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Introduction to THz Technologies

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Understanding the fundamentals of Terahertz devices and applications requires thorough consideration of passive and active components together with system perspectives. In terms of passive components, antennas are a key element for signal handling, while signal generation and detection can be achieved by various means such as photoconductive (PC) devices, photomixers, plasmonic PC devices, and quantum cascade lasers (QCLs). In addition to these approaches are based on optical concepts, electronic approaches are also explored and implemented. These include advanced devices using two-dimensional (2D) layer technology, plasma field-effect transistor detectors, diode multipliers, and resonant-tunneling diodes (RTDs). THz systems combine such passive and active devices for responding to various application needs such as communication and sensing.

System operation at THz frequencies requires signal generation, emission, propagation, and reception. A key element for such systems is antennas that are discussed in Chapter 2. To fulfill the resolution or sensitivity requirements of most submillimeter-wave instruments, especially very high gain reflector-based antennas are necessary. These are illuminated by antenna feeds integrated with the transceiver/receiver front-ends and based on horns or silicon lens antennas. Horn antennas are easily connected to a waveguide-based front-ends and can be easily manufactured while presenting good radiation properties. Lenses can on the other hand be easily integrated with bolometer detectors and silicon-based front-ends. They are often used to couple to direct detectors instruments and used in planar form with superconducting-insulator-superconducting (SIS) and hot-electron bolometric (HEB) mixers as well as in PC systems on bow-tie and logarithmic spiral form.

New THz antenna arrays based on horns and lenses benefited from advances in photolithography and micromachining to respond to the needs of multi-pixel systems operating at submillimeter wave-bands. Another important point for successful THz system operation is the reduction of transmission losses which can be high in metals. To overcome this difficulty, superconducting-based microstrip lines can be used and employed in phased arrays. A disadvantage of this approach is the need for cryogenic cooling for operation which makes

it impractical. Of major importance is the good understanding of the operation of integrated lens antennas and the way one can analyze them. Consideration of this type will be presented together with detailed discussions on elliptical lens and semi-hemispherical lens antennas, excitation of shallow lenses by leaky-wave/Fabry–Perot feeds, and fly-eye antenna arrays.

THz sources and receivers benefit from the availability of technologies relying on ultrafast photoconductors and PIN-based photodiodes and operate at frequencies that can exceed 300 GHz. These are analyzed and compared in detail in Chapter 3 by considering the associated optical and transport physics, but also practical effects such as contact effects, thermal stress, and circuit limits. A variety of THz PC sources are studied including PC-switches, photomixers, p-i-n photodiodes, and metal-semiconductor-metal (MSM) bulk photoconductors. The fundamental principles of THz antenna coupling are discussed and the input impedance, as well as the increase in the equivalent isotropic radiated power (EIRP) of the transmitting antenna, are reviewed for planar antennas on dielectric substrates. Resonant antennas and self-complementary antennas are also studied. Good understanding of material growth is necessary for ultrafast photoconductors and low-temperature GaAs, as well as InGaAs are considered for this purpose. To characterize with high precision THz components and in particular their power properties, a new, traceable thin-film pyroelectric detector technology is discussed. Wireless communications and spectroscopy are two major applications of THz technology. These are extensively discussed together with device as well as signal processing considerations for their better understanding.

Further information on the generation of THz continuous waves based on the optical heterodyne approach is provided in Chapter 4 by employing two-slightly detuned infrared lasers. The ultrafast photoconductors necessary for this purpose are based on sub-picosecond carrier lifetime semiconductors such as low-temperature grown GaAs and InGaAs:Fe and uni-travelling-carrier (UTC) InP/InGaAs photodiodes. Electrical models are extracted for the photoconductors, PIN photodiodes, and UTCs, and their efficiency and maximum power achieved are examined. Attention is paid on the characteristics of backside illuminated and waveguide-fed UTC photodiodes. Planar and micromachined antennas are being considered for photomixing systems and attention is paid on their on wafer as well as free-space characterization.

Plasmonics based approaches can be used to enhance the performance of PC antennas and are discussed in Chapter 5. Good understanding of the photoconductor physics is necessary for this purpose together with consideration of the impact of the PC antenna and its operation as emitter and detector of pulsed and continuous-wave (CW) THz radiation. The fundamentals of plasmonics are analyzed for better performance optimization of THz devices and design considerations are made for plasmonic nanostructures. Studies are also performed on PC THz devices with plasmonic contact electrodes, large area plasmonic PC nanoantenna arrays, and plasmonic PC THz devices with optical nanocavities.

QCLs are promising devices for THz signal generation. Chapter 6 discusses their design, state-of-the-art performance and limitations, and potential for improvement based on novel materials systems. Intersubband (ISB) transitions in quantum wells (QWs) allow laser emission at THz frequencies and provide a solution to the difficulty encountered due to the lack of materials with sufficiently small bandgap energies. The basic physics involved in them is reviewed including optical absorption and emission processes and phonon-assisted

nonradiative transitions. Considerations are made for the design of the QC gain medium and optical cavity, as well as the use of plasmonic waveguides to achieve strong optical confinement. Other QCL properties of interest are spectral coverage, output power, and temperature characteristics. The limitations imposed in the use of GaAs/AlGaAs QWs due to, the presence of THz-range optical phonons and thus ability to cover the entire THz spectrum emit without cryogenic cooling can be overcome through the use of GaN/AlGaN QWs, where the optical phonon frequencies are above THz range, and SiGe which has significantly weaker electron-phonon and photon-phonon interactions compared to III-V compound semiconductors.

2D layer technology can be used for various devices including those operating at THz as described in Chapter 7. Of interest is their very strong tunable electromagnetic response at THz, which can be utilized for realizing active devices such as amplitude and phase modulators as well as active filters. Beam shaping and real-time terahertz imaging can be achieved using metamaterial structures as well as large arrays. Graphene and graphene-based, as well as transition-metal dichalcogenides, offer the possibility of realizing terahertz devices. Their modeling is discussed and system applications of them are considered using modulator arrays in terahertz imaging.

To respond to the needs of THz sensing, imaging, and communication technology for detectors with high responsivity, selectivity, and large bandwidth plasma wave electronics are explored in Chapter 8. Different material systems can be investigated for this purpose and responsivities up to tens of kV/W and noise equivalent power (NEP) down to the sub-pW/Hz^{1/2} range have been achieved. Very high-speed communications can take advantage of their bias dependent tuning and possibility of very high modulation frequency up to 200 GHz. Devices studied for this purpose include field-effect transistors with resonant and broadband detection characteristics. Silicon and graphene materials are used for such devices. Graphene and 2D-layered materials (Black Phosphorous), as well as diamond, are other possible candidates.

Details on multipliers fundamentals and their space applications are provided in Chapter 9. Their basic properties are analyzed together with a consideration of their noise characteristics. A practical approach is presented for the design of frequency multipliers and the evolution of THz frequency multiplier technology is discussed with an emphasis on the building of local oscillators. The design and fabrication of modern terahertz frequency multipliers are discussed and the case study of 2.7 THz balanced triplers is analyzed. Power combining together with integration considerations are also made. A new generation of room-temperature terahertz Schottky diode-based frequency multiplier sources presents 1 mW of output power at 1.6 THz and measured conversion efficiencies follow the theoretical limit predicted by physics-based numerical models. These yield a very significant increase in performance above 1 THz in both conversion efficiency and generated output power.

Frequency multipliers using diodes have offered the possibility of generating up to THz signals using initially hybrid approaches and later on planar and integrated design. These are discussed in Chapter 10 with main emphasis on GaN-based approaches which offer the possibility of handling the high-power levels currently possible at millimeter-wave frequencies, enabling compact size signal generation at THz. Theoretical considerations of GaN Schottky diodes using analytical and numerical approaches allow a better understanding of their non-linear properties and the way they can be best optimized. Parameters of interest

to be studied are the device structure (materials, composition, geometry), breakdown voltage, I–V characteristics, as well as parameters the series resistance and C–V characteristics. They can be correlated to performance properties such as power handling capability, losses, and nonlinearity. Optical and E-Beam lithography may be used for diode fabrication. The latter opens the possibility for sub-micron anode realization, meeting the requirements of THz applications. Small but also large-signal characterization allows to extract their properties and derive models for their circuit applications. They can also assist in explaining difficulties arising in performance optimization from periphery effects, dislocation assisted reverse current. The large-signal network analyzer (LSNA) method can provide rapid evaluation of diodes which is important for rapid device development and multipliers. Various multiplier device types, designs, and fabrication approaches are being considered for frequency multipliers. This includes GaN-based vertical device and heterojunction designs, i.e. InN/GaN, transistors.

RTDs is a good candidate for THz oscillators at room temperature and are discussed in Chapter 11. Promising results with oscillation frequency up to 650 GHz have been reported in the 90s for RTDs with planar antennas. Improvement in the RTD structure for short electron delay time and the antennas for low conduction loss allowed more recently demonstration of operation reaching ~ 2 THz and both low, i.e. GaAs and InP, and large bandgap materials, i.e. GaN have been used for their fabrication. Progress on structure optimization for high-frequency and high-output power operation, resonator and radiator type, frequency-tunable RTD oscillators, and compact THz sources allow their consideration for applications such as wireless data transmission, spectroscopy, and imaging.

Wireless communication systems at THz are described in Chapter 12. Since the electromagnetic spectrum is saturated on most already allocated frequencies, systems operating above 100 GHz, i.e., in the 200–320 GHz range draw considerable interest for very high-speed wireless transmissions. Electronic and photonic building blocks are of interest for this purpose. THz transmitters, receivers, and the basic architecture of transmission systems are discussed together with various devices suitable for T-ray communication such as photomixers and approaches suitable for the generation of modulated THz signals. Integration approaches, ways of interconnection, and antennas are key components to be investigated for the realization of THz communication systems. Communication links using both electronic- and photonic based approaches are also described.

The interest into solar system objects and the interstellar medium has led in space instrument investments and consideration of THz technologies that allow insight into solar system objects and the interstellar medium. The technology and engineering aspects of the heterodyne receiver which is the system of choice for conducting high-resolution spectroscopy for space applications I described in Chapter 13. Its critical components such as mixers (Schottky diode, SIS Mixer, and Hot-Electron Bolometric Mixers) and local oscillators (frequency multiplied chains) are also analyzed together with three distinct space science applications for THz instruments and how these applications are currently driving technology development. These include planetary science and miniaturization, astrophysics, and THz array receivers, as well as, earth science: and active THz systems.