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Terahertz (THz) Frequency Sources and Antennas - A Brief Review

P. Mukherjee · B. Gupta

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Abstract In this paper we review THz radiation properties, generation methods, and antenna configurations. This paper suggests some new class of antennas that can be used at THz frequency, like optical antennas or Carbon nanotube antennas. THz technology has become attractive due to the low energy content and nonionizing nature of the signal. This property makes them suitable for imaging and sensing applications. But at the same time detection and generation of THz signals has been technologically challenging. This paper presents a comparative study of the generation techniques for THz frequency signals giving emphasis to the some new techniques like Quantum Cascade lasers which has created significant research interest. The main aim for this study is to find out the materials suitable for fabricating THz devices and antennas, a suitable method for generation of high power at THz frequency and an antenna that will make THz communication possible.

Keywords Terahertz (THz) · Antennas · Imaging · Sensing · Quantum cascade laser

1 Introduction

Terahertz (THz) frequency spectrum, can be defined as the portion of the sub millimeter wavelength electromagnetic (EM) spectrum between approximately 1 mm and 100 μm of wavelength (300 GHz-3 THz) (Fig. 1) and it has the potential of playing a major role in technological and scientific application areas [1–4]. THz frequency range lies in the gap between microwave band and infrared band of frequencies. Thus combination of technologies used in these two ranges can be applied to develop THz systems.

THz radiation exhibits the following properties [5]:

- *Penetration*—THz waves pass through common clothing and packaging materials with relatively little attenuation.

P. Mukherjee (✉)
Department of Electronics and Telecommunication Engineering,
Institute of Engineering and Management, Salt Lake, Calcutta, India
e-mail: pinakimail@yahoo.co.in

B. Gupta
Department of Electronics and Telecommunication Engineering, Jadavpur University,
Calcutta 700032, India

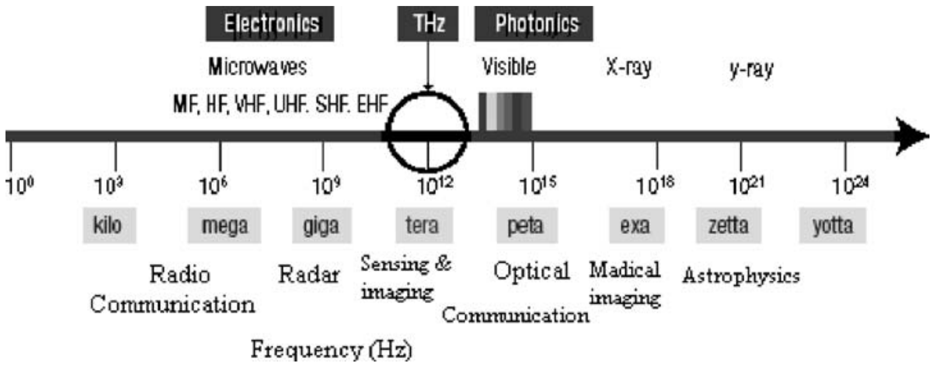


Fig. 1 The electromagnetic spectrum showing the 'THz gap' between microwave and infrared band.

- *High-resolution imaging*—the short wavelengths of THz signals in comparison to microwaves can be used to provide images with submillimeter resolution.
- *Spectroscopy*—many solids exhibit characteristic spectral features in the 0.5–3.0 THz region. This enables different chemical substances to be detected—even when sealed inside a packet or concealed in clothing.
- *Non ionizing*—THz radiation is nonionizing and can be used at very low power levels in the microwatt range due to the availability of high sensitivity coherent detection schemes. This property of THz radiation makes it suitable for use in biological and medical applications [6, 7] like medical imaging for detection of infected tissues.
- *Low scattering*- The longer wavelength of THz signals compared to visible light allows for much lower scattering.
- *Intensity*- THz signals are much easier to focus and collimate than radio waves.

Thus THz signals can be applied for sensing and imaging purposes. Detection, identification and characterization of explosives and weapons, hidden under clothes for protecting citizens and state from organized crime, preventing terrorist acts and responding to natural and man-made disasters are some of the important areas of probable THz signal application. But there are certain issues that need to be reviewed before applying them for these purposes. Atmospheric condition is one of them. Atmospheric attenuation and scattering from atmospheric particulates are two major concerns of development of sensors in the THz spectral region. Figure 2 shows the variation of atmospheric attenuation as a function of frequency for different weather conditions [8]. Figure 2 indicates that the most adverse condition is met in hot tropical climates. Imaging is a technique in which the reflected signal from the object (also called signature) is received by a receiver and the image of the reflector is created from this signature. The reflected signal will be affected by reflective properties of the materials as well as the frequency of operation. As the frequency increases there will be more diffuse scattering and resulting in a "natural" image. But higher attenuation at higher frequencies will limit the range of detection. Imaging in transmission is also one of the upcoming research and application areas in which the signal transmitted through the material is analyzed for detection.

2 Terahertz Sources

Although THz frequency band lies in the gap between microwave band and infrared band, the sources available in these two bands can not be used for THz range [9]. It is difficult to

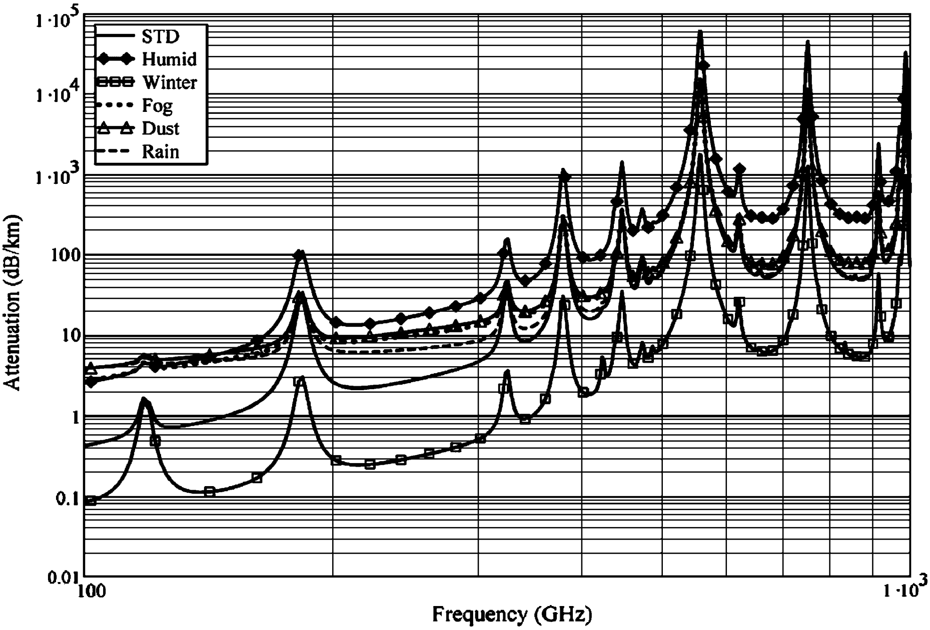
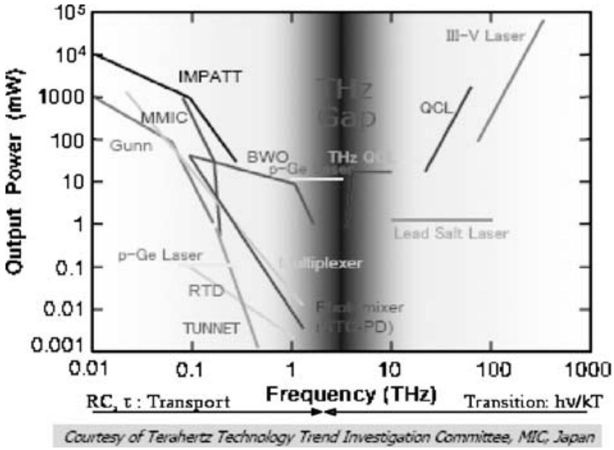


Fig. 2 Atmospheric attenuation at sea level pressures for six different conditions of temperature, humidity, and atmospheric particulates [8].

fabricate solid state sources in THz range [10] because the size becomes very small leading to very small power available. Figure 3 shows output power variation of conventional solid state sources. It can be seen that the efficiency of the sources falls drastically for higher THz range. The carrier transit time also becomes very short compared to microwave frequency signals. On the other side, conventional laser sources are not available at THz band because suitable semiconductors are not available. Recent researches have revealed the fact that Quantum cascade concept for semiconductor GaAs/AlGaAs heterostructures (Quantum Cascade laser) can be used for generation of THz signals. A Quantum Cascade laser comprises a series of thin layers of semiconductors. The thickness of the layers is so small that this is

Fig. 3 Power performance of different THz sources.



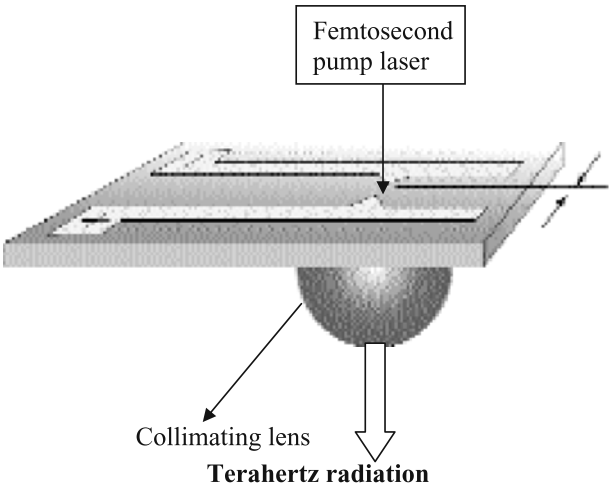
referred to as one dimensional multiple quantum well confinement.When one electron passes through a particular layer it emits a photon and immediately enters the second quantum well . Typically 25 to 75 active wells are arranged in a QC laser, each at a slightly lower energy level than the one before–thus producing the cascade effect, and allowing 25 to 75 photons to be created per electron journey. Quantum cascade laser has been successfully operated between 1.9 THz and 4.8 THz with output power up to 90 mW, single mode operation and narrow linewidth [11–16]. IMPATT diode, which is a powerful solid state source for mm amd sub-mm wave frequencies can also be used as a THz source [17–18]. The semiconductor material for developing IMPATTs should have higher breakdown voltage and higher thermal conductivity for having high RF power out of it. Wide bandgap SiC meets this criterion and is the ultimate choice for this. Ref. 17 presents a simulation based study of the dynamic performance of wide-bandgap 4H-SiC based double drift region (*p*++-*p*-*n*-*n*++) IMPATT diode at terahertz frequency (0.7 Terahertz) region. The simulation results show that the power out of a SiC based IMPATT diode is quite high (2.5×10^{11} Wm^{-2}) at a frequency of 0.7 THz.

Electro-optic rectification (different frequency mixing) is another process of producing THz radiation. A semiconductor along with a femtosecond pulse source produces THz radiation. A time dependent polarization in the THz frequency range is induced by a high electric field femtosecond pulse. This method can not generate THz frequency signals over broad frequency bands in THz frequency range. Another type of widely used THz source is Optically Pumped Terahertz Laser (OPTL). It consists of a grating-tuned carbon dioxide pump laser and a Far-Infrared (FIR) gas cell mounted in a laser resonator. These systems are smaller and can operate at several discrete frequencies ranging from 300 GHz to10 THz in time domain THz spectroscopy and sensing ultrashort laser pulses are generated to produce THz radiation.

A broadband short-pulse terahertz source used in Time Domain Spectroscopy (TDS) is shown in Fig. 4.

A split antenna, fabricated on a semiconductor substrate is used as a switch. A dc bias is applied across the two parts of the antenna, and an ultrashort pump-laser pulse (<100 fs) is focused in the gap in the antenna. The bias–laser pulse combination allows electrons to rapidly jump the gap, which induces current in the antenna and produces a terahertz radiation. This radiation is collected and collimated by a hemispherical lens (shown at the bottom side of the substrate) to produce a THz beam [19]. BWOs are electron tubes that can produce output at lower end of THz Frequency range. However they require very high magnetic field

Fig. 4 A broadband short-pulse terahertz source [19].



(~10 KG). Direct multiplied sources (DM) cannot produce THz signals directly. They take signals at millimeter wave frequency and multiply them to THz frequency. They can produce signals with frequency up to 1 THz (approx.). The output power available from them is small (~1 μW). These types of sources are mainly used as local oscillators in radio astronomy applications. Free electron laser (FEL), synchrotron light sources and optical parametric sources are also used for generation of THz signal. In free electron laser, an electron beam is accelerated to relativistic speed and it is sent through an array of magnets placed within a laser cavity. Due to the interaction of the accelerated electron beam with magnetic field a photon is emitted whose wavelength can be tuned to THz range by changing the electron beam energy or magnetic field strength. Synchrotron THz radiation from relativistic electrons have high power (~W) and broad linewidth [20]. However, FEL and synchrotron THz sources suffer from limitations in terms of cost and size. In optical parametric process, by using GaSe, $ZnGeP_2$, GaP, $LiNbO_3$ *etc*. more than hundreds of watt THz peak power can be generated. These THz sources also have narrow linewidth and are tunable making them useful for high resolution spectroscopy [21].

3 Terahertz Antennas

Different antenna structures have been proposed and used for the THz frequency range. In most of the cases the polarization state of the radiation emitted by THZ antenna has received less attention. Rudd *et al.* [22] first reported the measurement of cross-polarized component of the fields radiated from a THz dipole antenna as shown in Fig. 5. A dipole antenna situated in a pyramidal horn cavity etched in silicon, as shown in Fig. 8, has been operated at 0.8 THz (λ=375 μm) [23]. Corner reflector array antennas are widely used in THz frequencies. An array of four wavelength traveling wave antennas backed by 90° corner reflectors have been tested at 2.52 THz [24]. Figure 9 shows the configuration of the antenna. Centrally fed Bow-Tie antennas, which is a flat-plane version of the biconical antenna can also be used as a THz antenna. These antennas are very wideband in nature. A 3/2 λ bow tie antenna coupled to a MOM (metal oxide metal) diode designed at 28 THz [25] has the potential for use in arrays of antenna-coupled IR detectors.. A Planar antenna in the form log-periodic spirals or twin slots or twin dipoles [26], mounted on the back of a dielectric lens, is a typical configuration that is used in astronomical receiver for sending signal to a quasi-optical mixer [27]. This structure has the advantage that it can be easily fabricated along with the mixing device on the same substrate P. J. Burke [28] first predicted that it is possible to have a nanotube transistor with THz cutoff frequencies. Zeng *et al.* first reported [29] the simulated results for carbon nanotube THz antenna array. A

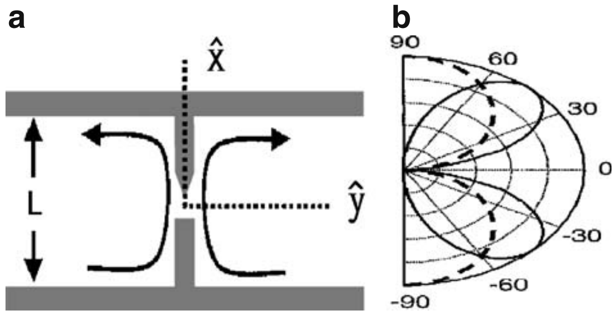


Fig. 5 (a) Schematic of the THz dipole antenna (b) and its radiation pattern. The dashed curve corresponds to free space radiation pattern and the solid curve shows the pattern when the structure is fabricated on a high dielectric substrate.

photoconductive terahertz antenna with radial symmetry has been reported in [30]. Yagi antennas, consisting of array of dipoles of different lengths, have one driven element, one reflector and a number of directors. They can be used as optical antennas.

The THz dipole antenna shown in Fig. 5 generates a cross-polarized component of electric field which is orthogonal to the axis of the dipole. The dipole antenna of length 60 μm is fed by two strip lines at both the ends. The arrows indicate the flow of current from one of the strips through the dipole to the other strip. The antenna is fabricated upon low temperature grown GaAs. The electric field component of the antenna is given by

$$\mathbf{E}_Q \propto \sin\theta \cos\theta \sin 2\varphi \,\widehat{\theta} + \sin\theta \cos 2\varphi \,\widehat{\varphi}, \tag{1}$$

Where φ is measured from x axis. For the *s*-polarized emission, (s polarization is in the plane of polarization perpendicular to the surface) the largest peak-to-peak electric field amplitude is approximately 7% of the *p*-polarized (in the plane of the surface) emission. The radiation pattern is distorted by the presence of the dielectric substrate [31]. In ref. [22],this antennas has been used in THz time domain spectroscopy as a transmitting antenna, which is also shown in Fig. 4 where the antenna has been coupled with a lens.

Reference [29] discusses about a novel THz antenna made of array of Carbon nanotubes. Finite length dipole antennas can be formed with CNT. They can be investigated using Hallen's-type integral equation. Antenna effect of Carbon nanotubes have been confirmed in Ref. [32]. As a receiving antenna the effect is maximized when the length of the antenna is multiple of half-wavelength. Carbon nanotube antennas may be analyzed using transmission line model. In this model several additional effects are to be considered [33]. In addition to the magnetic inductance and electrostatic capacitance, two additional components called quantum capacitance and kinetic inductance must be included in the equivalent circuit. The wave velocity in a CNT will be modified to

$$V_p = \frac{1}{\sqrt{L_k C_{total}}} \tag{2}$$

where $\frac{1}{C_{total}} = \frac{1}{C_g} + \frac{1}{C_{ES}}$, C_q is the quantum capacitance ,C_{ES} is the electrostatic capacitance and L_k is the kinetic inductance.

As can be seen from Fig. 6(b), that gain improves with increase in the length of the antenna. Gain can also be increased with increase in the number of elements in the array and suitably choosing the inter element distance d. The directivity is also good for the antenna (Fig. 6(c). So the Carbon Nanotube antenna can be properly designed to get sufficient power radiated or received from it.

Figure 7 shows a photoconductive terahertz antenna with radial symmetry, which has been reported in [30]. In quasi-optical configurations, it is difficult to design waveguides or coaxial waveguides for carrying terahertz pulses. This is due to the fact that lowest-order (TEM) mode of such guides possesses a radial electric field polarization. Here, a novel cylindrically symmetric substrate antenna design which is compatible with THz time domain spectroscopy is presented. Using theoretical analysis and finite elements method, properties of the radiated far-field pattern has been explored and it has been shown that the field possesses the desired radial polarization pattern. Design of this antenna is based on Finite Element Method (FEM) model. Neglecting the effect of the dielectric substrate, the fields radiated from the antenna can be thought of as a superposition of those from a large number of dipoles, each pointing radially away from the origin. The resulting field can be easily computed, since the field from each one of these point dipoles can be found by simply shifting and rotating a classical far-

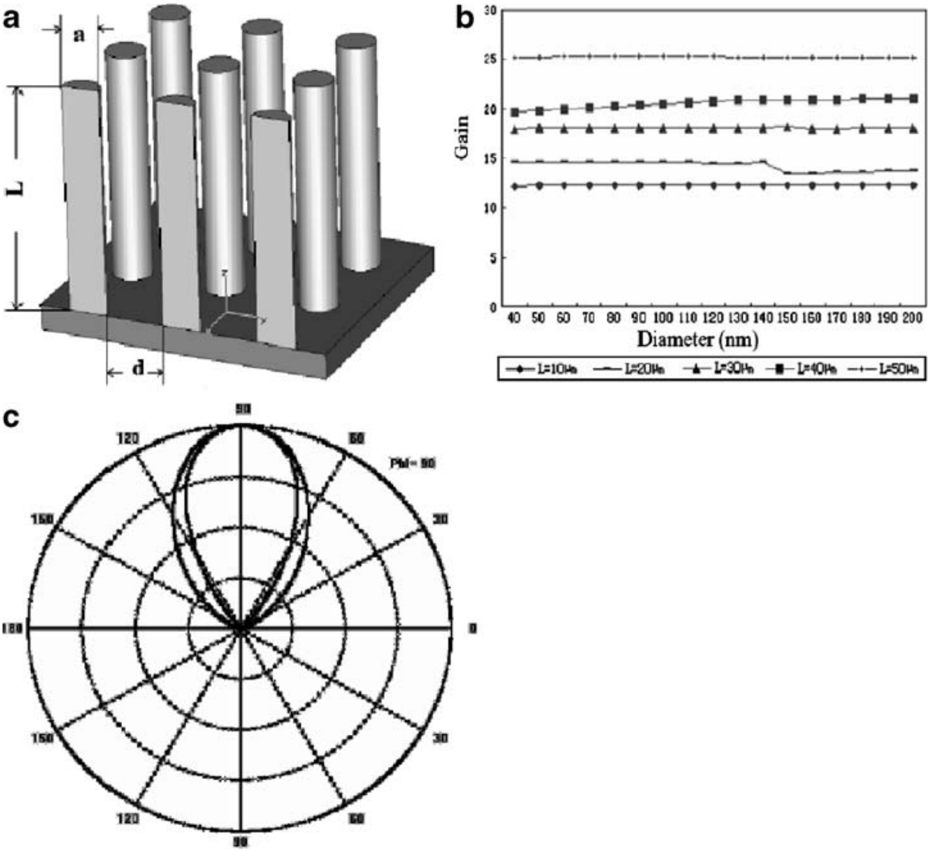


Fig. 6 (a) Carbon Nanotube Antenna array (b) variation of gain with diameter and length of Carbon Nanotube. (c)Directivity pattern of the antenna for d=λ/8 (inside pattern) and d=λ/40(outside pattern).

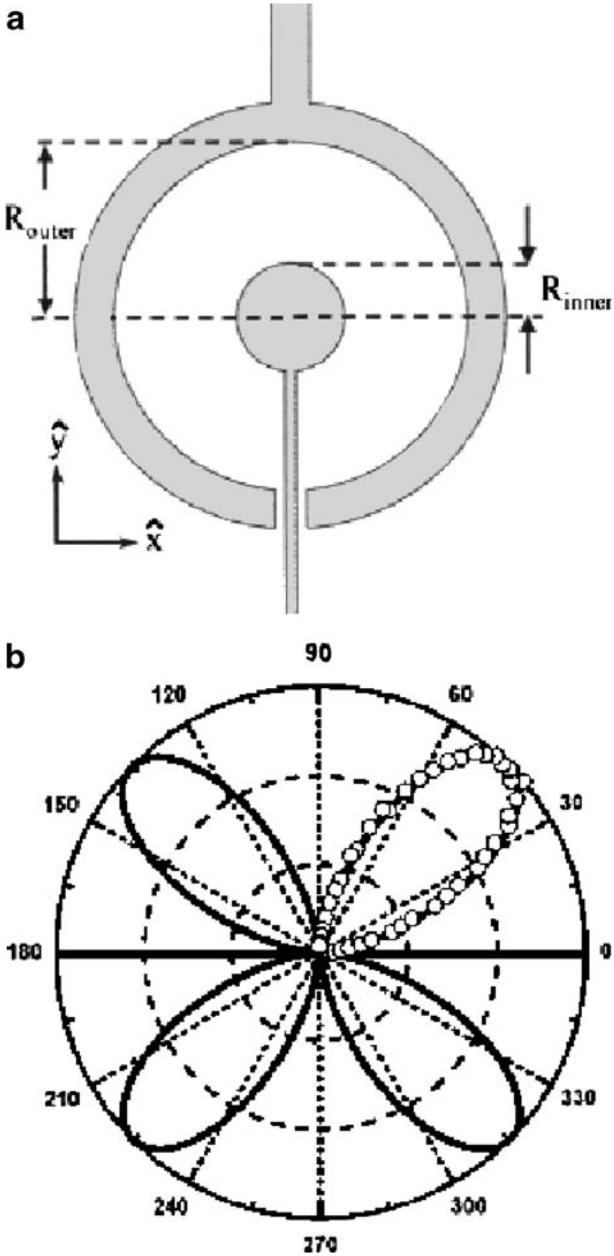
field dipole pattern. Then the antenna is fabricated on a substrate of high dielectric constant €=12.25, the approximate value for GaAs.

The integrated horn antenna [23] comprises of two stacked wafers where the horn cavity is etched on the front wafer. A dipole antenna suspended in a 1 pm thin dielectric is placed at the back side of the front wafer and the back wafer acts as a reflecting structure (Fig. 8). The horn antenna is treated as a number of stepped waveguides connected to each other and the Green's function for the dipole antenna is obtained. The electric field inside the horn may be written in terms of the electric current on the strip dipole as shown below:

$$\mathrm{E} = \int_{\mathrm{Sd}} \mathrm{G.Jdx'dy'} \qquad (3)$$

where G is the modified dyadic Green's function for the structure and $\boldsymbol{S_d}$ is the surface of the strip dipole. The green's function is used for calculation of input impedance and resonant properties of the feeding strip. Results show that this antenna is a very high efficiency antenna with a very high gain. This may solve the power problem for THz antennas. The theoretical and experimental results for the antenna has been presented in Ref. [34, 35]. A 256-element imaging array [36] of this kind of integrated horn antenna has been fabricated

Fig. 7 (a) The proposed radially symmetric antenna and (b) it's far field radiation pattern.



and tested at 802 GHz. The array period is 500 pm, and the total array size is 8×8 mm^2. The radiation patterns of the antenna array have been measured at 802 GHz (Fig. 9b), showing a directivity12.3± 0.2dB for 1.41 λ horn aperture. The measured patterns are symmetrical with a main-beam efficiency of 88% in a 100° beamwidth.

Corner cube antenna consisting of a traveling wave antenna backed by a corner reflector is extensively used in submillimeter-wave receivers [37–42]. The integrated corner-cube

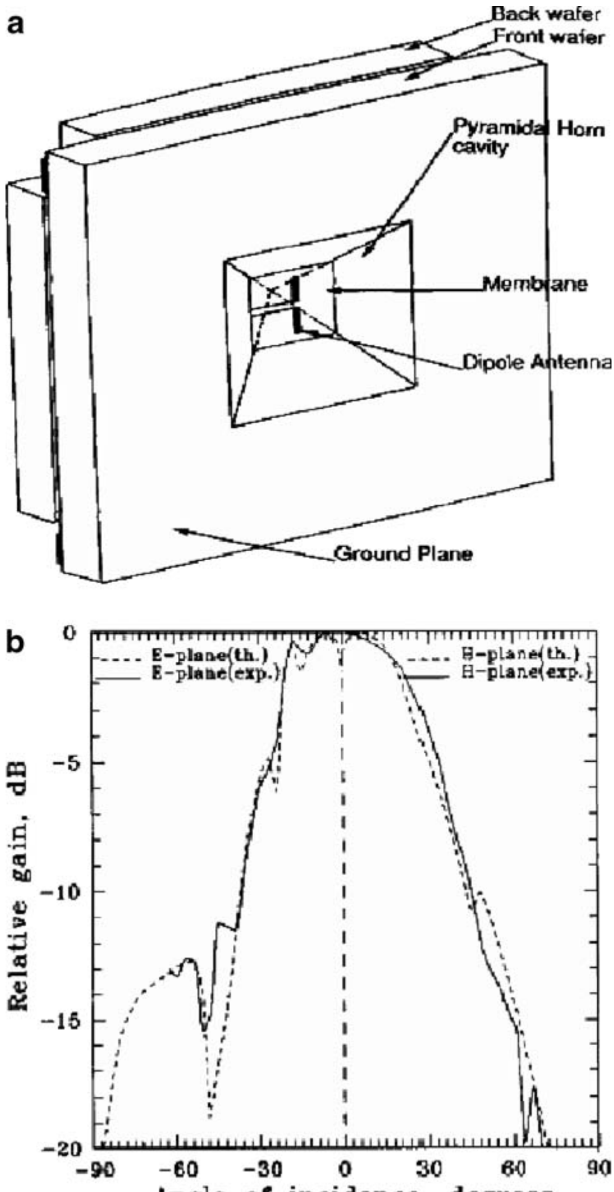


Fig. 8 (a) An integrated horn antenna (b) theoretical and experimental E-plane & H-plane pattern measured at 802 GHz for a 256 element two dimensional horn array.

antenna consists of a cavity etched in silicon wafers, inside which a traveling-wave antenna is suspended on a 1-μm dielectric membrane formed by depositing a 3-layer $Si0_2$-Si_3N_4, (Fig. 9(a)). The membrane electrical thickness is 0.02 λ at 3 THz, so the traveling-wave antenna effectively radiates in free space at 119 μm. Figure 9(b) shows that this antenna has a high gain and can work efficiently at low power level

Length of the antenna and the distance of the antenna from the apex of corner reflector are the design parameters in this design. This antenna has the advantage that it is fully monolithic and is easily reproducible for array applications.

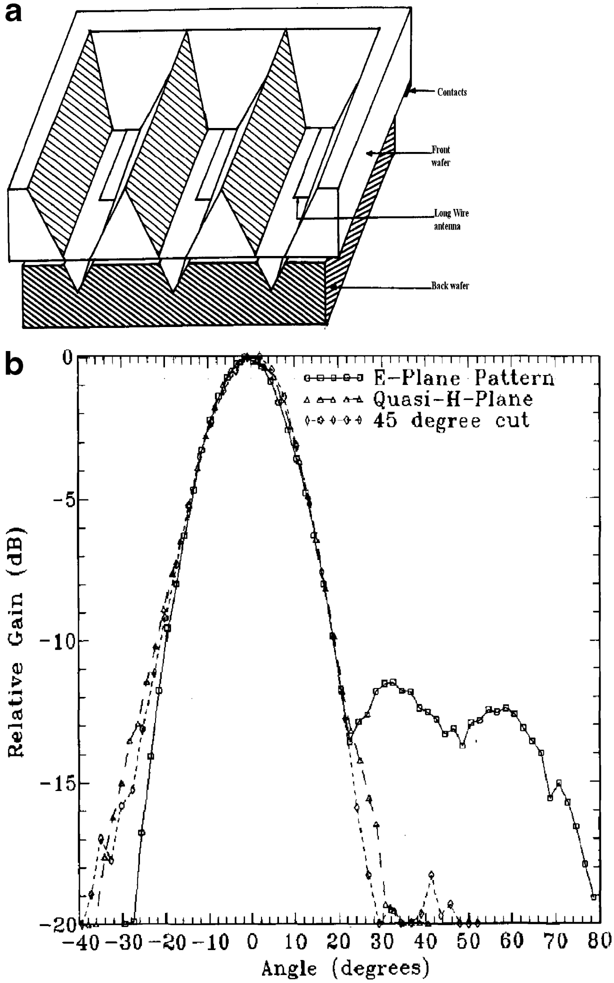


Fig. 9 (a) A corner reflector imaging array (b) and its radiation pattern measured at 3 THz.

4 Conclusion

THz sources and THz antennas are two critical areas where advances of technology are required. Sources are also to be designed that can produce high power at an affordable cost. From the information available from different surveys and investigations it can concluded that conventional electronics fails to produce THz frequency signals efficiently. The available technology is very costly and to work with THz signals, one needs to be well funded. Among the different types of sources reviewed Quantum Cascade Laser works best for generation of THz signals. However extending this concept below 10 THz is a challenge. Among the semiconductors available Wide band gap SiC is a good choice for fabricating solid state sources at THz frequencies. Research on IMPATT THz sources is still in the simulation level.

Because of its huge scope of applications, new and simple antenna configurations are required to be designed in THz frequency region which will be ultrawideband as well as easily integrable with transmitters and receivers. In THz region the size of the antenna becomes so small that it becomes difficult to fabricate them. Each of the various types of THz antennas reviewed in this paper possesses some unique feature. Figure 5 gives the simplest design for generation of THz signal- a dipole antenna. Carbon nanotube is a technology which has many potential applications. Ref. 29 shows that they can be used in THz frequency also. But the research is still in nascent stage. Experimental results are not yet available. Both integrated horn antenna and corner cube antenna are part of an integrated monolithic receiver. These structures are very compact and leave sufficient space for the electronic circuitry of the receiver. GaAs or Si is the obvious choice for the basic substrate of most of the antennas. All the antennas can be used as an array thus improving gain of the antenna. Also in optical domain, the antenna concept is new. An optical antenna is a device that efficiently couples the energy of free space radiation to a confined region of subwavelength size. In recent years optical antennas has acquired great interest because a number of interesting applications have emerged. For example, it is found that the radiative decay rate of fluorescent dye molecules are strongly enhanced by the presence of an optical nanoantenna [43]. Dipoles, monopoles, bowties, patches, and Yagi–Uda arrays are some of the structures that have been investigated in optical regime. Optical antennas have become possible in large part due to recent advances in fabrication technology, allowing sub-100 nm structures to be routinely produced.

References

1. D. L. Woolard, W. R. Loerop, and M. S. Shur, Eds., Terahertz Sensing Technology, Singapore: *World Scientific*, **1**, (2003), Electronic Devices and Advanced Systems Technology.
2. D. L. Woolard, W. R. Loerop, and M. S. Shur Eds., Terahertz Sensing Technology. Singapore: *World Scientific*, **2**, (2003), Emerging Scientific Applications and Novel Device Concepts.
3. D. Mittleman Ed., Sensing With Terahertz Radiation, ser. Opt. Sci., Berlin Berlin, Germany: Springer-Verlag, (2003).
4. F. C. De Lucia, D. T. Petkie, R. K. Shelton, S. L. Westcott, and B. N. Strecker, THz + 'X'—a Search for New Approaches to Significant Problems, *Proc. SPIE.*, **5790**, (2005), pp. 219–230.
5. Dwight L. Woolard, Elliott R. Brown, Michael Pepper, And Michael Kemp, Terahertz Frequency Sensing and Imaging : A Time of Reckoning Future Application ?, *Proceedings of The IEEE*, **93**, No. 10, (2005) pp.1722-1743.
6. P. H. Siegel, Terahertz Technology in Biology and Medicine. IEEE Transaction on Microwave Theory and Techniques. **52**, 2438 (2004).
7. P. H. Siegel, Terahertz Technology. IEEE Transactions on Antennas and Propagation **50**, 912 (2002).
8. R. Appleby, and H. B. Wallace, Standoff Detection of Weapons and Contraband in the100 GHz to 1 THz Region. IEEE Transactions On Antennas And Propagation. 55(), (11)), 2944–2956 (2007).
9. A. G. Davies, E. H. Linfield, and M. B. Johnston, The Development Of Terahertz Sources and Their Applications. Phys. Med. Biol. 47, 3679–3689 (2002).
10. J. M. Chamberlain, R. E. Miles, C. E. Collins and D. P. Steenson, New Directions in Terahertz Technology, ed. J M Chamberlain and R E Miles (NATO ASI Series, Kluwer) 1997.
11. B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, Operation of Terahertz Quantum-Cascade Lasers at 164 K in Pulsed Mode and at 117 K In Continuous-Wave Mode. Opt. Express **13**, 3331–3339 (2005).
12. S. Barbieri, J. Alton, H. E. Beere, J. Fowler, E. H. Linfield, and D. A. Ritchie, 2.9 THz Quantum Cascade Lasers Operating up to 70 K in Continuous Wave. Appl. Phys. Lett. **85**, 1674–1676 (2004).
13. L. Ajili, G. Scalari, J. Faist, H. E. Beere, J. Fowler, E. H. Linfield, D. A. Ritchie, and A. G. Davies, High Power Quantum Cascade Lasers Operating at $\lambda \approx 87$ μm and 130 μm. Appl. Phys. Lett. **85**, 3986–3988 (2004).
14. A. Tredicucci, L. Mahler, T. Losco, J. Xu, C. Mauro, R. Köhler, H. E. Beere, D. A. Ritchie, and E. H. Linfield, Advances in THz Quantum Cascade Lasers: Fulfilling The Application Potential, in *Novel In-Plane Semiconductor Lasers IV*, C. Mermelstein, D. P. Bour, eds., Proc. SPIE, **5738**, (2005), 146–158.
15. L. Mahler, R. Köhler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, D. A. Ritchie, and A. G. Davies, Single-mode Operation of Terahertz Quantum Cascade Lasers with Distributed Feedback Resonators. Appl. Phys. Lett. **84**, 5446–5448 (2004).
16. A. Barkan, F. K. Tittel, D. M. Mittleman, R. Dengler, P. H. Siegel, G. Scalari, L. Ajili, J. Faist, H. E. Beere, E. H. Linfield, A. G. Davies, and D. A. Ritchie, Linewidth and Tuning Characteristics of Terahertz Quantum Cascade Lasers. Opt. Lett. **29**, 575–577 (2004).

17. M. Mukherjee, N. Mazumder, and Sitesh Kumar Roy, Prospects of 4H-SiC Double Drift Region IMPATT Device as a Photo-Sensitive Terahertz Frequency Regime, Hindawi Publishing Corporation, Active and Passive Electronic Components, Volume 2008, Article ID 275357, 9 pages doi:10.1155/2008/275357
18. M. Mukherjee, N. Mazumder, S. K. Roy, and K. Goswami, GaN IMPATT Diode: a Photo-Sensitive High Power Terahertz Source. Semiconductor Science and Technology **22**(12), 1258–1267 (2007) (10).
19. E. R. Mueller, Terahertz Radiation: Applications and Source, The Industrial Physicist, American Institue of Physics, (2003), 27–29.
20. G. L. Carr, M. C. Martin, W. R. Mckinney, K. Jordon, G. R. Neil, and G. P. Williams, High-Power Terahertz Radiation From Relativistic Electrons. Nature **420**, 153–156 (2002).
21. K. Kawase, J. Shikata, and H. Ito, Terahertz Wave Parametric Source. J. Phys. D: Appl. Phys. **34**, R1–R14 (2001).
22. J. V. Rudd, J. L. Johnson, and D. M. Mittleman, Quadrupole Radiation from Terahertz Dipole Antennas. Opt. Letters. **25**(20), 1556–1558 (2000).
23. C. Fumeaux, G. D. Boreman, W. Herrmann, F. K. Neubuhi, and H. Rothuizen, Spatial Impulse Response of Lithographic Infrared Antennas. Appl. Phys. Lett. **38**, 37–46 (1999).
24. S. S. Gearhart, C. C. Ling, G. M. Rebeiz, H. Davee, and G. Chin, Integrated 119-μm Linear Corner-Cube Array. IEEE Microwave and Guided Wave Letters **1**, 155–157 (1991).
25. G. M. Rebeiz, L. F. B. Katehi, W. Y. Ali-Ahmad, G. V. Eleftheriadws, and C. C. Ling, Integrated Horn Antennas for Millimeter-Wave Applications. IEEE Antenna and Propagation Magazine. **34**, 7–16 (1992).
26. P. Goldsmith, Quasioptical Systems, IEEE Press, (1998)169.
27. M. Bin, Ph.D thesis, Cal.Inst.Tech., (1997).
28. P. J. Burke, Carbon Nanotube Devices for GHz to THz Applications, Proceedings of SPIE, **5593** (SPIE, Bellingham, WA, 2004),pp.52-61.
29. Y. Lan, B. Zeng, H. Zhang, B. Chen, and Z. Yang, Simulation of Carbon Nanotube THz Antenna Array. International Journal of Infrared and Millimeter Waves. **27**(6), 871–877 (2006).
30. J. A. Deibel, M. D. Escarra, and D. M. Mittleman, Photoconductive Terahertz Antenna with Radial Symmetry, Quantum Electronics and Laser Science Conference (QELS), (2005) pp. 1239–1241.
31. P. U. Jepsen, THz Radiation Patterns from Dipole Antennas and Guided Ultrafast Pulse Propagation, M.S. Thesis (Odense Universitet, Odense, Denmark, 1994).
32. G. W. Hanson, Fundamental Transmitting Properties of Carbon Nanotube Antennas. IEEE Transactions on Antennas and Propagation **53**(11), 3426–3435 (2005).
33. P. J. Burke, S. Li, and Z. Yu, Quantitative Theory of Nanowire and nanotube Antenna Performance. IEEE Transactions on Nanotechnology **5**(4), 314–334 (2006).
34. W. Y. Ali-Ahmad, G. V. Eleftheriades, L. P. Katehi, and G. M. Rebeiz, Millimeter-Wave Integrated-Horn Antennas, Part 1-Theory. IEEE Transactions on Antennas and Propagation **39**(11), 1575–1581 (1991).
35. W. Y. Ali-Ahmad, G. V. Eleftheriades, L. P. Katehi, and G. M. Rebeiz, Millimeter-Wave Integrated-Horn Antennas, Part II- Experiment. IEEE Transactions on Antennas and Propagation **39**(11), 1582–1586 (1991).
36. W. Y. Ali-Ahmad, G. M. Rebeiz, H. Davee, and G. Chin, 802 GHz Integrated Horn Antennas Imaging Array. Intl. J. Infrared Millimeter Waves **12**, 481–486 (1991).
37. H. R. Fetterman *et al.*, Far-IR Heterodyne Radiometric Measurements with Quasi-Optical Schottky Diode Mixers. Appl. Phys. Lett. **33**, 151–154 (1978).
38. E. Sauter, G. V. Schultz, and R. Wohleben, Antenna Pattern of an Open Structure Mixer at a Submillimeter Wavelength and of Its Scaled Model. Int. J. Infrared and Millimeter Waves **5**(4), 451–463 (1984).
39. J. Zmuidzinas, A. L. Betz, and R. T. Boreiko, A Corner-Reflector Mixer for Far-Infrared Wavelengths. Infrared Phys. **29**, 119–131 (1989).
40. H. P. Roser, E. J. Dunven, R. Wattenbach, and G. V. Schultz, Investigation of a Heterodyne Receiver with Open Structure Mixer at 324 and 693 GHz. Int. J. Idrared and Millimeter Waves. **5**(3), 301–314 (1984).
41. W. M. Kelly, M. J. Gans, and J. G. Eivers, Modeliing the Response of Quasi-Optical Comer Cube Mixers, *Instrumentation for Submillimeter Spectroscopy,* E. Kollberg, Ed., Proc. SPIE. 598, 72–78 (1986).
42. E. N. Grossman, The Coupling of Submillimeter-Wave Corner-Cube Antenna to Gaussian beams. Infrared Phys. **29**, 875 (1989).
43. G. W. Hanson, and P. de Maagt, Guest Editorial for the Special Issue on Optical and THz Antenna Technology. IEEE Transactions On Antennas And Propagation **55**(11), 2942–2943 (2007).