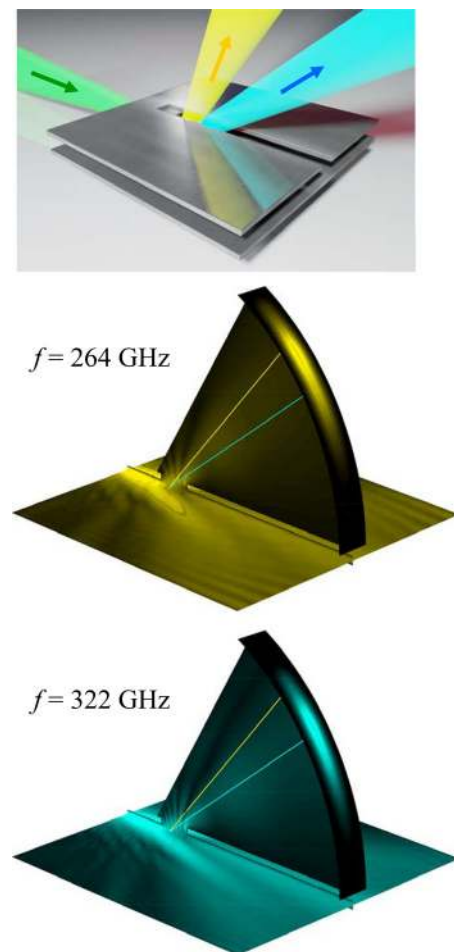


FIG. 7. A schematic of a terahertz demultiplexer, along with two numerical finite element simulations. Here, two carrier waves, at frequencies of 264 GHz (yellow) and 322 GHz (blue) are emerging from the slot in a leaky-wave antenna, and propagating into free space in different directions.¹³⁷ The two simulations show each frequency component individually, although they propagate together inside the waveguide, and emerge simultaneously, as shown in the upper illustration. In these simulations, the spacing between the waveguide plates is a constant, $b = 0.733$ mm. Diffraction causes spreading of the two output beams, so that they begin to overlap at angles between the two solid lines. Even so, it is still possible to obtain error-free transmission of both data streams.¹³⁸

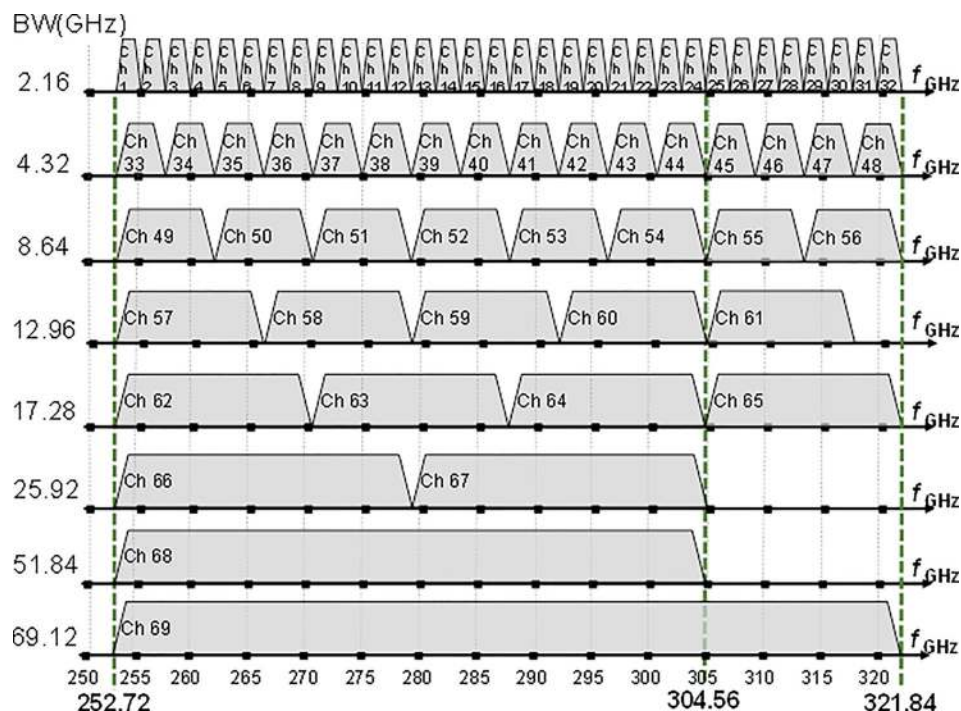


FIG. 8. Channel diagram, as proposed by the IEEE 802.15 WPAN working group.¹⁷¹ This channelization, which has been approved by the IEEE standards body, is to be discussed as part of the ITU agenda at the 2019 World Radio Conference, along with protocols for wireless links in the range 275–450 GHz. The adoption of a uniform standard is an important step in the commercial development of any wireless technology.

areas of science. It has now moved beyond the point where it is interesting to simply duplicate at terahertz frequencies that which has previously been done at other frequencies.

On the other hand, there are clearly still barriers to overcome. One of the most persistent of these involves the interfaces among distinct research communities. Since the terahertz spectral range lies in between electronics and optics, there has historically been a substantial disconnect between those who have entered the field from the high-frequency end and those who came from the low-frequency end. There are also historic divisions among different technology platforms for accessing the terahertz spectrum—for example, researchers who employ vacuum electronics sources do not tend to interact much with researchers who rely on laser-based sources, even though both are generating radiation at the same frequency, and sometimes even for the same purpose. Researchers with these distinct backgrounds still mostly attend different conferences and publish in different journals. Yet, these cultural divides are starting to blur. The larger conferences are growing to encompass more distinct research communities. Two journals^{168,169} devoted specifically to the science and technology of long-wavelength electromagnetic radiation (but which are agnostic with respect to the technology platform or technique used) are becoming more prominent. Obviously, it is to the benefit of all to encourage this process to continue. In the near future, it seems inevitable that it will do so, since some of the most creative ideas emerge as a result of such cross-pollination.

A different sort of challenge facing terahertz technology lies in the issue of regulation. Currently, in the US, there are no applicable health and safety standards for exposure to millimeter-wave or terahertz radiation; in cases where this has been a concern, such as for millimeter-wave body scanners at airports, regulators have simply relied on

extrapolation of standards developed for lower frequencies.¹⁷³ These older standards assume that the only effects of radiation exposure on biological media are thermal, and that there are no non-thermal mechanisms for light-matter interaction. Given the high concentration of water in living tissue, this is probably a reasonable assumption for determining the exposure limits even up into the terahertz range. Yet, there is a small body of evidence which suggests that alternate mechanisms could be relevant, under certain circumstances.¹⁷⁰ Should terahertz technologies become more widespread in public use, this issue will inevitably become important. Even more concerning, there is no uniform regulatory standard for operating THz systems in the US, in any frequency band above 95 GHz. This state of affairs inevitably stifles innovation, as companies will be reluctant to develop a technology that cannot be licensed. Some nations have begun to allocate specific bands, but a patchwork of nonuniform regulation is detrimental, and a worldwide standard is an obvious need. At the upcoming World Radio Congress in 2019, a proposal will be considered to begin to define protocols for THz wireless personal area networks (WPANs). This proposal follows up on the recently approved IEEE channelization standards for the range 252.72–321.84 GHz, as illustrated in Fig. 8, along with other MAC and PHY layer specifications.¹⁷¹ Any researcher with an interest in THz communications should be watching these developments very carefully.

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