Chapter 1
Plasma Sensing Using Terahertz Waves

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Abstract The terahertz (THz) region of the electromagnetic spectrum, the far-infrared, has numerous applications towards characterizing low-energy phenomena in a number of wide and diverse materials. One of these exciting new areas is in plasma diagnostics. There are many experimental and theoretical methods to determine plasma parameters in a dc glow discharge. Pulsed terahertz (THz) techniques such as THz-Time Domain Spectroscopy (THz-TDS) can offer a non-contact solution towards characterizing various plasma properties. Further studies in the area of millimeter and microwave radiation have shown that the interaction of the THz radiation with fundamental plasma such as DC glow discharge plasma can be utilized towards development of inexpensive detection schemes and detectors. Here we discuss the importance of these schemes in lieu of imaging systems and describe experiments we have conducted which support these results. In particular we find that a typical Drude model approach is insufficient in describing the transmission of the THz waves through the "cold" plasma. Results are given in the area of this promising research.

1.1 Introduction

The development of terahertz wave technologies and their applications offers the potential user an invaluable opportunity in understanding a variety of important concepts in physics, namely optics, as well as a deep understanding of the field of ultra fast photonics and photo detection methods. Scientists in this field have benefited from the recent developments in ultra fast laser technologies and RF technologies and applied these new gained techniques into characterizing a wide variety of phenomena. Undoubtedly, the most successful of these applications has

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been in the development of time-domain terahertz spectroscopic [1–4] and imaging systems [5–8] which has been utilized in the characterization of dielectrics and semiconductors. This pulsed technique has allowed users to not only characterize the real and imaginary dielectric function of these materials at the same time, but also their dynamical behavior; which given the energy of the terahertz waves (few meV) can be used to study a plethora of energetic events in these systems.

These imaging schemes have driven applications in defence and security where engineers are trying to develop detectors and sources that work in the terahertz (300 GHz–10 THz) and millimeter region (30–300 GHz) of the electromagnetic spectrum. Given the nature of the terahertz wave (its low energy) and the level of the background radiation from the Sun, exotic imaging techniques that rely on homodyne and heterodyne detection techniques are being developed not just in the laboratory but commercially as well (as we see in airports today), where the noise level can be up to 15 orders of magnitude less than the background levels [9]. The problem of reducing the background level while trying to detect signals whose source powers are already no more than a few milliwatts has resulted in systems whose cost benefit is not enough to merit their full scale commercial production. While advances are still being made to bridge this gap, scientists are combining technologies once used in microwave and RF systems in order to find cost effective imaging solutions. Most notable examples have been the implementation of DROs and Schottky diode multipliers as well as Gunn diodes in imaging systems [10]. The common denominator for why these systems are being preferred rely on its ability to detect terahertz signals at room temperature which given an average background temperature of 300 K and a temperature of 30 K at 1 THz, is quite an impressive feat.

1.2 Plasma Based Detectors

Another technique that has recently gained attention due to its low-cost, room-temperature operation is plasma detection of terahertz radiation. It was shown that miniature neon indicator lamp glow discharge detectors (GDD) can be used as single pixel detectors for terahertz and millimeter waves [11]. These are very attractive since they are very inexpensive and require no cooling, and can be integrated into focal plane array architectures. These detectors are based on a miniature electrical discharge plasma formed between two metallic leads. The breakdown in the gas results in emission of visible radiation, a common result seen with most laboratory generated plasmas. It was shown that the incident millimeter wave electric field causes an enhancement in the collisions as well as the rate of ionization thus affecting the current density inside the plasma. The authors showed that by quantifying that change they were able to infer the strength of the incident millimeter wave radiation. Here we present an introduction into the theoretical and experimental basis for plasma interactions with a terahertz field. Our own findings suggest that the plasma can not be described by a model which does not take into account the probing terahertz radiation. These findings show that research into plasma based detection methods may offer a new window of opportunity in defence based terahertz technologies.

1.3 Background

The interaction of the electromagnetic field with the plasma is generally described by models which consider the motion of an electron gas under a driving field which may or may not have resonances but definitely is dependent on the density of the gas which results in the level of opacity of the plasma to the impinging electromagnetic field [12]. Since these models (Drude Model) do not consider the effects of the impinging field itself the only parameters which affect the transmission of the millimeter or terahertz wave radiation will be the electron density and the collision frequency. For standard laboratory plasmas (electrical discharge plasmas) with electron densities in the range $10^8\,\mathrm{cm}^{-3} \le n_e \le 10^{14}\,\mathrm{cm}^{-3}$, the plasma frequency lies in the range $90\,\mathrm{MHz} \le n_e \le 90\,\mathrm{GHz}$. Accordingly, to measure the plasma density it is therefore important to operate at frequencies closer to the plasma frequency. Using this approach, time-domain terahertz techniques, owing to their broadband nature have been employed successfully to probe these plasmas below and above the plasma frequency [12–16]. In the past various plasma diagnostic methods have been used towards characterizing these properties in laboratory generated plasmas. Techniques such as Langmuir probe [17], optical emission spectroscopy [18], microwave probe [19], and Thomson scattering [20, 21] have all been used to measure the electron density. Pulsed terahertz characterization methods have been used to successfully measure the densities of laser generated plasmas [22–25] which typically have densities a few orders of magnitude larger than electrically generated plasmas (typically generated with RF or DC applied fields). In general to accurately measure these parameters using terahertz pulses high density plasmas are needed. Thus electrically generated plasmas are typically done so using high power RF fields [12] or high voltage electrical discharge pulses [14]. In doing so, time-dependent plasma diagnostics is possible due to the short pulse duration (ps) allowing for a large range of density fluctuations to be characterized within the plasma. For these reasons, static, DC generated plasmas are typically not characterized using THz pulses. These are typically weakly ionized "cold" plasmas with electron temperatures on the order of a few thousand Kelvin and collision frequencies on the order of $1/100$th of the plasma frequency. Therefore, according to the Drude Model, for low electron density plasmas i.e. cold plasmas, transmission of electromagnetic waves through it are not expected to be affected.

While the case can be made that the discharge region in the glow discharge detector is fairly short enough to permit a high electron density, it would not be nearly enough as compared to that of a high voltage electrical pulse generated or high peak power laser pulse generated plasma. Our measurements through DC generated "glow discharge" plasmas also suggests that the THz field is interacting at a level beyond the limits of the Drude model, whereby the collision frequency is being affected directly by the THz field. These changes can not be approximated within the workings of the Drude model:

$$\frac{\varepsilon(\omega)}{\varepsilon_0} = 1 - \frac{\omega_p^2}{\omega^2 - i\omega\gamma_p} \tag{1.1}$$

where γ_p is the collision frequency and ω_p is the plasma frequency and ε_0 is the permittivity of free space. Basically this formula describes a static interaction and does not take into account the dynamical behavior of the medium as the THz wave passes through. For radiation with angular frequency $\omega >> \omega_p$, where ω_p is given by $(ne^2/m\varepsilon_0)^{1/2}$, a uniform plasma is essentially transparent, but a glow discharge plasma is characterized by a negative glow region and a positive neutral region. The negative glow region, visibly the brightest region, is close to the cathode and is bounded by the Faraday dark space. Measurements have shown that microwave radiation incident near these regions change the current through the plasma [26,27]. The change in the current is thought to be due to microwave heating in this region where an increase in the electron temperature causes the relatively slow moving electrons to diffuse out rapidly and reach the anode thus changing the current passing through the load [26].

$$\Delta J \approx \frac{e^2\eta_0 M \nabla n P_D}{3km^2(\omega^2 + \nu^2)} \tag{1.2}$$

where e is the electron charge, η_0 is the free space impedance, M is the gas molecule mass, n is the electron density, P_D is the radiation power on the detector, k is Boltzmann's constant, m is the electron mass, ω is the electromagnetic radiation frequency, and ν is the electron-neutral atom collision frequency. Additionally a change in the plasma current can also be attributed to enhanced ionization from a reduction in the ionization potential due to the input microwave field [26]. The enhanced ionization effect towards a change in the plasma potential was shown to play a role in microwave absorption through both the anode and cathode regions.

$$\Delta V_s = \frac{eE_o^2 d^2}{2V_i \mu_e m} \frac{\nu}{\nu^2 + \omega^2} \tag{1.3}$$

where, E_o is the amplitude of the high frequency field, d is the length of the cathode/anode fall regions in the glow discharge, V_i is the ionization potential of the gas, and μ_e is the electron mobility. Furthermore, recent measurements have shown that the absorption of the incident radiation is dependent on the orientation of the polarization of the incident microwave/millimetre wave field with respect to the electric plasma discharge field. In these measurements it was found that when the millimeter wave electric field is in the direction of the plasma electric field the change in the plasma current was much larger than when it was orthogonal to the plasma electric field [28]. These measurements were done on GDD gaps which is on the order of mm or comparable to the illuminating radiation wavelength. From the above results, it can be concluded that while the Drude model explains the behavior

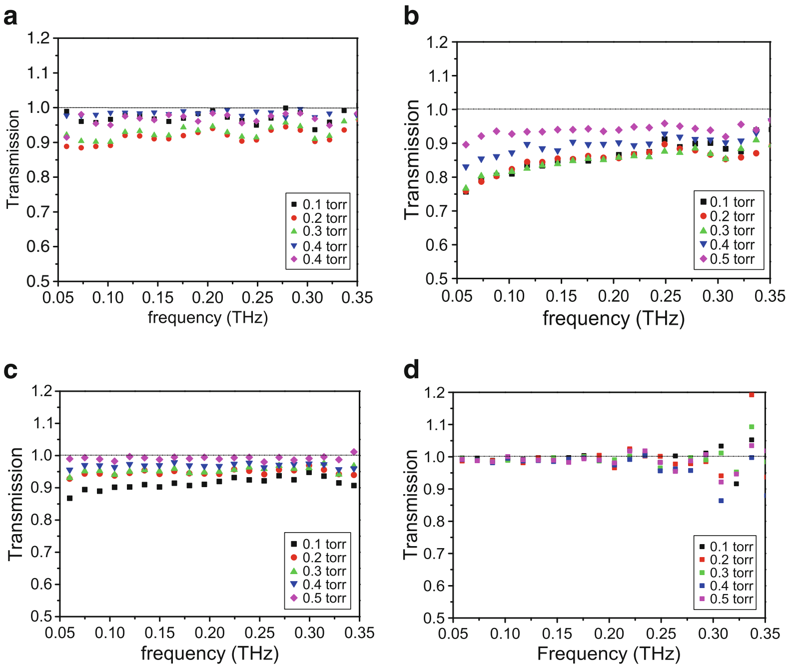

Fig. 1.1 Figure (a–c) are THz transmission curves for when its polarization orthogonal to the plasma electric field at different pressures through a DC glow discharge plasma for discharge currents of 5, 10 and 15 mA respectively. Figure (d) shows the typical THz transmission curve for when its polarization is parallel to the plasma electric field at different pressures at any discharge current

of a static system it fails to accurately describe the interaction of a high frequency field $\omega >> \omega_p$ with a relatively low density plasma, because it does not take into account heating and possible enhancement in ionization.

1.4 Measurements

Using THz-TDS we were able to study the glow discharge plasma on a much larger scale ($d >> \lambda$) and investigate the transmission of the terahertz pulses for both parallel and perpendicular orientations of its polarization with respect to the plasma DC electric field. The measurements were performed with a standard time-domain THz set-up driven by a 70 MHz Ti:Al_2O_3 mode-locked laser where the THz beam was sent through a table top plasma chamber whose electrode diameter and distance (d) between anode and cathode were 15 and 9 cm respectively. The THz beam was 5 cm in diameter and passed through the region between the anode and cathode to be detected by a lock-in at an amplitude modulation rate of 2.5 kHz. Since the windows of the plasma chamber were made from Kodiak glass, the usable bandwidth of the transmitted waveform (typically about 1 THz) was limited to 0.35–0.4 THz. The polarization of the THz beam could be rotated by 90° so as to compare the transmitted beam with both parallel and perpendicular polarization directions with respect to the applied plasma electric field. The measurements were conducted initially in air plasma where the pressure was adjusted between 0.1 and 0.5 torr. Typical discharge currents in the plasma were adjusted between 5–10–15 mA and the potential after discharge was on the order of 500 V across the 9 cm gap. Typical measurements are shown in Fig. 1.1(a–c) for orthogonal polarization and Fig. 1.1(d) for parallel polarization.

Electron densities for these plasmas are believed to be very low with plasma frequencies lying in the MHz–GHz range well below the center frequency of our bandwidth and collision frequencies are also negligible. Using Eq. 1.1 and an appropriate formalism to describe the Fresnel transmission coefficient one can estimate that the transmission should be unity for all frequencies across our bandwidth regardless of the collision frequency. The fact that our transmission is less than 1 for the particular case of orthogonal polarization suggests that the broadband THz field is interacting with the plasma as was observed previously for microwave and millimeter wave radiation. The discrepancy that may be expected due to the low average power of the THz beam (few microwatts) is balanced by the fact that THz-TDS employs a more sensitive detection technique than microwave or most direct detection millimeter wave systems (due to phase sensitive detection). Even though this is a pulsed detection system, our measurement technique ensures that for every point we average over tens of millions of pulses which can be regarded as measuring a static response through the plasma similar to the millimeter wave measurements given earlier. Thus we may expect that either the THz beam lends its energy to enhanced ionization or heating of the plasma as it traverses the medium. The fact that in these measurements we see the transmission affected for the orthogonal orientation suggests that the interaction is due to enhancement of ionization rather than heating of the plasma which would have resulted in a net diffusion current towards the anode [26]. This assumption is further supported by the fact that these measurements were done near the anode (i.e. the 5 cm diameter THz beam passed near the anode), where we expect the positive column of the discharge to lie.

1.5 Conclusion

Although weakly ionized "cold" plasmas are typically considered to be transparent at high RF frequencies, studies show that fairly inexpensive glow discharge detectors can be used to detect millimeter wave radiation. Here we showed that the THz transmission through low density DC discharge plasmas generated on a larger scale and in a laboratory setting was also affected for different orientations of its polarization with respect to the plasma electric field. The mechanisms of the discharge – THz field interaction can be complex and dependent on the different regions within the glow discharge. Especially since pulsed THz radiation has a high peak power

(100 mW) non-linear interactions within the plasma could also be responsible for the decrease in transmission, however these effects are generally dominant near the plasma frequency [29, 30]. The basic attributes that makes this type of detection system advantageous is its room temperature operation as well as its low cost and complexity. The fact the transmission through the glow discharge is polarization sensitive is also an added advantage for development of these techniques for military and defence applications.

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