The "challenging" world of Terahertz radiation and imaging

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***Abstract*—THz propagation through materials may reveal unique macroscopic and physical properties of their internal structure without the damage associated with ionizing radiation. The generation, radiation, and detection of THz signals relays into an intermediate region between microwave and optical frequencies seen as a transition in device physics from classical transport to quantum transition. The physical properties and parameters of the antennas and electronic devices at these frequencies (0.1-10THz) will we compared with their microwave and optical counterparts, the important differences highlighted and its significance in terms of spectral bandwidth and signal-to-noise ratio for near and short range imaging systems reviewed. Finally, some of the recent significant developments in the field will be summarized and the potential applications and future challenges and opportunities identified.**

I. Introduction

There is an on-going trend towards the use of higher portions of the electromagnetic spectrum. In most cases the driving force is the application to remote sensing and imaging. There are undoubtful benefits in terms of spatial resolution derived from the submillimeter wavelength at frequencies above 300 GHz.

This push towards higher frequencies is hindered by many technological difficulties in all the subsystems involved in the generation, transmission and detection of signals. Antenna design faces specific challenges that range from the need of microfabrication to the requirement to consider the electromagnetic interaction at the nanoscale, and in most applications antenna design is heavily constrained by the way signals are generated and detected.

In this review paper three different approaches to antenna design are presented. They are organized in increasing frequency of application, and the different design approaches as well as their limitations are discussed.

At the sub-THz frequencies the wavelength is of the order of some tenths of millimeter. At these frequencies it is possible through microfabrication techniques to adopt well-known antenna concepts such as horns and lenses based on classical electromagnetic design. In this case the biggest challenge is to provide robust designs in front of fabrication tolerances. Ultimately, the fabrication tolerances set the upper frequency limit to which these microfabrication techniques can be applied.

At the THz regime antenna design is essentially conditioned by the way signals are generated and detected. A common approach in THz generation is the use of photocondutor effect to radiate wide spectrum time domain signals in the THz band. THz radiation is caused by induced carrier movement by a short duration light pulse on a photoconductor antenna. The radiation and reception of this wide band signals can be efficiently done by classical wide band antennas, such as spiral, Vivaldi and other well-known UWB antennas, but the challenge resides in adequately model the interaction between the light source and the photoconducting antenna.

The potentiality to build elements such as carbon nanotubes opens up the possibility to design antennas structured at the nanoscale for higher frequency applications. In this case macroscopic description of materials is not useful in the antenna design and the interaction of the electromagnetic waves at the nanoscale must be considered.

In the following sections a thorough review of each of the three previously described cases is presented.

II. Microwave Antennas at THz

The Terahertz region, as a spectral gap between the microwaves and infrared implies a technological challenge in antenna design and fabrication. When designing THz antennas, one approach would be scaling the antenna structures to the THz band.

Planar antennas are characterized by its robustness, low volume, low-cost fabrication and their potential for integration. The dipole, double-dipole, slots and double slots (Fig. 1) are the standard antenna types usually fabricated using regular photolithography or electron-beam lithography.

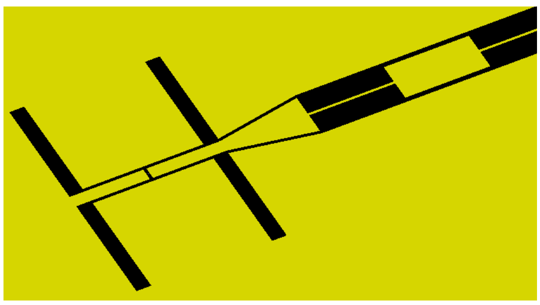
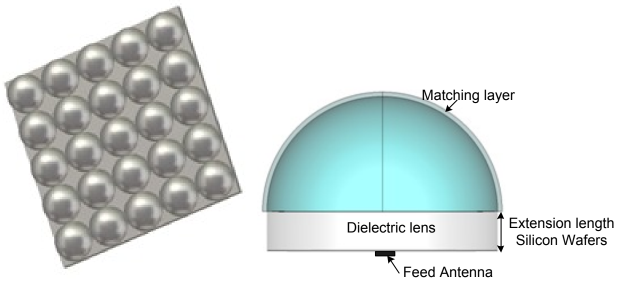


Fig. 1. Double-slot antenna

When high bandwidth is required, angular antennas (bow-tie, Archimedean spiral and log-spiral antennas), selfcomplementary antennas (log-periodic antennas) and self-similar antennas (fractal and log-periodic antennas) are employed. The materials commonly used are copper, aluminum or gold for the antenna and Silicon, Sapphire and GaAs for the substrate. However, substrates are very fragile and thin at THz range. Thick dielectric substrates experience from power loss into substrate modes. One method to eliminate the substrate modes is by placing the antenna on a dielectric lens of the same dielectric constant as the planar antenna wafer [1]. The system radiates most of its power into the dielectric side, making a unidirectional pattern on the high dielectric lenses (Fig. 2a). Silicon is a dielectric material commonly used for this purpose for its handling convenience with photolithographic [2] or machining techniques [3]. To solve the lens reflection at free-space a coating layer of dielectric constant $\varepsilon_{coat} = \sqrt{\varepsilon_{si}}$ and thickness of $t_{coat} = \lambda_{coat}/4$ is integrated above the dielectric surface (Fig. 2b).



(a) (b)

Fig. 2. (a) Silicon Lens array. Dielectric lens provides mechanical rigidity and therman stability. (b) Feed antenna integrated on a dielectric lens

Another method to combine a thin substrate is to place the antenna on a very thin dielectric membrane. The membranes are built-in on silicon or GaAs wafers and the antennas radiate as if suspended in free-space. However, after integration, appropriate design methods must be used to provide a unidirectional pattern.

Horns are typically used at microwave frequencies. Milling and turning are the most general techniques for horn fabrication. However, at THz frequencies they become very small structures and they require alternative fabrication methods. Using silicon microfabrication, one can develop an array of antennas using a photo-lithographic process by stacking thin gold plated silicon wafers with tapered holes. The tolerance will depend on the photo-lithographic exposure and etching, as well as on the number and alignment of these wafers. Because of the fabrication tolerance, this process works acceptably for frequencies up to 800 THz. Stepped or corrugated horns (Fig. 3) are designs that adapt to this fabrication technique. Another commonly used method is laser machining technique [4]. This procedure will allow fabricating a 3D geometry, allowing the construction of Picket-Potter horns [5] and smooth walled horns. However, it will not be cost-efficient for large arrays.

When we talk about THz imaging system like in Fig. 4, parabolic mirrors and lenses are evenly used as focusing elements. Parabolic mirrors are usually made out of aluminum which is opaque for THz radiation. High surface accuracy is required to avoid scattering effect. While parabolic mirrors are classically utilized in the microwave regime, lenses are typically used at optical frequencies. The main problem of lenses is the absorption losses inside the lens material. Table I shows different materials that are regularly employed for THz lens construction

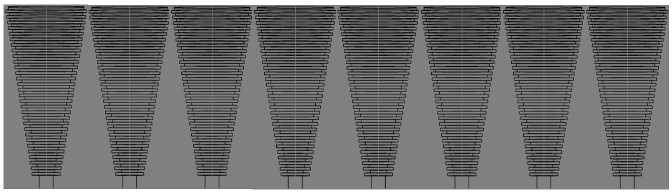


Fig. 3. Corrugated horn array by stacking thin gold plated silicon wafers

TABLE I
MATERIALS USED FOR THZ LENS FABRICATION

Material	**N**	**10^{-4}tanδ**	**F [GHz]**
Acryl	1.61	81-135	60-300
Mylar	1.75	360-680	120-1000
Polyethylen	1.52	3.6-4.4	90-270
Rexolite	1.59	15-40	120-550
Styropor	1.03	0.53-0.81	200-260
Teflon	1.43	2.5-17	120-1110
TPX	1.46	5.6-13	300-1200

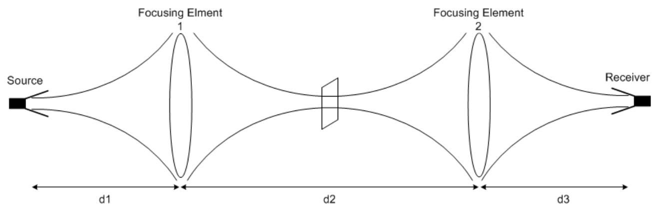


Fig. 4. Set up for a THz imaging system with lenses as a focusing element. Distances d1, d2 and d3 must be determined to avoid Gaussian-beam coupling

III. PHOTOCONDUCTIVE ANTENNAS AT THZ FREQUENCIES

A common technique to measure radiation power in Terahertz frequencies is using hot electron bolometers. The main advantages of these devices are their high sensitivity, the sub-nanosecond time response and a low noise equivalent power (NEP) in the order of $10^{-14}W/\sqrt{Hz}$ [6]. However, in order to obtain a good performance in terms of sensitivity and NEP at Terahertz frequencies, the bolometer should be designed using superconductors and cooling down the device in a cryostat. To prevent this photoconductive antennas arise as an alternative solution to work at room temperature.

A. Time Domain THz Photoconductive Antennas

THz photonics has arisen as a important technology for the generation, reception, and manipulation of both pulsed and continuous-wave THz signals. A remarkable application of the Terahertz waves is the time domain spectroscopy (THz-TDS), comprising a frequency range from 0.2 THz to 3 THz [7]. Thanks to its wide bandwidth, this technique is used to characterize the so-called spectrum fingerprint of many materials in a wide variety of interest areas (i.e. pharmacology, alimentary, non-destructive testing…). A typical scheme of a THz-TDS system is shown in Fig. 5.

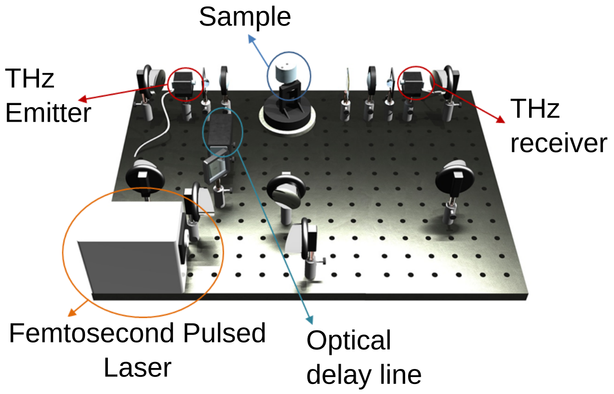


Fig. 5. Schematic design of a THz-TDS system for imaging purposes

Metals have a small skin depth at these frequencies leading to high propagation losses in the transmission lines. Therefore conventional antennas with the transmitter/receiver away from the antenna are not suitable at THz frequencies. In order to avoid this problem, photoconductive antennas [8] are used to bring closer the generation and detection of Terahertz radiation at the antenna port. These antennas are fabricated using a semiconductor substrate with small carrier lifetime (i.e. LT-GaAs) where the RF energy is generated by means of the photoconductive process, in which a semiconductor is biased using a DC voltage and a femtosecond laser excites the semiconductor. Fig. 6 shows an scheme of a dipole photoconductive antenna. In this process, free charges are created at the semiconductor due to the incoming laser radiation while the current density changes rapidly due to the bias voltage. The current generated by the incident laser radiation at time delay t is described by the following equation:

$$J(t) = e\mu \int_{-\infty}^{\infty} E(t')N(t'-t)dt' \tag{1}$$

where $E(t)$, $N(t)$, e and μ are the incident field of THz radiation, the number of photocreated carriers, the elementary electric charge, and the electron mobility respectively. The radiation pulse width emitted by the antenna depends on the laser pulse width and the temporal width of $N(t)$. The time duration of the latter is restricted by several factors, such as momentum relaxation of photocarriers, and carrier lifetime of photoconductive material.

The photocurrent produces an electromagnetic energy that is coupled into a radiation beam using planar antennas (i.e. dipole [9], bowtie, spiral [10]). Finally, this beam is focused into free-space using an hyper-hemispherical plano-convex lens.

The election of the proper antenna depends on the required application bandwidth and wave polarization. Moreover, the impedance matching is still a challenge in photoconductive antennas. The resistance of a LT-GaAs photoconductor is typically greater than 10 kOhm whereas the impedance of planar antennas on dielectric substrate is usually below 100 Ohm. Thus, resonant antennas like the slot and dipole antennas have an advantage over broadband antennas, since the impedance of the latter is smaller. When designing the antenna using a EM simulator, a lumped or discrete port may be used taking into account the photoconductor impedance. Additional aspects have to be considered when designing a photoconductive antenna. The effect of the substrate on the antenna behavior [11] is one example, since usually the thickness of the substrate is comparable to the wavelength, leading to surface waves trapped in the substrate. Furthermore, conventional photoconductive antennas have an almost omni-directional radiation pattern and they suffer from back radiation thus having low beam efficiency. In order to solve this issue, a photoconductive horn has been developed with a directivity close to 19 dBi [12].

The same antenna structure is used for detection of THz radiation. In this case the free electron charges produced by the photoconductive effect interact with the impinging THz field, hence creating a current at the DC bias port.

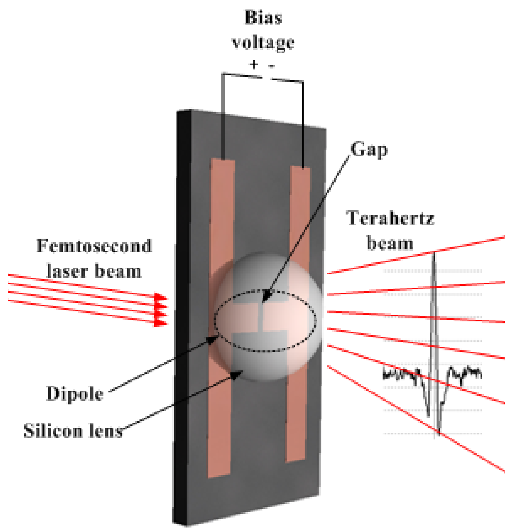


Fig. 6. Schematic of a dipole photoconductive antenna in transmission mode.

B. CW Photomixer Antennas

Photoconductive photomixers (CW) have been widely employed to generate Terahertz signals by means of a heterodyne mixing, gaining high value due to its compactness and widely tunable frequency range.It is commonly integrated with an antenna and used as a THz emitter and detector.

In Fig. 7 it is shown a schematic of a THz emitter based on a photomixer. Two laser beams with a slight difference in their central frequencies combine within a photoconductive film, producing an interference signal known as beat frequency. This frequency modulates the conductance of a biased photoconductive switch, so that electrical oscillations are produced at THz frequencies, which are transmitted to free space via an antenna or silicon lens.

As in the case of the time-domain antennas, detection is performed in the same way as emission but with a reverse scheme. In that case the photomixer acts as a homodyne receiver in which the time delay and amplitude of the EM-THz signal provides the information of the scene under test.

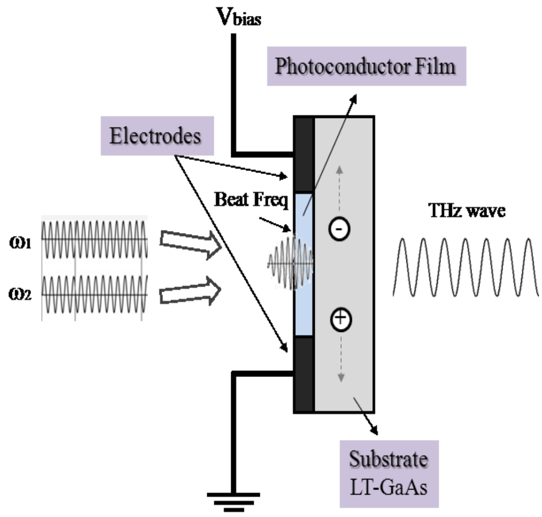


Fig. 7. Photomixer emitter schematic. The carrier density in the LT-GaAs oscillates at the optical beat frequency, inducing a terahertz signal in the antenna (electrodes), which is then emitted in phase with the incident optical beat.

CW photoconductive antennas also suffer from impedance mismatch, nevertheless a variety of designs have been developed to improve it. Namely, in [13] a folded dipole antenna is numerically computed by means of EM simulations, in which several parameters are optimized, furthermore in [14] a Yagui-Uda antenna is designed and simulated using EM software as well in order to obtain a high well-matched input impedande to transmit the maximum power from the photomixer.

IV. Carbon nanotubes at Terahertz frequencies

Carbon nanotubes are one-dimensional structures formed by an hexagonal lattice of carbon atoms, called graphene, rolled to form a seamless cylinder [15], see Fig. 8. The direction of the rolling, its radius and the number of layers determine the electronic properties, such as the conductivity, or their semi-conducting effect. Common dimensions for carbon nanotubes are a few nanometers in radius, and lengths can vary from micrometers to several millimeter.

Due to their small size, carbon nanotubes are good candidates for nano-fabrication and pose an extraordinary opportunity for fabrication of terahertz components, such as antennas and detectors. Moreover their structure would be highly compatible with nano-electronics based on graphene.

A. Single carbon nanotube at THz frequencies

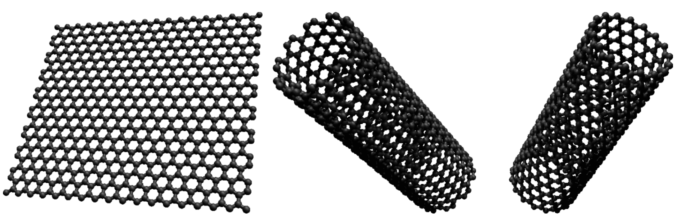
In [16], [17] a model for the conductivity for single wall carbon nanotubes is proposed for frequencies below optical interband transitions:

$$\sigma = \frac{2e^2 v_F}{\pi^2 \hbar a \left(\nu + j\omega\right)} \tag{2}$$

where e stands for the electron charge, v_F is the Fermi velocity, usually between $8.1 \cdot 10^5$ and $1 \cdot 10^6 \mathrm{m/s}$, $\hbar$ is the reduced Planck constant, a is the radius of the nanotube, and ν is its relaxation frequency, which for terahertz frequencies is on the order of $\frac{1}{3\mathrm{ps}}$. Several things can be stated from this formula; on one hand it can be observed that the real part of the conductivity is finite, nevertheless carbon nanotubes are expected to present a much better conductivity than conventional metals of the same dimensions, and therefore should perform better under the same conditions. On the other hand, there is a non-null imaginary part in the conductivity, unlike with conventional metals which at these frequencies, still far away from the plasma frequency, have a finite but real conductivity. This imaginary part in the conductivity arises from the incapability of the electrons to follow the electromagnetic wave, due to its own inertia, and introduces an inductive effect in the propagation of the electromagnetic wave. In fact this effect is usually modeled, [18], as an extra inductance, L_K, which is several orders of magnitude above the magnetic inductance, L_M. This implies that for a transmission line model with carbon nanotubes, the electromagnetic wave propagates at a much slower speed along the nanotube and therefore resonance arises at a much smaller scale, in the order of 50 to 100 times smaller as shown in Fig. 9 that presents an example of the expected resonances for a carbon nanotube of length of $200 \mathrm{nm}$

To assess the radiating properties of single carbon nanotubes, we must take into account three effects:

- The radiation resistance of the antenna will be small, as it is proportional to the square of the length for small dipoles.
- The losses in the antenna can be high, since although extremely good conductor, the carbon nanotube has a small cross section.



(a) Graphene (b) Carbon nanotubes (armchair and zigzag)

Fig. 8. Graphene sheet and different carbon nanotubes, depending on the rolling direction.

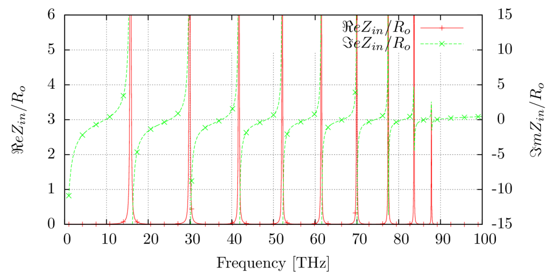


Fig. 9. Predicted input impedance for a carbon nanotube of total length 200nm, $a = 2.7$nm.

- The characteristic impedance intrinsic to the carbon nanotube, [17], [18], is on the order of $k\Omega$.

It can be seen that isolated carbon nanotubes might present a extremely low radiating efficiency, on the order of 10^{-4} [17], with a high mismatch to external circuitry of 50Ω.

B. Bundles of carbon nanotubes

To improve the performance of carbon nanotubes, several authors [19] study their behavior when they are joined to conform bundles of carbon nanotubes. [19] shows how the efficiency of carbon nanotubes antennas can be greatly increased when a large amount of nanotubes are placed in parallel. Additionally the input impedance of the nanotubes will be greatly reduced which improves the matching condition of the nanotubes. It must be noted that the expected reduction in dimensions due to the L_k is reduced as the number of nanotubes in the bundle increases, although it still remains with reduction factors of 2-3 for efficiencies of 50%.

C. Photomixing / reception

Carbon nanotubes can also be used for generation and detection of terahertz radiation. As presented in III, terahertz radiation can be generated using a photoconductive material whose conductance is modulated by optical radiation. In [20] carbon nanotubes are presented as an alternative to LT-GaAS as the semiconducting material. In this scenario, and due to the high mobility in carbon nanotubes, the generated power is larger than in LT-GaAs. Moreover, in [21], [22] some initial studies are being done on the use of carbon nanotube as the detector itself, working for instance in a bolometer way.

V. Summary and Conclusions

The straight-forward extension of classical designs to terahertz frequencies is in most cases not possible. Some of the factors that must be considered are: technological limitations in fabrication, some materials are not well described by their macroscopic properties , and the signal generation and detection technologies may impose requirements on the antennas that are not common at lower frequencies.

In consequence the design of antennas for terahertz frequencies is a fertile field ready to plough by engineers who master EM theory, material properties and microfabrication techniques.

Acknowledgments

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