Opening the Terahertz Window With Integrated Diode Circuits

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Abstract—**The terahertz region of the electromagnetic spectrum, spanning from 100 GHz through 10 THz, is of increasing importance for a wide range of scientific, military and commercial applications. This interest is spurred by the unique properties of this spectral band and the very recent development of convenient terahertz sources and detectors. However, the terahertz band is also extremely challenging, in large part because it spans the transition from traditional electronics to photonics. This paper reviews the importance of this frequency band and summarizes the efforts of scientists and engineers to span the "terahertz technology gap." The emphasis is on solid-state circuits that use nonlinear diodes to translate the functionality of microwave technology to much higher frequencies.**

Index Terms—**Terahertz detectors, terahertz sources, terahertz technology.**

I. Applications of Terahertz Technology

THE TERAHERTZ region of the electromagnetic spectrum, defined here as spanning from 100 GHz through 10 THz, has often been described as the most scientifically useful yet least explored region of the spectrum. This is because of both the wealth of molecular resonances that occur in this band and the unique properties of terahertz waves. Chemists use terahertz spectroscopy to study the structure and dynamics of a wide range of molecules. If the molecule's measured resonance features match their theoretical predictions with precision, then they have solid experimental verification of the validity of their models. Once the spectral features of a particular molecule are precisely known, other scientists use this information to identify these molecules in remote environments. For example, radio astronomers have identified hundreds of molecules in space and have thereby gained a great deal of information about the structure and dynamics of the Universe, particularly with regard to the formation of stars in molecular clouds [1]. Similarly, atmospheric scientists are able to measure the trace constituents of the upper atmosphere with terahertz remote sensing from airborne platforms and satellites [2], [3]. Their work has recently focused on studies of ozone depletion cycles since ozone and the primary molecules involved in the destruction of ozone have resonances in this frequency band.

Other applications of terahertz technology include plasma diagnostics [4], studies of solid-state physics, short-range, high data rate communications, compact range radars [5] and more recently studies of biological macromolecules, such as DNA and proteins. The recent determination that biomaterials interact with terahertz radiation has opened the door for many new and practical applications in biology, medicine and security [6]–[8]. A particularly exciting application of terahertz technology is the detection of concealed weapons [9] and contraband [10]. The great promise of terahertz imaging systems is the ability to see through clothing with the required spatial resolution to detect concealed weapons, whether made of metal, ceramics, plastics or other materials. In addition, terahertz radiation is nonionizing so that health risks are minimal (as opposed to X-rays). These characteristics are due to the unique electromagnetic properties of terahertz radiation and can not be duplicated in other regions of the spectrum.

There are essentially two modes of achieving a practical terahertz imager. In passive imagers the natural blackbody radiation of the subject, combined with reflections from the thermal background, are used as the signal. Since all materials have different reflectivity and emissivity, concealed items can be detected even if they are at the same physical temperature as the underlying skin, regardless of their material composition. The drawback of passive imagers is that the thermal radiation is extremely weak and achieving the required receiver sensitivity is a challenge. The second mode is active imaging, where the subject is illuminated with a source of terahertz energy and the reflected signal is detected. This can increase the signal strength by many orders of magnitude, thereby allowing the use of less sensitive, but more practical, direct detectors. Although active illumination of the subject may create additional safety concerns and legal issues, it seems likely that for many applications these barriers can be overcome, particularly since terahertz photons are nonionizing and the terahertz intensity will be quite low.

II. The Terahertz Technology Gap

It is clear that there are many present and future applications of terahertz technology. In fact, if one considers the myriad applications of the microwave and infrared bands that bound the terahertz spectral region, it seems logical that terahertz technology should eventually play as large a role in society as these

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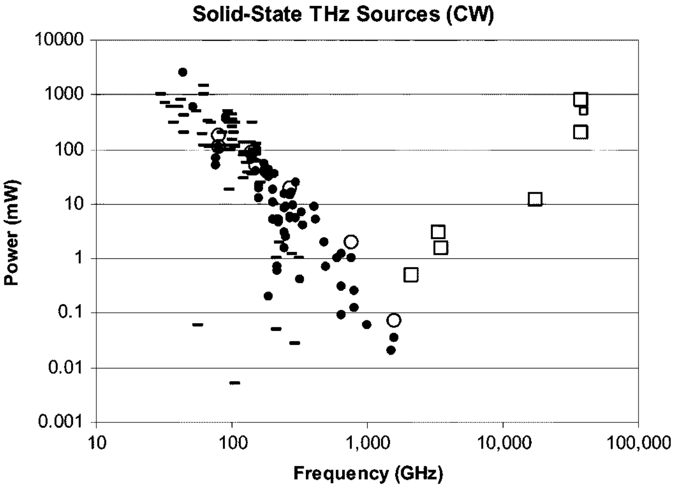

Fig. 1. Terahertz gap with respect to source technology. Quantum cascade lasers (□) are progressing downward from higher frequencies, while electronic technology is progressing upward. Frequency multipliers (●) dominate other electronic devices (−) above about 150 GHz. Cryogenic results are shown as hollow symbols.

more developed bands. The main reason this has not occurred to date has been the difficulty of achieving a mature technology base in this unique spectral region. The terahertz frequency band spans the transition from classical electronics to quantum optics, or photonics. Below 100 GHz, electronic devices such as amplifiers and oscillators are common. Above 10 THz, solid-state lasers, light-emitting diodes, and optical detectors are readily available. However, in between, neither of these technologies is particularly practical and the result is a technology gap in terms of both sources and detectors of terahertz power. Fig. 1 is a graph of output power versus frequency for state-of-the-art terahertz sources. Only solid-state continuous-wave (CW) sources are included and there is no attempt to consider other factors such as tuning bandwidth in this simple graph. Other CW technologies, including tube devices, such as backward wave oscillators[1] and gyrotrons, can yield much more power. Although these are very useful for many laboratory applications [11], they are inherently large, expensive, and somewhat unreliable. Additionally, short pulse terahertz sources based on femtosecond optical lasers and an Austin switch are available [12]–[14]. These are useful for very broadband and low-resolution spectroscopy and certain imaging applications. However, the spectral brightness of these sources is extremely low, even if one considers the peak rather than time-average power.

The data shown in Fig. 1 indicates that sources based on frequency multipliers outperform all other solid-state electronic sources, such as amplifiers, resonant tunneling diodes, Impatts and Gunn oscillators above about 150 GHz. This is because of the inherent physical and operational simplicity of the multiplier diodes, which yields a fundamentally better high-frequency response. Above 2 THz, the quantum cascade (QC) lasers dominate [15], [16]. They are particularly useful in the infrared bands and in the higher end of the terahertz band. However, below about 4 THz, they require cryogenic cooling to achieve CW operation. QC lasers will play a major role in the development of the terahertz field. However, there are fundamental physical obstacles that will likely prevent them from operating in CW mode below a few terahertz, especially if room-temperature operation is required. Also, issues such as frequency stability, tuning bandwidth, and lifetime have not yet been sufficiently addressed in this emerging technology.

III. BRIDGING THE GAP WITH NONLINEAR DEVICES

One particularly useful method of bridging the terahertz technology gap involves the use of nonlinear devices to translate the functionality of lower frequency electronics into the terahertz band. Examples include frequency mixers that can convert a high-frequency signal to a lower band where it is more easily amplified and analyzed and frequency multipliers that can translate a signal to a higher harmonic frequency. In principle, any nonlinear electronic device can be used as a mixer or multiplier. However, in order to achieve reasonable conversion efficiencies and low noise in the terahertz band, only a few types of devices are feasible. Assuming for the purposes of the present discussion that only room-temperature devices are considered,[2] GaAs Schottky barrier diodes are presently the best solid-state device for this application and components based on these devices have set the standard for performance for the past several decades.

Schottky barrier diodes are preferred because of their inherent simplicity and their lack of any minority carrier storage effects. GaAs is used because it offers an excellent combination of: 1) high mobility, required for terahertz response; 2) sufficiently large bandgap (and therefore barrier height) to reduce leakage currents; and 3) a fairly mature and cost efficient processing technology. Although other III–V materials are also used in certain applications, as is noted below, the great majority of terahertz circuits use GaAs. This is due to the excellent balance between mobility and bandgap offered by GaAs and the maturity and simplicity of GaAs processing.

As is evident from Fig. 1, the performance of the diode multipliers gradually degrades as the frequency is increased. This is true of all electronic circuits in this frequency band and is due to a variety of both fundamental and practical limitations. All electronic devices are limited by parasitic circuit elements such as series resistance and shunt capacitance. As the operating frequency increases, terahertz diodes must be made smaller to reduce junction capacitance, but this increases series resistance, thereby resulting in a fundamental design tradeoff. Electron transport is also subject to a variety of transit time and scattering time limitations. For example, Gunn diode oscillators (GDOs) are fundamentally limited by the scattering time of electrons into the satellite valleys. Although GDOs have been made to generate power up to several hundred gigahertz [17], these results are achieved by coupling energy at a harmonic of the fundamental oscillation frequency.

Another fundamental limitation is the finite velocity of electrons in the crystal. In most high-efficiency frequency multipliers; the nonlinear capacitance of the diode is used to generate the harmonics. Since the reverse breakdown voltage can be many tens of volts, the power handling of such a varactor

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[1] For example, http://www.mtinstruments.com.

[2] If cryogenic cooling is allowed, superconductive mixers yield far better noise performance than is possible with a semiconductor diode.

diode is much greater than a forward biased diode used in varistor mode. Also, a varactor offers lower inherent resistive losses and can therefore be much more efficient. However, the variable capacitance is achieved by physically moving electrons. As the frequency is increased, there is less time to move the electrons across the same distance, and eventually the depletion region edge cannot be moved fast enough to keep up with the input frequency. At this point, the performance is severely degraded.

Eventually, even the impedance of a passive element of semiconductor becomes complex as dielectric relaxation (capacitive) and charge carrier inertia (inductive) effects become significant. In fact, these phenomena cause a well-known plasma resonance that falls in the terahertz band [18]. Through clever device and circuit design, the impact of these effects can be minimized, resulting in a gradual degradation of device performance as frequency increases, rather than a dramatic cut-off. Today, diode mixers and detectors are available to 5 THz [19] and useful multipliers are available to about 2 THz [20].

IV. TERAHERTZ DIODE AND CIRCUIT FABRICATION TECHNOLOGY

The first terahertz diodes were whisker contacted devices, as pioneered by Young and Irwin [21] and later Schneider [22] and Mattauch [23]. The whisker contact, although difficult to assemble, was extremely useful because it presented the minimum possible shunt capacitance and was technologically feasible at the time. In fact, whiskered diodes are still in use today in some applications and in their time they allowed many ground breaking scientific measurements, particularly in radio astronomy. The diode contact shown in Fig. 2 was launched in NASA's Upper Atmosphere Research Satellite and measured the concentration of ozone in the atmosphere at 205 GHz [3].

More recently planar diodes have been successfully developed and integrated diode circuits are now available. For, example, Fig. 3 shows an integrated 600-GHz mixer circuit. The metal regions form waveguide probes to couple the energy from a rectangular waveguide to the quartz microstrip circuit, as well as frequency filters and impedance matching elements. The substrate material is quartz, which is used for its low dielectric constant. The GaAs epitaxial layers, only a few microns thick, are bonded to the quartz at the wafer level [24]. The GaAs is then nearly completely removed in subsequent processing, leaving only small mesas onto which the Schottky and ohmic contacts are formed. Air-bridged fingers are used to contact the anodes with minimum shunt capacitance. In this example, an anti-parallel diode pair is used to form a subharmonically pumped mixer where the local oscillator frequency is roughly one-half of the signal frequency. This integrated circuit needs only to be placed in an appropriate waveguide housing and contacted with bond wires for DC contact and the mixer is complete. This basic circuit style is useful up to at least 1 THz and a similar integration technology has been developed by NASA. In fact NASA has developed a very low noise mixer for 2.5 THz [25] that was recently launched on the NASA Aura satellite to provide the first global measurements of hydroxyl (OH) and hydroperoxy (HO2) radicals that are part of the hydrogen catalytic cycle for ozone destruction.

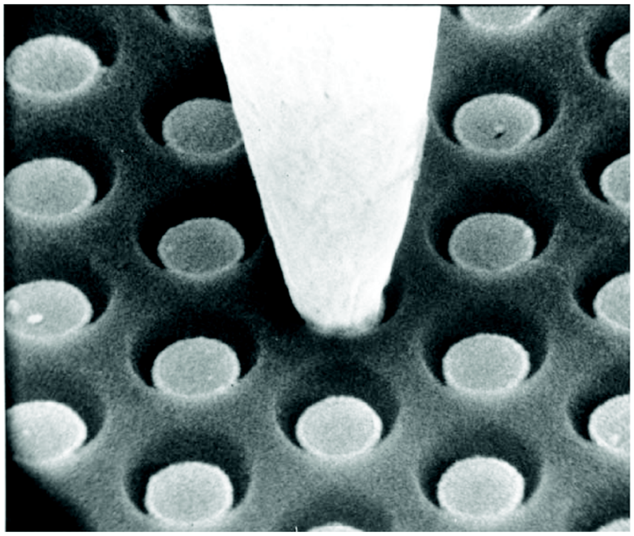

Fig. 2. SEM image of the whisker contacted diode that was launched on the Upper Atmosphere Research Satellite in 1991. This mixer diode was used to measure ozone concentrations at roughly 205 GHz. The anode diameter was about 2.5 μm.

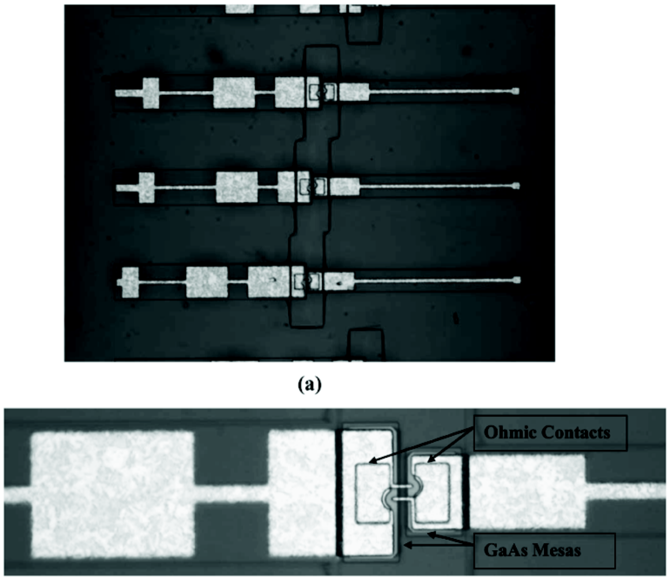

Fig. 3. Integrated GaAs mixer circuit. (a) The quartz wafer before dicing. The structures at each end are waveguide probes for the local oscillator (left) and signal (right) and the high/low filter prevents the signal from propagating to the LO waveguide. (b) A close-up of the GaAs diode mesas and the anti-parallel anode fingers (between the ohmic contacts). The background material is the quartz substrate used to reduce parasitic capacitance. The GaAs mesas are only 3-μm-thick and exist only in the central region where the diodes are formed. This mixer operates in the WR-1.7 waveguide band from 440 to 660 GHz.

Other materials and diode structures are beginning to find niche applications within the terahertz frequency band. For example, heterostructure barrier varactor (HBV) diodes based on InAlAs/InP materials have been used to achieve frequency multiplication in the 100–500 GHz frequency band [26]–[28]. Also, a group in Germany has recently developed a tripler circuit with excellent performance using nonuniform doping profiles and a blocking barrier contact [29].

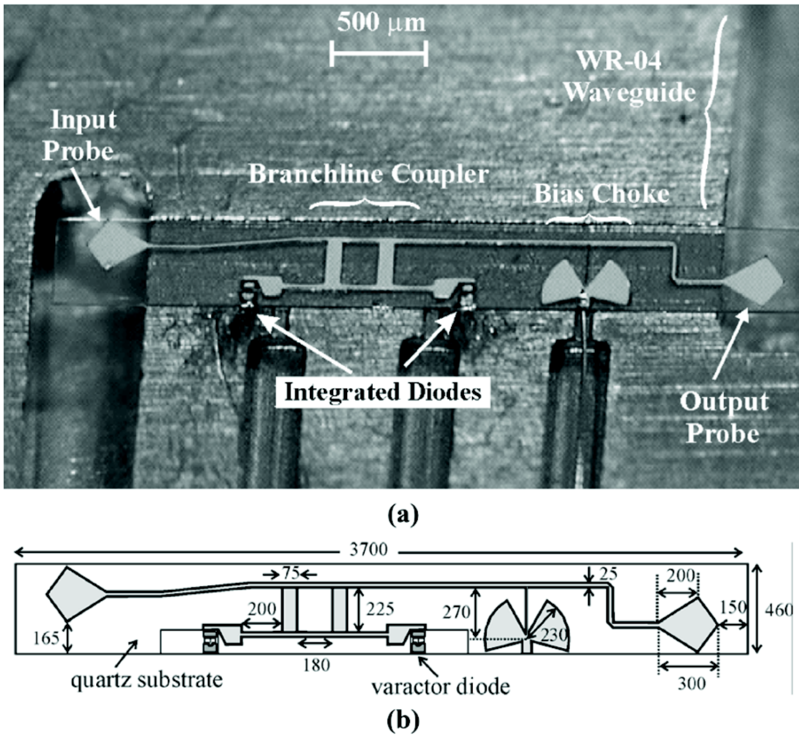

Fig. 4. (a) Photograph of an integrated balanced phase-shifter circuit mounted in a WR-4 waveguide housing [30]. The integrated module consists of waveguide probes, a branchline hybrid, a DC bias network, and two integrated GaAs Schottky barrier varactors. (b) Schematic of the phase-shifter chip. All dimensions are in microns.

V. TERAHERTZ CIRCUITS

The goals of the terahertz circuit designer are to couple the terahertz power efficiently into and out of the nonlinear diodes, to reduce any noise added to the signal and to ensure that unwanted signals (harmonics or mixing products) are suppressed. Two recent technological advances have greatly improved the performance of terahertz circuits. The first is the advent of fast and accurate circuit simulation tools that model the linear three dimensional electromagnetic structure of the diode embedding environment and solve the nonlinear circuit. These include Ansoft's High Frequency Structure Simulator and Eagleware's Genesis, as well as a number of competing products. The second has been the development of integrated diode circuits, such as that shown in Fig. 3. Integration greatly reduces parasitic losses and allows micron level precision of the circuit structure. These factors have significantly improved the performance of terahertz mixers and multipliers and have allowed circuit designers to achieve components and systems that can be electrically tuned over complete waveguide bands. Just as important, the integrated circuits are easier to assemble, yield more uniform performance and have increased reliability.

A particularly interesting example is a proof-of-concept 220-GHz phase shifter that was recently developed at the University of Virginia. Fig. 4 is an image of the metal waveguide housing with the GaAs-on-dielectric integrated circuit placed in the microstrip channel. When the upper half of the housing, essentially a mirror image of the bottom, is placed on top, it completes the input and output waveguides and encloses the microstrip channel that houses the circuit. The integrated phase-shifter circuit incorporates impedance transformers designed to yield broadband operation and compensate for amplitude imbalance between bias states of the diodes. It has yielded a phase shift of 180 ± 15 degrees over a 55-GHz band with average insertion loss of 5.5 dB [30]. This style of phase shifter offers excellent reliability and very high (GHz) switching speeds. It also seems likely that the performance can be significantly improved in future designs.

VI. TERAHERTZ COMPONENTS AND SYSTEMS

Fig. 5 shows the output power of a very broadband frequency tripler. The output power level is sufficient for use as a mixer local oscillator and the efficiency is fairly flat across the entire waveguide band. This result is remarkable because the tripler achieves full waveguide band performance yet requires no mechanical tuning as the frequency is swept. This component was specifically designed for use in a major radio astronomy project called the Atacama Large Millimeter Array, or ALMA [31]. It will include roughly 64 radio telescopes operating as an array on a high mountain plateau in Chile. Each telescope will have receivers that yield nearly full frequency coverage from 100 GHz through 1 THz. The total frequency range is divided into ten receiver bands, each with dual receivers to measure two polarizations. The high-frequency mixers will use superconducting elements to achieve the greatest possible sensitivity [32], but the required local oscillator power will be produced by amplifiers near 100 GHz followed by diode based frequency multipliers. Clearly, such a large array of receivers (128 mixers and LO chains for each band) cannot rely on electronics with mechanical tuners, and therefore the recent

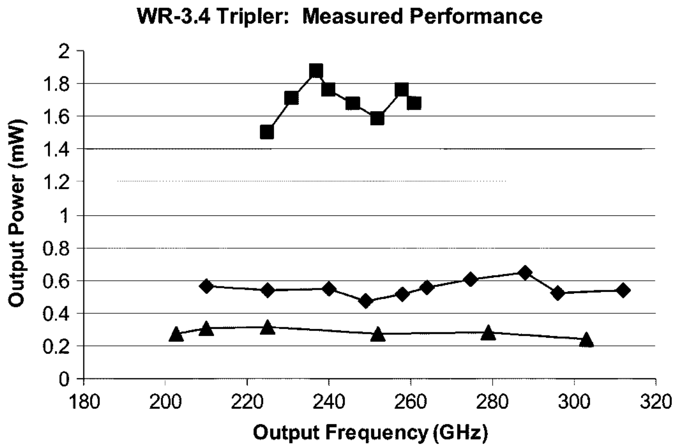

Fig. 5. Output power of a broadband tripler with an integrated diode circuit at three input power levels (50 mW, 20 mW, and 15 mW, top to bottom). The tripler requires no mechanical tuners and achieves full waveguide band performance. It is being used to supply local oscillator power for a superconductive mixer on the ALMA project.

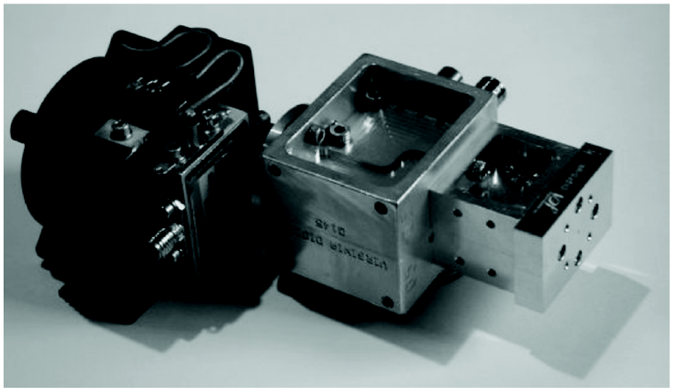

Fig. 6. All-solid-state terahertz source. This active multiplier chain increases the frequency of a standard commercial sweeper to the terahertz band through a single power amplification and a series of multiplication steps. The final multiplication factor is 72 and power levels of 10–25 μW are achieved across the WR0.65 waveguide band (1.1–1.7 THz]. The total length of the frequency extender is about 6 inches.

development of frequency multipliers with broad electronic tuning is one of the enabling technologies for this major science project.

Fig. 6 shows an active frequency multiplier chain with an output in the WR-0.65 waveguide band, which spans from 1.1–1.7 THz. The input SMA connector requires a signal of only a few milliwatts near 18 GHz. The signal is first frequency doubled and amplified by a commercial amplifier.[3] It is then multiplied by four by a pair of varactor doublers integrated into a single housing and then by nine by a pair of frequency triplers. The output is therefore 72 times the input frequency, or for this example 1296 GHz. Typical power levels are in the range 10–25 μW, depending on the exact frequency. The two final triplers operate well over the complete waveguide band. However, the power amplifier and the varactor doublers have more limited bandwidth. These "driver" components limit the output tuning band of the system to about 100–150 GHz. However, this bandwidth can be achieved anywhere within the total waveguide band, depending on the selection of the driver amplifier and quadrupler. Similar systems have also been developed as frequency extenders for conventional microwave synthesizers throughout the 100 GHz–1 THz frequency band.

VII. Summary and Conclusion

The recent development of integrated terahertz circuits that efficiently translate the functionality of microwave electronics to higher frequencies has enabled the development of a new range of terahertz components and systems. Useful components include frequency mixers, multipliers and up-converters, as well as phase shifters, comb generators and direct detectors. Typical systems include heterodyne receivers for communications and remote sensing, and both broadband frequency extension modules for microwave synthesizers and narrower band active frequency multipliers that generate significantly greater power over a narrower frequency band. These systems are finding use in an increasing range of important scientific experiments and are also likely to play an important role in imaging systems for weapons detection and bioagent and chemical scanners for Homeland Security. As this technology continues to mature, it is expected that the terahertz frequency band will eventually become as useful for scientific, military, and commercial applications as the microwave and infrared bands are today.

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