Terahertz and Mid Infrared Radiation: Generation, Detection and Applications (NATO Science for Peace and Security Series B: Physics and Biophysics)

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Mauro F. F. Pereira and Oleksiy Shulika

Terahertz and Mid Infrared Radiation Generation, Detection and Applications

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Preface

The range of the electromagnetic spectrum beyond the well-established telecom domain offers a huge potential for practical applications in many different disciplines. In 2004, the Massachusetts Institute of Technology (MIT) identified “THz technology within the ten technologies which will revolutionize our life”. The NATO Workshop “TERA–MIR 2009: International Workshop on Terahertz and Mid Infrared Radiation: Basic Research and Applications” focused on stimulating substantial advances concerning emitters and detectors of terahertz (THz) i.e. 0.3–10 THz (in wavelength from 1000 to 30 μm) and mid infrared (MIR) radiation, i.e. 15–120 THz (from 20 to 2.5 μm). The full use of these spectral regions in applications is only possible with optimum generation and detection of MIR and THz radiation, both representing challenging research in fundamental science and technology. Therefore, this workshop was intended to jointly focus on the development, realization and applications of MIR/THz emitters and detectors by taking advantage of the superior properties of semiconductor materials and lasers and to beneficially exploit their common aspects within a synergetic approach.

Many substances exhibit rotational and vibrational transitions in this region, hence giving access to a spectroscopic analysis of a large variety of molecules which play a key role in security as well as various other areas, e.g. air pollution, climate research, industrial process control, agriculture, food industry, workplace safety and medical diagnostics can be monitored by sensing and identifying them via MIR and THz absorption “finger prints”. Most plastics, textiles and paper are nearly transparent for THz radiation. Therefore, illegal drugs or explosives can be detected by their characteristic absorption spectra at THz frequencies with high selectivity and resolution in applications fields as industrial quality inspection control, customs inspection and security screening.

Moreover, MIR and THz radiation has no endangering effects on human beings and enables higher contrast for “soft matter” than X-rays. In comparison to standard optical technologies for wavelengths up to about 2 μm, sources and detectors for MIR and THz have not yet reached this level of maturity and there is still a large gap for features like wavelength tunability, spectral purity, high power and room temperature operation, which all are necessary for commercial applications. Plastic or ceramics are detected of by X-rays very poorly especially against a background of human body. Unlike X-rays, THz (or T-wave) is not a dangerous radiation, and in some cases T-wave sensors can reveal not only the shape of a hidden object but also its chemical composition. This unique combination of traits make T-waves perfect for effective applications like explosive detection, and security applications. Besides, -rays have high resolution in 3D space in case of THz ultrashort pulses.

The possibility to analyze chemical composition of substances by spectroscopic methods is of big interest. Even in case if the substance is in the plastic tank or under the cloth. However, there are many open problems on the path to practical and routine use of THz. Different possible solutions for those problems were discussed during the Workshop.

Presentations and discussions provided during the workshop in the frontier of Terahertz and Mid Infrared basic science and applications can potentially stimulate joint research and projects for designing new materials and devices. The workshop characteristic feature was a stronger emphasis on the mathematical and physical aspects of the research, together with a detail analysis of the application problems. The presentations and discussions allowed an interesting forum for discussion, towards unifying these two spectral domains (THz and MIR) from their common aspects of sources, detectors, materials and applications and discuss key interdisciplinary topics. In this common sense THz and MIR are considered jointly, the driving force for both regimes being applications, however, strongly motivated by fundamental physical and technological challenges.

The main THz and

MIR source is the quantum cascade laser (QCL). A strong emphasis was given to invited talks from leading scientists related devoted to turn this advanced technology into affordable commercial devices throughout the THz and MIR spectral ranges and exploit their enormous potential for security applications. However other alternative to THz QCLs were presented, e.g. frequency multiplication using semiconductor superlattices and amplifiers, THz Difference-frequency Generation in Quantum Cascade Lasers (generating THz from efficient MIR QCLs), Sub-Terahertz Imaging From Avalanching GaAs Bipolar Transistors, mm-Wave Signal from phase-Locked DFB via Four Wave Mixing, Josephson Junctions as THz sources, Clinotrons as THz sources, Semiconductor materials for pulsed THz sources, Superconducting THz electronics with Josephson vortices.

Details of state of the art THz and Mid Infrared detection have been given as well as progress towards integration of THz devices in microchips. Detection of explosives and other substances have been analyzed as well integration with fibres and the interaction of THz radiation of biomaterials. Advanced theoretical simulation methods and out of the box solutions for QCLs have been discussed including lasing without inversion. Furthermore detailed studies of fundamental physics related to intersubband optics (e.g. intersubband polaritons were presented). Metamaterials have also been discussed in both millimetre wave and THz ranges.

In summary this meeting allowed the attendees to get a global picture of the state of the art in TERA-MIR generation, detection and applications. We had an excellent opportunity to discuss further proposal possibilities and I hope that a few meaningful collaboration projects will be submitted after this meeting.

Mauro Fernandes Pereira
Oleksiy V. Shulika
February 2011

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We start the long acknowledgement list with our thanks to NATO and the Science for Peace project for the very generous financial support and continuous support with all necessary details which made the realization of The Advanced Research Workshop THz – MIR Radiation: Basic Research and Applications (2009) and this book possible. The co-chairs Mauro Pereira and Igor Sukhoivanov are grateful to NATO, which provided a fantastic opportunity for all of us to meet in Turunç. New joint proposals and scientific collaborations are already evolving thanks to this opportunity and we hope that they will have an impact in the development of research in the fascinating TERA-MIR range.

We further acknowledge UNESCO support with several grants for speakers from developing countries, obtained through the Institute of Theoretical and Applied Physics (ITAP). The Workshop took place at Loryma Resort in Turunç, Marmaris, Turkey. We thank staff and administration of Loryma, which extended every courtesy to the attendees and gave us an opportunity to meet in a stunning location by the sea. They did everything in their power to help us with all logistic issues related to bring people from all over the world to this meeting and helped create the perfect atmosphere for this meeting.

The other committee members played a major role in helping us selecting the speakers and reaching a final program conclusion, so here is a statement of our appreciation support given by Romuald Brazis, Wolfgang Elsaesser, Guido Giuliani, Janos Hebling, Martin Koch, Marian Marciniak, Ekaterina Orlova, Suleiman Ozcelik, Sergii Tarapov and Dmitro Vavriv.

In preparing this book we have relied on the timely contribution of the authors. Without their expert insight, motivation and commitment the publication of this volume would not have been possible. We, thus, extend our appreciation to all the authors. We also convey our thanks to Springer for the opportunity of publishing this volume.

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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 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 , the plasma frequency lies in the range 90 MHz n e 90 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 □ 100th 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: (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 , 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].
(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. (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 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.

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

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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2. A Study of Tunable Metamaterial Devices for the THz Region

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Abstract In order to cope with the “THz Gap”, metamaterial based devices operating at about 1 THz have been designed to have a tunable response. We studied the electromagnetic behaviour of periodic structures consisting of different “unit cells” based on the concept of Split Ring Resonator (SRR). The devices response in the required frequency region is simulated using a commercial electromagnetic code. Different modulation mechanisms have been investigated, including the use of liquid crystals, MEMS, semiconducting substrates.

2.1 Introduction

During the last two decades substantial progress has been achieved in the development of THz science and technology. However, there are several restrictions which limit the full exploitation of fruitful applications covering this frequency region. One of the main constraints is the so called “THz Gap”, which is basically due to the lack of appropriate response at those frequencies for many naturally existing materials. This problem can be solved using artificially structured electromagnetic materials, named metamaterials, typically comprised of periodic arrays of sub-wavelength metallic structures within or on a dielectric or semiconducting substrate. The use of this type of material, on an appropriate form such a Split Ring Resonators (SRR), could find application for the development of novel devices operating in this frequency region and aimed at filtering, modulating, and switching the electromagnetic signal. Since the first extensive studies on metamaterials, the attention of most researchers has been focused on the linear properties of these composite structures. However, to achieve the full potential of the unique characteristics of metamaterials, the ability to dynamically control the material properties or tune them in real time, through either direct external tuning or nonlinear response, is required. Here we have studied and compared different strategies in order to achieve tunability in the THz region, including the use of liquid crystals, MEMS, and semiconducting substrates [1–5].

2.2 Liquid Crystal

The proposed tuning system is based on the use of a liquid crystal (LC). Its properties can be controlled reorienting the LC molecular director, described by the angle θ, in respect to the oscillating electric field direction. LC molecules reorientation can be done using a static or slowly-varying electric field, by applying a magneto-static field or even using thermal control. Since the LC is the key element for this kind of tuning system, and in order to take full advantage of it, our study was focused on the influence of the LC intrinsic parameters and its interaction with the metamaterial unit cell to achieve the highest tuning performance. For this reason, two LC configurations were used. The first standard configuration implies the use of an appropriate amount of LC top layer covering the SRR (Fig. 2.1(a)) whereas the second one is based on the use of the LC in between two metallic structures. In such a case, a first SRR, the LC layer and then a second SRR are combined to give a sandwich configuration, as shown in Fig. 2.1(b). The use of a support to hold the second SRR suspended is compulsory, and several materials can be used for it, like the PI-5878G (HD Microsystems).

Fig. 2.1 LC configurations: (a) the LC top covers the metallic structure; (b) the LC is in between two metallic structures

The tunability of the designed system is represented by the shift of the resonance frequency plotted in the S_{21} parameter curve. LC properties are changed according to [6]. For those calculations, the LC under evaluation is represented as an anisotropic materials with an ordinary optical index $n_o = 1.38$, an extraordinary optical index $n_e = 1.43$, and thus a birefringence of 0.05. Therefore, in our simulations the LC layer permittivity is considered as [2.0449, 1.9044, 1.9044] and [1.9044, 2.0449, 1.9044] respectively for two orientations: θ = 0 □ and 90 □. We also used a variable parameter s representing the difference between the ordinary and the extraordinary permittivity, so that the LC layer is treated as [ε_x □ s, ε_x + s, ε_z]. Loss tangent values were set as $\tan\delta_o = 0.020$ for n_o and $\tan\delta_e = 0.016$ for n_e.

We started by modelling periodic structures consisting of different “unit cells”, with different Split Ring Resonator (SSR) based geometries [4, 5], as shown in Fig. 2.2. Several simulations were performed using CST, a commercial electromagnetic code, in order to see the device response in the required frequency region. In Fig. 2.3, the scattering parameter S_{21} vs frequency is plotted for the double SRR with internal large gap geometry reported in Fig. 2.2(a). The resonance frequencies depend on the chosen geometry and are located within the range between 4 and 8 THz for the same SRR dimensions. A much larger shift is observed in the sandwich configuration compared the top layer one with a significant modulation of the response (2.3% and 0.5% respectively).

Terahertz (THz) and Mid-Infrared (MIR) radiationÂ (TERA-MIR) can be transmitted through nearly any material without causing biological harm. Novel and rapid methods of detection can be created with devices operation in these spectral ranges allowing scanning for weapons, detecting hidden explosives (including plastic landmines), controlling the quality of food and a host of other exciting applications.Â This book focuses on mathematical and physical aspects of the field, on unifying these two spectral domains (THz and MIR) with regard to common sources, detectors, materials and applications, and on key interdisciplinary topics. The main THz and MIR source is the quantum cascade laser (QCL). Thus significant attention is paid to the challenge of turning this advanced technology into affordable commercial devices so as to exploit its enormous potential. However other alternatives to THz QCLs are also presented, e.g.Â sub-terahertz imaging from avalanching GaAs bipolar transistors, Josephson junctions as THz sources, semiconductor materials for pulsed THz sources,Â superconducting THz electronics with Josephson vortices.Â In summary this book delivers a global picture of the state of the art in TERA-MIR generation, detection and applications.

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