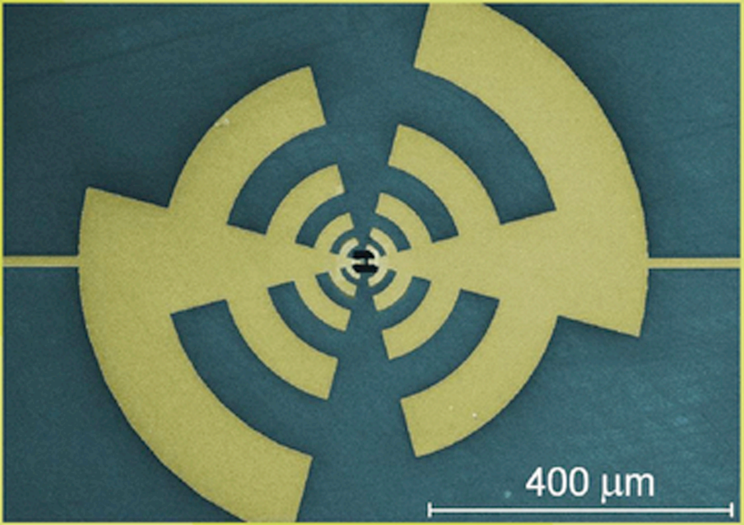

SEMICONDUCTOR TERAHERTZ TECHNOLOGY

DEVICES AND SYSTEMS AT ROOM TEMPERATURE OPERATION

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Preface

“Midway upon the journey of our life, I found myself within a forest dark, for the straightforward pathway had been lost.” These words from Dante Aliguieri can summarize the main motivation that we had for writing this book: trying to cover and explain recent advances in THz frequencies from a semiconductor technology perspective. Our motivation started with a meeting in Nürnberg (Germany) in October 2013, where we (all authors of this book) had agreed to meet to discuss the objectives and structure of the book in its present form.

THz frequencies have been investigated for a long time, since the middle of the twentieth century, having coined popular terms such as the “THz gap” to indicate the underdevelopment of this part of the electromagnetic spectrum. However, the technological challenge to develop efficient devices for both generation and detection of THz waves has only recently started to be addressed. The mechanisms that govern the propagation, emission, and characterization at THz frequencies have been studied and developed by both physicists and engineers. We have realized that, very frequently, there is a huge lack of knowledge about the different perspectives that are involved. Let us illustrate this point with an example: the photomixing technique for the generation of THz waves. Photomixing uses two lasers emitting at slightly different wavelengths that beat in a semiconductor device, obtaining the difference of the two lasers as the THz emitted frequency. It must thus be studied, taking semiconductor physics into account. Conversely, the study of the antennas and/or lenses attached for extracting the THz wave generated (or for the propagation and guiding of THz signals) is typically done by the classical approach of macroscopic electrodynamics. Engineers typically treat the photomixing process as a “black box” where they have to insert their antennas to get the best matching. On the other hand, the physicists who developed the device sometimes forget about the technology limits or have modest knowledge about antenna radiation mechanisms, and use classical topologies on the basis that they worked previously, not being aware that more efficient approaches are available. The result is that both research approaches, although totally valid and rigorous, have a lack of knowledge in the other area. In order to optimize the devices, the researchers need to address design issues that lead them into areas of expertise that they do not master. That is what we call entering into “the forest dark” of Dante.

We believe that partnership among researchers is the best approach to explore the new regions. With this spirit in mind, we organized the meeting at Nürnberg, contacting specialists from all the regions of the THz forest. The main objective for this book in the beginning was to shed some light into the different parts of the THz forest. We can affirm that the book is a self-contained manual for both physicists and engineers who are working or starting their research in semiconductor THz technology. The international team of authors, which comes from both areas of knowledge, that is, Physics and Engineering, wrote all the contributions with extreme care, explaining the basic concepts of their areas up to the current state-of-the-art. For this reason, an expert in an area could find a few pages of the book “rather elementary”. These are, however, strictly necessary to provide total consistency and the self-contained aspect of the book, and to cover fully the current state-of-the-art.

In Chapter 2, the theoretical background of terahertz generation by photomixing is discussed in detail. Basic design rules are specified for obtaining highly efficient optical to THz power conversion for both photoconductive and high frequency p-i-n diodes, considering pulsed as well as continuous-wave operation. State-of-the-art realizations of photomixers at 800 and 1550 nm laser wavelengths are shown. Limiting electrical and thermal constraints to the achievable THz power are also addressed. Finally, this chapter gives an overview of electronic means for THz generation, such as Schottky diodes, negative differential resistor oscillators, and plasmonic effects that are used in THz generation. The chapter starts with a quick overview of the most relevant THz generation schemes based on nonlinear media, accelerating electrons, and actual THz lasers. This serves to place in context the two schemes discussed in detail thereafter: photomixing and electronic generation. The chapter goes through the theoretical frameworks, principles of operation, limitations, and reported implementations of both schemes for pulsed and continuous-wave operation when applicable. The chapter also covers to a lesser extent the recently explored use of plasmonics to improve the efficiency of THz generation in photomixing, nonlinear media, and laser schemes.

Chapter 3 presents the theoretical background of antenna theory, tailored to terahertz applications. A general discussion is provided on the issues of THz antennas, especially for matching to the photomixer. Array theory is presented, together with an exhaustive and precise analysis of one of the most promising and new solutions for generating THz emission with high power levels, that is, the large area emitter concept.

In Chapter 4 we first briefly introduce Maxwell's equations and derive the Helmholtz equation, that is, a special case of the wave equation, and introduce its different solutions for fields that may propagate in THz waveguides. The second section describes different waveguides operating at THz frequencies, and the third section is devoted to the beam waveguide and quasi-optics. Material issues related to waveguides and quasi-optical components are also discussed. The chapter concludes with THz wave propagation in free space.

Chapter 5 is a comprehensive review of the physical principles and engineering techniques associated with contemporary room-temperature THz direct detectors. It starts with the basic detection mechanisms: rectification, bolometric, pyroelectric, and plasma waves. Then it addresses the noise mechanisms using both classical and quantum principles, and the THz coupling using impedance-matching and antenna-feed considerations. Fundamental analyses of the noise mechanisms are provided because of insufficient coverage in the popular literature. All THz detectors can then be described with a common performance formalism based on two metrics: noise-equivalent power (NEP) and noise-equivalent temperature difference (NETD). The chapter concludes with a comparison of the best room-temperature THz detector experimental results to date above ∼300 GHz, and suggests that as none of these detector types are operating very close to fundamental theoretical limits there is room for significant performance advances.

Several key topics in THz electronics are discussed in Chapter 6. We describe operating principles, limitations, and state-of-the-art of resonant-tunneling diodes (RTDs) and THz RTD oscillators. Furthermore, THz fundamental or sub-harmonic flip-chip Schottky diode mixer configurations are described. Different measurement techniques are commented and their properties outlined. The chapter also describes the use of advanced mixer configurations. Fabrication technologies for Schottky-diode based structures for THz wave applications are included, together with the low-barrier Schottky diode characterization for millimeter-wave detector design. Finally, low noise amplifiers (LNAs) for sub-millimeter waves are discussed, including up-to-date design approaches and resulting performance, with emphasis on the necessary technological modification to extend monolithic microwave integrated circuit (MMIC) approaches toward the THz region.

The THz spectral range has not yet been fully exploited to its full potential due to the current limitations in sources and detectors. To open the THz frequency range for applications, photonic solutions have been at the technological forefront. For instance, the advances of time domain spectroscopy techniques using short pulse lasers have enabled the provision offull spectroscopy data across the range. There are different types of systems and their development should be governed by the requirements of the potential application. Photonic techniques are desirable solutions for millimeter wave and THz generation in terms of their energy efficiency and, above all, their tuning range. Recent developments in this area target the improvement of optical-to-THz converters as well as enhancing the level of integration of semiconductor laser sources in order to address their main drawbacks, cost, and spectral purity. The purpose of Chapter 7 is to describe the main types of photonically enabled THz systems and the expected performances from their components. A description is provided of the key elements in designing each of the components and their limitations. The final part of the chapter is a discussion on potential future development and the importance of integration.

Finally, Chapter 8 summarizes and explains some novel approaches and applications of THz, such as liquid crystals, graphene technology, or resonator theory based on a nonlinear up-conversion process. This makes the approach very appealing for its use as highly-sensitive receivers.

We expect that the reader will find in the book not only answers but also at least some hints for continuing the advances in THz technology. Of course, we hope that the reader shares the same feeling of satisfaction experienced by the authors when writing and discussing the present book.

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Prof. Dr. Luis Enrique García Muñoz
Madrid, Spain, November 2014

Prof. Dr. Hans Hartnagel
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Darmstadt, Germany, November 2014

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Espoo, Finland, November 2014

Foreword

Terahertz technology is one of the most exciting areas being explored today by researchers interested in high frequency electromagnetic systems and associated solid-state devices, antennas, quasi-optical components, and related techniques. Although tantalizing in its potential, terahertz technology has also been frustratingly slow to develop to maturity. This book represents the most detailed and up-to-date exposition of the current state of the art for terahertz technology, and an exposition of the reasons for its slow progress. It contains discussions of terahertz sources, including the scaling up of microwave and millimeter wave oscillators and frequency multipliers, as well as the mixing of infrared or optical lasers to produce difference frequencies in the terahertz band. Radiation of terahertz signals is described, including the use of antennas as well as the direct radiation from emitting sources. Terahertz propagation in various types of waveguides is discussed, in addition to propagation characteristics of the atmosphere. Detection of terahertz signals by direct detection methods using diodes, bolometers, and pyroelectric devices is presented, along with noise characteristics of these techniques. Electronic devices useful for detection, mixing, generation, amplification, and control of terahertz signals are thoroughly described.

This book includes seven chapters written by the leading researchers in terahertz technology research today. Chapter authors represent research groups from around the world, including workers from Spain, Germany, Italy, the United Kingdom, Japan, Finland, Ireland, and the United States. Again reflecting the uniqueness of terahertz technology as an interdisciplinary effort, contributors come from the fields of both engineering and physics, as do the subjects reported here. For these reasons, this work should prove to be of interest and value to researchers, teachers, and students.

The terahertz frequency band (100 GHz to 10 THz) is located between microwave frequencies at the low end, and far-infrared frequencies at the high end. Although initial work at terahertz frequencies was done as early as the 1970s, major progress on systems using such frequencies has been slow due to the difficulty in fabricating sources, detectors, amplifiers, antennas, and other components at such high frequencies. On the other hand, terahertz technology, being positioned between microwave technology and optical technology, can benefit from the unique methods and techniques of each of these domains. A good example of this is presented in Chapter 2, where the generation of terahertz power is described using solid state oscillators and frequency multipliers (scaling up of techniques and devices commonly used at microwave and millimeter wave frequencies), as well as generation using photomixing of two lasers (a common technique in the optical domain). Several other examples of how terahertz technology capitalizes on both electronics technology and optical technology are described in other chapters. As most new technology is built “on the shoulders of giants”, terahertz technology has two sets of “giants” to build upon.

Applications of terahertz technology include sensors, imaging for medical and security purposes, and short-range communications. One of the earliest applications of terahertz frequencies was for astronomical spectroscopy, as many of the more complex molecules being searched for in space have resonances at these frequencies. Terahertz frequencies also provide unique features for communications systems, providing extremely high bandwidth, and built-in resistance to eavesdropping due to extremely high rates of atmospheric attenuation. As more progress is made with solid state components for terahertz frequencies, it is certain that more applications will be found for this unique technology. Such progress seems to be accelerating: it was just recently announced that the first MMIC amplifier operating above 1 THz has been developed in the US. Developments like this mean that we can look forward to seeing terahertz technology move from the research lab into practical and affordable commercial and science applications in the near future. This book will provide the background that workers will need to be productive in this exciting field.

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1

General Introduction

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In this book, we define TeraHertz (THz) waves as the part of the electromagnetic spectrum with wavelengths ranging from 3 mm down to 30 μm, that is, from 100 GHz to 10 THz covering the upper part of millimeter waves (30–300 GHz), the whole range of submillimeter waves (300 GHz to 3 THz), and the lower end of infrared waves (from 3 THz to visible light).

THz science and technology is a relatively young area both in research and applications. THz applications started from radio astronomy in the 1970s. This was based on the property that molecules and atoms can be identified by their radiation spectrum caused by their rotational and vibrational resonances. Since then the THz band has found many other potential applications because it provides unprecedented bandwidth and opportunities for completely new sensor applications. It is feasible and potential for many ground-based commercial applications as well as for Earth science applications: remote sensing of the Earth's surface and atmosphere, broadband high data-rate indoor (e.g., smart home) and short-range outdoor wireless communications, short-range, long-range, and multi-function automotive radars and ultra wide band (UWB) high-resolution radars, telematics for road traffic and transport, both between vehicles and between vehicles and infrastructures, imaging for security, medical, and other purposes.

In free space, transmission of THz waves typically requires line-of-sight between the transmitter and the receiver. The length of a terrestrial communication hop cannot be very long since the water vapor of the atmosphere is highly absorbent, ranging from not more than a few meters to hundreds of meters. On the other hand, this high attenuation enables one to limit THz-communication distances to secure distances. Depending on the relative humidity (between 25 and 100%), the atmospheric attenuation at sea level and at a temperature of 25 °C ranges from 0.3 to 1 dB km^{-1} at 100 GHz and from 50 to 250 dB km^{-1} at 700 GHz. At water vapor absorption peaks, for example, at 557 GHz, the attenuation may reach values over 10^4 dB km^{-1}.

So far the employment of THz systems for applications has been slow because of the immature technology. The frequency range from 0.1 to 10 THz is often called the terahertz gap, because technologies for generating and detecting this radiation are much less mature than those at microwave or infrared

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frequencies. Mass production of devices at the terahertz gap frequencies and operation at room temperature have mostly not yet been realized. High-power THz waves (beyond the kilowatt levels) with microwave concepts can be generated by using vacuum tube generators, such as backward wave oscillators (BWOs) and free electron lasers (FELs), and lower THz power waves by multiplying semiconductor oscillator frequencies from the microwave or low millimeter wave bands by Schottky diode multipliers to the THz waves. On the other hand, THz radiation with photonics means may be generated by using optically pumped gas lasers or photomixers pumped with two infrared semiconductor lasers. In the latter case, the power of the THz signal is typically only microwatts. Additionally it is possible to generate THz signals of very low power values (nanowatt levels) by ultrashort bias pulsing, and this technique has been very successful in THz characterization of chemical elements.

However, recent strong advances in the development of semiconductor components and their manufacturing technology are making THz systems and applications more feasible and affordable. The terahertz gap is shrinking slowly but definitely due to strong developments from both directions, from microwaves and from photonics.

New approaches to the design and manufacturing of THz antennas are another indispensable basis for developing future applications. THz frequencies require integration of antennas with the active electronics. In most applications, electronic focusing and beam steering is needed or is at least a very valuable asset. One of the main components of a radar sensor is a beam-steering device that scans surroundings for hidden objects. Another application that requires implementation of the same technology is point-to-point wireless communication systems. If beam steering is implemented in receiving and transmitting antennas, a self-adapting mechanism can be elaborated for innovative performance of the future secure high-capacity communication links. Because the RF (radiofrequency) spectrum in the microwave region is highly populated with different communication standards, a possible frequency range for high-capacity communication systems, which require a wide bandwidth, can be found at millimeter wavelengths, for example, at 86, 150, and 250 GHz.

This book is intended to be valuable for researchers in this field, for industrialists looking to open new markets, and particularly also for teaching at university level. Therefore it concentrates on those parts of the subject which are important for these aspects. Other important scientific areas such as THz spectroscopy are not treated in detail, except for the possibility of its use in security by identification of explosive materials.

2

Principles of THz Generation

Sascha Preu[1], Gottfried H. Döhler[2], Stefan Malzer[3], Andreas Stöhr[4], Vitaly Rymanov[4], Thorsten Göbel[5], Elliott R. Brown[6], Michael Feiginov[7,*], Ramón Gonzalo[8], Miguel Beruete[8], and Miguel Navarro-Cía[9]

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2.1 Overview

The THz frequency range (100 GHz to 10 THz) is situated between microwaves and infrared optics. For a long time, it was called the "THz gap", since there were no efficient sources and detectors available, in contrast to the neighboring microwave and optical domains. In the meantime, a multitude of means to generate THz radiation has been developed in order to close this gap. For the highest THz power levels, that is, tens of watts average power and tens of microjoules pulse energies [1–3], factory hall sized free electron lasers (FELs) and synchrotrons have been constructed. A heavily accelerated, relativistic electron beam is guided into an undulator, a structure where the electron is deflected back and forth by alternating magnetic fields. The acceleration of the relativistic electrons perpendicular to their main direction of propagation results in dipole radiation along the propagation axis. In FELs, the undulator is

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[*] Presently with Canon Inc., Frontier Research Centre, THz Imaging Division, Tokyo, Japan

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usually situated inside a THz cavity [4, 5]. The cavity field acts back on the electron beam, resulting in microbunching, that is, dicing the electron beam into packets. Constructive interference of all electron packets occurs, resulting in a laser-like behavior.

Another source is the backward wave oscillator (BWO). This could be considered as the small brother of a synchrotron or FEL. It consists of a vacuum tube that houses an electron source and a slow wave circuit (instead of an undulator). At resonance, a wave is built up in the slow wave circuit that propagates in the opposite direction to the electron beam, hence the name “backward wave” oscillator. In contrast to FELs, BWOs are table-top sources. They provide power levels in the range of milliwatts (at 1 THz) to 100 mW (at ~100 GHz) [6].

True THz lasers are gas lasers, p-germanium (p-Ge) lasers and quantum cascade lasers (QCLs). Gas lasers use polar molecules as the laser medium. Many spectral resonances of molecule rotations of basically all polar molecules (e.g., methanol) are situated in the THz range and therefore suited as THz laser levels. The gas cell, set up within a THz cavity, is usually pumped with an infrared laser, in most cases a CO_2 laser [7]. Only the THz wavelength that is in resonance with both the cavity and a rotational resonance of the molecule is amplified. Average power levels in the milliwatt range can easily be achieved with record continuous-wave (CW) levels above 1 W [8]. However, the frequency is limited to the molecule-specific resonance frequencies. The p-Ge laser consists of p-type germanium mounted in a crossed E (electric) and B (magnetic) field. The laser transitions are either transitions from light to heavy hole valence subbands or transitions between cyclotron resonances [9, 10]. The laser cavity is the crystal itself or an external cavity [11]. So far, p-Ge lasers have to be operated in a cryogenic environment. QCLs consist of a superlattice of quantum wells which is electrically biased [12]. Each superlattice period consists of several quantum wells of different width and barrier thickness. The upper and lower laser levels are extended over several suitably designed wells. Strong coupling through a narrow barrier allows filling of the upper laser level. In order to achieve population inversion, fast depletion of the lower level is ensured by resonant longitudinal optical (LO) phonon-assisted transitions to lower states and strong coupling to the neighboring “ground state” through a narrow barrier. This ground state represents the injector into the upper laser level of the next period of the “quantum cascade” structure, which is comprised of the order of $N \approx 100$ periods. Ideally, a single electron produces 1 THz photon for each sequence in the cascade. As the *spontaneous* radiative transitions between the upper and lower laser levels are competing with by orders of magnitude more efficient non-radiating phonon-assisted transitions, the dark current density in QCLs is high. With sophisticated design, it has become possible to achieve very high THz photon densities in high-Q laser cavities, such that ultimately the stimulated laser transitions largely outnumber the non-radiative processes. Although the threshold currents are high, the quantum efficiency above threshold becomes high and CW power levels in the tens of milliwatts are available in the upper part of the THz range [13]. However, the tunability is limited by the linewidth of the THz resonator (usually the QCL chip itself), and it is very challenging to operate a QCL below 1 THz [14]. Both p-Ge lasers and THz QCLs require cryogenic operation. This often hinders commercial applications.

Another very important optical method of THz generation is nonlinear frequency conversion [15]. Many materials show nonlinear components of the electric susceptibility, χ. The polarization, $P(t)$, of a crystal caused by incident light with field strength $E(t)$ is given by

$$P(t) = \varepsilon_0 \left(\chi^{(1)} E(t) + \chi^{(2)} (E(t))^2 + \chi^{(3)} (E(t))^3 + \dots \right), \tag{2.1}$$

where $E(t)$ is the sum of all incident electric fields. The strength of the *nonlinear* components (i.e., $\chi^{(n)}$ with $n > 1$) depends strongly on the crystallographic structure of the material. For THz generation, the second-order nonlinearity, $\chi^{(2)}$, is most commonly used. For two incident lasers that differ slightly in frequency, this term contains a component of the difference frequency. $P(t)$ then oscillates and emits photons at the difference frequency that can easily be chosen to be in the THz range. Since $P^{(2)}(t) \sim (E(t))^2$, high fields are required for efficient generation. Therefore, mostly pulsed laser sources are used, with a few CW examples also demonstrated. It also works for single to few THz cycle pulses, since the pulses contain a broad frequency spectrum. The optical laser signal and the THz signal have to co-propagate through some length, $l \sim 0.5$ mm, of the nonlinear crystal. The THz (phase) refractive index and the optical (group) refractive index have to be matched in order to assure propagation at the same speed of light ("phase-matching"). Due to the Manley–Rowe criterion (simply speaking, one pair of optical photons can only generate 1 THz photon), $\chi^{(2)}$ THz generation is very inefficient the further the THz frequency and the optical frequencies are apart (if secondary photons are recycled, however, efficiencies above the Manley–Rowe limit are possible). Typical power efficiency values for THz generation with near-infrared (NIR) lasers are in the range of 10^{-5} [15]. However, the high available power of state of the art pulsed laser systems, the high THz peak power (50 kW in Ref. [16]), the large frequency coverage, and room-temperature operation make nonlinear THz generation very attractive for many applications.

A detailed description of all these approaches is beyond the scope of this book. This chapter will therefore focus only on THz generation by photomixing and by electronic means.

Much like nonlinear THz generation, photomixers down-convert optical photons to THz photons. In contrast to polarization of a crystal, where *one pair* of optical photons generates *one THz photon*, a pair of optical photons generates *one electron–hole pair* in a semiconductor. Each electron–hole pair can emit *many THz photons*. Therefore, THz generation via photogenerated electron hole pairs is typically much more efficient than nonlinear generation, particularly at the lower end of the THz spectrum. This approach works well at room temperature and under ambient conditions, and offers an extremely large tuning range. These sources can be operated with a single, few cycle pulsed laser (broadband operation), two pulsed lasers with pulse widths much longer than the inverse THz frequency (quasi-continuous-wave operation), and in the CW mode (requiring two CW lasers). They are very versatile and are used in many applications. In this chapter, we will develop the theoretical framework, the limitations, and provide various realizations of photomixers.

In Section 2.3 we will discuss the fundamentals of electronic generation of THz radiation. This includes electronic high frequency oscillators such as negative resistance devices (resonant tunneling diodes, and Esaki diodes) and electronic up-conversion of microwave radiation to the THz domain using Schottky diodes and hetero-barrier varactors. Since microwave circuits offer high power levels and high efficiencies, electronic THz generation is very successful and offers many applications. Such applications range from astronomic applications on satellites to table-top applications in the laboratory.

2.2 THz Generation by Photomixers and Photoconductors

2.2.1 Principle of Operation

For simplicity, we start with CW or quasi-continuous-wave photomixing. The formalisms are simpler to understand since all equations have to be derived only for a single THz frequency. However, most results will also be valid and applicable for pulsed operation. A photomixer consists of a semiconductor that is excited with a pair of lasers with powers P_1 and P_2, and optical frequencies $\upsilon_{1,2} = \overline{\upsilon} \pm f_{\mathrm{THz}}/2$, that is, they differ in frequency by the THz frequency. The frequency of the lasers must be sufficiently high in order to generate electron–hole pairs in the semiconductor by absorption, that is $\upsilon_{1,2} > E_{\mathrm{G}}/h$, where E_{G} is the band gap energy of the semiconductor (e.g., $E_{\mathrm{G}} = 1.42$ eV for GaAs) and h is the Planck constant. The lasers with electric field strengths $E_{1,0} \sim \sqrt{P_1}$ and $E_{2,0} \sim \sqrt{P_2}$, are heterodyned, resulting in a total optical field strength of

$$\vec{E}(t) = \vec{E}_1(t) + \vec{E}_2(t) = \vec{E}_{1,0}\mathrm{e}^{\mathrm{i}(\overline{\omega}+\omega_{\mathrm{THz}}/2)t} + \vec{E}_{2,0}\mathrm{e}^{\mathrm{i}(\overline{\omega}-\omega_{\mathrm{THz}}/2)t-\mathrm{i}\varphi}, \tag{2.2}$$

where $\omega_i = 2\pi\upsilon_i$ are angular frequencies and φ is the relative phase. The optical intensity is

$$I_{\mathrm{L}}(t) \sim |\vec{E}(t)|^2 = E_{1,0}^2 + E_{2,0}^2 + 2|\vec{E}_{1,0} \circ \vec{E}_{2,0}| \cos(\omega_{\mathrm{THz}} t + \varphi), \tag{2.3}$$

as illustrated in Figure 2.1a–d.

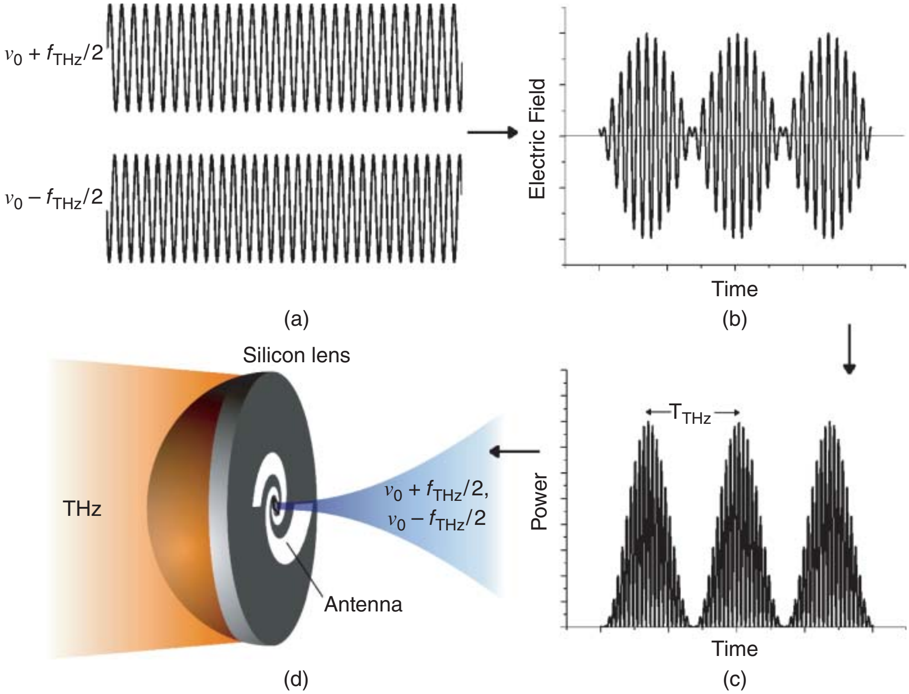

Figure 2.1 Schematic of the photomixing process. (a) Two lasers are heterodyned, (b) resulting electric field, (c) resulting power modulation with a beat node at the difference frequency and (d) the heterodyned lasers are focused on a photomixer. It is connected to an antenna to radiate the THz signal. A silicon lens assists to couple out the THz beam to free space.

Expressing Eq. (2.3) in terms of power yields

$$P_L(t) = P_1 + P_2 + 2\sqrt{P_1 P_2}\cos\beta \cdot \cos(\omega_{THz}t + \varphi), \tag{2.4}$$

where β is the angle between the electric fields (polarizations) of the lasers. An *ideal* semiconductor device (i.e., all light is absorbed, no losses) will generate a photocurrent

$$I_{Ph}^{id}(t) = \frac{eP_L(t)}{h\bar{\nu}} = \frac{e(P_1 + P_2)}{h\bar{\nu}} + 2\frac{e\sqrt{P_1 P_2}}{h\bar{\nu}}\cos\beta \cdot \cos(\omega_{THz}t + \varphi), \tag{2.5}$$

with a DC component of $I_{DC}^{id} = e(P_1 + P_2)/h\bar{\nu}$ and an AC amplitude of $I_{THz}^{id} = 2e\sqrt{P_1 P_2}\cos\beta/h\bar{\nu}$. The AC current is maximized for $P_1 = P_2 = P_L = ½\,P_{tot}$ and $\beta = 0$, that is, the two lasers have identical power and polarization, yielding $I_{THz}^{id} = eP_{tot}/h\bar{\nu} = I_{DC}^{id} = I^{id}$, where $P_{tot} = 2P_L$ is the total laser power. The total current reads

$$I_{Ph}^{id}(t) = I^{id}[1 + \cos(\omega_{THz}t + \varphi)]. \tag{2.6}$$

The AC current is usually fed into some kind of antenna with radiation resistance R_A and an (ideal) THz power is radiated,

$$P_{THz}^{id} = \frac{1}{2}R_A(I_{THz}^{id})^2 = \frac{1}{2}R_A\left(\frac{e}{h\bar{\nu}}\right)^2 P_{tot}^2 \tag{2.7}$$

To summarize, two laser beams that differ in frequency by the THz frequency are absorbed by a semiconductor device. The device produces an AC current at the difference frequency of the lasers, namely