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Abstracts
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Content

Posters

A.01 Towards Terahertz Quantum Imaging

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Acquiring images in the terahertz frequency range remains a technological challenge, particularly when compared to existing techniques in the visible or near-infrared spectral range. There, semiconductor detectors are widely used due to the comparable high photon energies, and cameras with high efficiency are available in most smartphones. In contrast, the detection of terahertz waves typically requires cooled detectors or coherent detection schemes, making true terahertz cameras uncommon. However, implementing the novel idea of quantum imaging with undetected photons [1] in the terahertz frequency range could combine the best of both worlds: the high sensitivity of common CMOS-based cameras and detectors for the visible and near-infrared range with the advantages of terahertz waves.

To apply this scheme to the terahertz frequency range, we generate pairs of terahertz/visible photons via spontaneous parametric down-conversion (SPDC) in periodically poled lithium niobate (PPLN) using a 660 nm pump source performing type 0 quasi phase-matching to reach the terahertz frequency range. After passing through a single-crystal nonlinear interferometer, the frequency-shifted signal photons are detected using highly efficient and narrowband volume Bragg gratings to suppress the pump wavelength. An uncooled scientific CMOS camera is used as the detector.

The terahertz idler photons are generated and propagate in free space, interacting with an imaging target. The photons are either reflected or not. If the correlated signal and idler photons are processed appropriately, interference can be observed between them. The interference of each part of the spectrum depends not only on itself but also on the counterparts. Therefore, any change in the optical properties in the terahertz spectral range, such as a change in reflectivity, directly affects the interference of the corresponding signal. Terahertz radiation can be used for measurement purposes, while visible signal radiation contains the same information but allows for the use of sophisticated optical detectors for detection.

Here, we report our latest results on progress towards quantum imaging in the terahertz spectral range using this novel detection principle.

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A.02 Terahertz Tomography by Multi-Pixel Detection and A Priori Consideration

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Terahertz tomography, i.e. a transmission scan from many different angles, complements the well-established unidirectional non-destructive testing techniques. Imaging a sample with tomography is beneficial, especially when a dielectric sample shows complicated structures and features lined up in propagation direction, such as in 3D printing or extrusion processes [1]. Thanks to the coherent measurement, one can determine the intensity, as well as the time of flight of the radiation passing the object, allowing the reconstruction of the sample's full complex refractive index [2].

Due to its low photon energy, terahertz radiation suffers strong interactions with the sample, including refraction, scattering, and diffraction. Therefore, a priori information about the sample must be considered to accurately model the measurement process. We use a ray-tracing procedure to predict the paths on which the probing radiation travels through the imaging scene and include the result in the reconstruction procedure to cope with the above-mentioned optical effects. [3].

Furthermore, we perform off-axis measurements along the full range of the detector to facilitate the detection of radiation deviating from its originally straight beam path. Including this data in the reconstruction process can lead to a significant increase in imaging quality.

However, acquiring this off-axis data comes with the drawback of increasing measurement times drastically. We therefore employ multi-channel arrays to acquire up to eight detector pixels at a time and mitigate the problem [4].

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A.03 Optical Damage Thresholds of Fiber-Tip Spintronic Terahertz Emitters

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As all solid-state terahertz emitters, spintronic terahertz emitters are subject to material destruction if a specific optical damage threshold is exceeded. This becomes a major challenge in applications where either a high electric field strength or a small beam diameter is required.

However, to date, only a few publications have addressed the challenge of optical damage threshold and these were limited to a low-repetition-rate regime below 400 kHz [1, 2]. To the best of the authors' knowledge, the high-repetition-rate regime has not yet been targeted in a dedicated publication despite its critical importance for a variety of applications [3-5].

During the conference, we'd like to close this gap and introduce the necessity of classifying the optical damage threshold into two regimes: a low-repetition-rate regime characterized by a fluence-dependent threshold, and a high-repetition-rate regime characterized by an average-power-density dependent threshold (see Fig. 1 (c)). Taking advantage of our recently developed single-mode fiber-tip STEs [5], where the pump mode field is guaranteed to be nearly identical for each sample due to their waveguiding nature, we were able to measure the optical damage thresholds with high accuracy. By repeating the experiment at various repetition rates between 100 kHz and 1 GHz (and CW), we were able to prove the existence of the yet unpublished high-repetition-rate optical damage regime and to identify the transition point between the low- and high-repetition-rate regime.

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A.04 A Comparative Study on the Measurement of the Noise-Equivalent Power (NEP) of Resonant Terafets via a Blackbody Radiator or a CW Photomixer Emitter

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Patch-antenna-coupled field-effect transistors (Resonant TeraFETs) have recently overcome a major drawback caused by the buried metal ground-plane, which prevents the usual in-coupling of THz radiation from the backside and has limited their application as fast and highly sensitive detectors for spectroscopy, security, or remote sensing applications in the terahertz range (0.3 THz to 10 THz). This progress was enabled by the introduction of front-sided illumi¬nation through a superstrate lens, enabling a minimum optical NEP of 17 pW/√Hz. TeraFETs are operable at room temperature and can be realized in various material technologies (Si-CMOS, AlGaN/GaN, graphene etc.).

We present experimental data demonstrating that the optical NEP of resonant (narrow¬band) TeraFETs can be determined with black-body radiation. We examined three patch-antenna-coupled TeraFETs, fabricated by a commercial 65-nm Si-CMOS process at the TSMC foundry and equipped with superstrate lenses. The respective resonance frequencies lie in the range from 0.5 THz to 0.8 THz. For comparison, we also measured with a slot-dipole antenna TeraFET, resonant at 0.47 THz. We determined the signal-to-noise ratio (SNR) of the respective detector illumi¬na¬ted by the full spectrum of a square-wave-modulated black-body radiator. Due to the properties of the black-body This value is compared with the minimum NEP obtained using a CW photomixer emitter. Based on our experimental data, we see agreement between the two previously described techniques for the characterized detectors. The reasons for deviations within individual detectors are currently under investigation.

A.05 Observation of Parasitic Frequency Components Emitted by CW Photomixers

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We present findings regarding unintended frequency components in the emission spectrum of photomixer sources used for continuous wave (CW) terahertz generation. Photomixer systems featuring high-frequency tunability are commonly paired with direct power detectors, for instance, to characterize sources or detectors. In this setup, spectral components beyond the intended terahertz emission, occurring at the difference frequency of the two excitation lasers, can distort measurement results significantly. Through our investigations, we identify the presence of spurious mixing signals during broadband measurements employing a broadband antenna-coupled field-effect transistor as a terahertz detector (TeraFET).

These measurements reveal a shallowing of absorption lines and a signal plateau at higher frequencies, indicating the presence of unwanted background signal components. We conduct an in-depth examination of the photomixer emission using a Michelson Interferometer-based spectrometer. We establish a clear link between the observed unintended frequency components and the mode spectra of the semiconductor lasers with reliable quantitative agreement. Furthermore, we propose a potential approach to address some of these challenges, highlighting the importance of our findings in alleviating distorted measurement outcomes. Importantly, the critical issue of parasitic mixing has received limited attention in the literature, particularly in the domain of terahertz CW photomixer emitters widely used for spectrally resolved measurements.

A.06 A Compact Heterodyne Millimeter-Wave/Terahertz Spectrometer for Remote Sensing

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Heterodyne spectroscopy is a widely used technique to detect gases in the millimeter-wave/terahertz (mmW/THz) range in the Earth's atmosphere or in space. This is because many atomic and molecular transitions occur in this frequency range. Due to the high attenuation of terahertz radiation by water vapor, airborne instruments must be used. Two examples are Stratospheric Observatory for Infrared Astronomy (SOFIA) and Oxygen Spectrometer for Atmospheric Science on a Balloon (OSAS-B), both operating around 4.7 THz.

We are developing a compact heterodyne spectrometer operating around 240 GHz that can be placed on board a small balloon or a small satellite, such as a CubeSat, for long-term measurements at higher altitudes. This will allow for studying the Earth's atmosphere with respect to photochemical processes, pollution or climate change.

For the front-end, an integrated SiGe BiCMOS receiver with a tunable local oscillator (LO) operating from 225 GHz to 255 GHz is already available. We are currently investigating suitable back-ends. Previously, we used a digital Fast Fourier Transform Spectrometer (dFFTS), however, its size, weight, and power consumption are not suitable for an implementation in a compact instruments. In this contribution, we present a method to measure the spectrum by tuning the LO of the receiver. The signal is passed through a narrow bandpass filter and the power of the respective intermediate frequency (IF) band is measured with a power detector and a voltmeter. This results in a much more compact and power-efficient setup at the expense of a longer measurement time because not all frequencies are acquired simultaneously.

We measured a noise temperature of 10,000 K and an Allan time of 17 s at 230 GHz for this system. We also demonstrated, that this setup is capable of measuring the rotational transition of carbon monoxide (CO) at 230.538 GHz in a laboratory setup.

Recently, compact dFFTS have emerged as another viable option for the back-end, which we will compare with the tuning of the LO in a next step.

A.07 A Compact CW THz Gas Sensing System Based on a Dual-Wavelength MOPA Laser

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THz Spectroscopy has been used for gas sensing due to the non-ionizing and non-destructive features and its frequency in range with the rotational modes of gas molecules. In contrast to time-domain spectroscopy (TDS) systems, continuous wave (CW) THz technology has advantages of higher frequency resolution and spectral brightness [Hübers2011], thus suitable to detect gas molecules even with different species in one setup.

In most of the current CW THz gas sensing systems, two tunable distributed feedback (DFB) lasers are used for generating the beat signal [Hepp2016]. Although they provide generally high stability, small linewidth and a certain tuning range, the two lasers take up not only space but also effort to control them individually. For most gas measurement scenes such as in industrial environments, space and simplicity are of great concerns. To overcome the drawbacks of the two-laser system, we present in this work a more compact setup implementing only one laser for the CW THz system: a micro-integrated dual-wavelength master oscillator power amplifier (MOPA) in the wavelength range of 785 nm [Müller2022].

The MOPA laser is based on Y-branch distributed Bragg reflector (DBR) ridge waveguide (RW) diode lasers and an anti-reflection coated tapered amplifier(TA). The shoebox-sized turnkey laser system is not only compact in size but it also provides a computer-based interface, in which all the current and temperature settings can be configured. The two emission wavelengths of the MOPA laser can be tuned through separate heaters, keeping the same advantage of the above mentioned DFB lasers but achieving compactness and operability in real industrial gas measurement scenarios.

In the homodyne setup for CW THz generation and detection, two photoconductive antennae are used, between which is a home-made aluminum-based multi-pass gas cell. With a total internal beam path length of 1.4 m the gas cell provides sufficient absorption of the gases according to the Beer-Lambert law. In the first stage of our work water vapor was investigated. The laser was gradually tuned in the range of a water absorption line, and the detected THz radiation was compared with that of the cell purged with nitrogen.

The feasibility of utilizing the single MOPA laser to our CW THz gas sensing setup provides possibility to detect and analyze more gas species in future works.

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A.08 Free-space Terahertz Measurements with a Photonic Spectrum Analyzer

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The rapid evolution of 5G and 6G technologies has spurred the development of advanced instrumentation, such as spectrum analyzers, to meet the growing demand for high-resolution measurements in the terahertz regime. In this study, we present a novel photonic spectrum analyzer (PSA) design based on an optoelectronic hybrid system. The system involves phase-locking of three continuous-wave (CW) distributed-feedback diode lasers by mixing the laser light with the radiation of a high-power, electronic narrow-band emitter. Two heterodyne optical phase-locked loops, employing a photoconductive antenna and a PID controller, synchronize the laser beat signals with the reference source. Notably, our approach eliminates the need for frequency extenders, simplifying the architecture and reducing costs compared to state-of-the-art spectrum analyzers.

Through our hybrid system, we achieve laser difference frequencies ranging from 10 MHz to over 1 THz with precision in the range of several Hz. Furthermore, the flexibility of our design allows for easy extension to higher frequencies by incorporating suitable electronic emitters or cascading additional lasers. We validate the system's capabilities by measuring various spurious harmonics of electronic emitters in a CW free-space terahertz spectrum analyzer setup.

This PSA represents a significant advancement in terahertz instrumentation, offering enhanced resolution, cost-effectiveness, and versatility. Beyond its immediate applications, this technology holds promise for a wide range of fields, including telecommunications, spectroscopy, and sensing, driving further innovation in the era of next-generation wireless communications.

A.09 Enroute: Electric Field and Current Induced Second Harmonic Generation in Graphene

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Because of its exceptionally high THz nonlinearity, graphene is currently discussed as a technological platform for a variety of THz nonlinear photonic applications ranging from saturable absorbers to THz frequency multipliers. Recently we showed successfully that (i) the nonlinearity of graphene can be controlled over two orders of magnitude by applying moderate gate voltages in the sub-Volt regime and (ii) that a specifically designed grating-graphene meta-material enables further increase in the THz nonlinearity via plasmonic field enhancement. In these previous works, we have focused on studying nonlinearities of odd-orders, since monolayer graphene is a centrosymmetric material, where even-order susceptibilities cancel out. Next step is to investigate if an effective second order nonlinearity can be efficiently generated by applying appropriate inplane DC electric fields or currents (V or I), thus breaking the inversion symmetry, such as what has recently been demonstrated and observed in GaAs. We will quantify the achievable magnitude of electric-field induced second-order THz nonlinearity in graphene in order to elucidate its potential for nonlinear photonic applications relying on even-order susceptibilities, such as difference frequency generation. The derived results will directly allow us to evaluate the potential of graphene devices of this type as e.g. efficient mixers in heterodyne spectroscopy applications.

A.10 Continuous-Wave Terahertz Difference-Frequency Generation from Intersubband Polaritonic Metasurface

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1. Introduction
The THz radiation, ranging from 100 GHz to 10 THz, has received a growing amount of attention with numerous applications. Many of these applications require continuous-wave (CW) sources to produce THz radiation with sufficiently narrow linewidth, e.g., for high-resolution spectroscopy and/or heterodyne detection. Photomixers currently stand as the preferred technology for generating broadly tunable narrow-band CW THz radiation spanning from 0.1 to 3 THz. However, the performance drops dramatically with the increase of THz frequency and their practical usability is limited to frequencies below ~ 2.5 THz [1]. To generate broadly- tunable THz frequencies surpassing 2.5 THz, other THz sources such as THz difference frequency generation (DFG) is typically used. However, THz DFG sources demonstrated so far either require very high pump powers for THz generation, which limits them to pulsed operation [2] or utilize long nonlinear crystals which limits their tunability [3]. THz quantum cascade lasers (QCLs) require cryogenic cooling for CW operation [4] and room-temperature THz DFG-QCLs are complex in production [5].

We have recently demonstrated a new class of nonlinear optical metasurfaces based on coupling optical modes in nanoresonators with intersubband transitions in semiconductor heterostructures engineered for a large nonlinear response [6]. Experimental measurements using mid-infrared second harmonic generation confirmed that these intersubband nonlinear metasurfaces (ISM) can provide effective nonlinear response exceeding 106 pm/V. Here we report the first experimental demonstration of the ISM designed for THz DFG. When pumped by CW low power (~ 100mW) commercial mid-infrared lasers, the metasurface provides THz power output exceeding 40nW in the 2.5-5 THz spectral range, which is supperior to the power output provided by the state-of-the-art photomixing systems in this frequency range [7].

2. Results
The metasurface is made of an array of double-metal nanoresonators which are designed to have resonances at the two mid-infrared pump frequencies and at the output THz frequency. A 900 nm thick semiconductor heterostructure made of 23 repetitions of coupled-quantum-well structures is positioned inside of the nanoresonators. The energy levels and electron wave functions in the heterostructures are engineeried to produce giant nonlinear optical response for THz DFG [8]. The optical modes of the nanoresonators are optimized to produce large nonlinear overlap integral with theintersubband nonlinearity [6] for efficient THz DFG. Calculations predict the effective nonlinear response of our metasurface as high as 106 pm/V, which should result in several µW of THz DFG output power assuming 40mW of optical pumping. Proof-of-concept metasurfaces were fabricated using wafer bonding, substrate removal, and electron beam lithography resonator nanopattering.

Two CW tuneable single linewidth mid-infrared lasers (8.8-11µm) were used to test the metasurface. By using a 90° through hole mirror and a combination of PE and Quartz filters, we separated the THz radiation from the mid-infrared pump and sum frequency signal. The THz power was measured with a calibrated Golay cell detector. The proof-of-concept metasurface was able to reach up to 40nW when pumping 230mW at a wavelength of 10.6µm and 52mW at a wavelength of 9.2µm (at 4.2THz). We were also able to reproduce the characteristic power dependencies to the square of the pump power for DFG systems, measure the single line THz spectra, and further tune the output frequency from 2-5.5 THz.

3. Conclusion

We present the monolithic proof-of-concept ISM that achieves THz output power up to 40 nW. Theoretical simulations predict that orders of magnitude improvements in the THz power output are possible through iterative optimization of the metasurface nanoresonators to provide resonant frequencies well matched with both the pump frequencies and the THz DFG output.

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A.11 Interdigitated Terahertz Metamaterial Sensor

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Terahertz (THz) biosensing applications have developed into a rapidly growing field of research due to the characteristic properties of many biomolecules in the THz frequency range and the comparatively low-energy and non-ionizing properties of this radiation. Since the difference between THz radiation (1 THz = 300 µm) and the size of typical biomolecules (a few 10 nm) is very large, metamaterial-based sensors have established themselves as an advantageous concept for terahertz biosensing. These sensors consist of periodically arranged resonant structures on a supporting substrate and ideally have a very narrow resonance response. Surface functionalization with the desired analyte can lead to a change in the dielectric contrast in the immediate vicinity of the sensor surface, resulting in a shift of its resonance frequency.

The development of such sensor concepts represents a major challenge, but is crucial to unlocking their full potential for scientific research and advanced applications. In this work, we present an interdigitated electric split-ring resonator (ID-eSRR), which significantly increases the detection sensitivity compared to an eSRR without interdigitated structures.

All structural parameters of the sensor were designed to achieve a resonance frequency of 280 GHz. The unit cell itself is rectangular and has a side length of 240 µm, the width of the metal structures is 13.8 µm. Six pairs of fingers with a length of 11 µm and a width of 0.6 µm are inserted within the gap of 12 µm width and 13.8 µm height. Our simulations have shown, that due to the interdigitated finger structure inside the gap, the sensor exhibits a significantly higher Q-factor and stronger electric-field enhancement over a sizable area compared to a standard eSRR.

To validate the simulation results the biosensor was fabricated on a 500 µm thick fused silica substrate via electron beam lithography and a 10/200 nm thick Cr/Au metallization process.

In a proof-of-principle experiment using a SiO2 layer as an analyte simulant a remarkable frequency shift of 33.5 GHz for an analyte layer thickness of 150 nm could be achieved, which is eight times higher than the measured frequency shift of 4 GHz for the eSRR covered with the same thickness of SiO2. This new sensor concept thus offers great promise for the label-free and amplification-free detection of minute amounts of analytes, particularly biomolecules, which will be tested next.

A.12 Towards Sub-Cycle Resolved Symmetry Modulations in Barium Titante

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Phonons exhibit a mostly unexplored leverage on the microscopic mechanisms and dynamics of domain formation in ferroelectrics. A common tool to investigate structural dynamics is pump-probe spectroscopy employing intense CEP-stable THz pulses to linearly or nonlinearly drive IR- or Raman-active modes, respectively [1]. Hereby, the differentiation into the phonon- and light-field-driven symmetry breaking is crucial and remains an open research question. In this talk, we demonstrate non-resonantly employed THz-induced second harmonic generation (TFISH, [2]) as a tool to sub-cycle resolve the pure light field-driven response of ferroelectric Barium Titanate (BTO) to strong single-cycle THz fields. BTO is a non-centrosymmetric perovskite oxide with a strong ferroelectric polarization in its tetragonal phase at room temperature. The intrinsic second harmonic generation (SHG) in BTO at room temperature enables self-heterodyning. BTO samples are stable as single- and multi-domain structures, offering different intrinsic SHG magnitudes. For the non-resonant excitation, an optical rectification based tabletop-THz source is used to generate THz pulses between 0.2 and 4 THz [3]. As an outlook, we present resonantly employed TFISH as a tool to resolve the impact of coherent phonon excitation on the symmetry and domain modulations [4], employing difference frequency generation based multi-THz pulses at the phonon frequencies.

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A.13 Characterization and Optimization of Laser-Generated THz Beam for THz Based Streaking

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At the Ferninfrarot Linac- Und Test-Experiment (FLUTE) at the Karlsruhe Institute of Technology (KIT), a new and compact method for longitudinal diagnostics of ultrashort electron bunches is being developed. For this technique, which is based on THz streaking, strong electromagnetic pulses with frequencies around 240 GHz are required. We present the setup for generating THz pulses using tilted-pulse-front pumping in lithium niobate at room temperature, as used at FLUTE. Excited by an 800 nm Ti:Sapphire pump laser with a 35 fs bandwidth-limited pulse length, conversion efficiencies up to 0.03 % were achieved. Furthermore, the status of the commissioning of the diagnostics is shown.

P.01 Imaging of Structures Embedded in 3D-Printed Objects Using Terahertz Frequency-Domain Spectroscopy

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We demonstrate the ability of terahertz frequency-domain imaging to identify structures, embedded at a depth of 1 mm, in 3D-printed plastic objects. The objects are imaged in a raster-scanning pixel-by-pixel fashion at a resolved lateral resolution of 0.5 mm. To the best of our knowledge, this is the first measurement campaign on 3D-printed plastic objects using terahertz frequency-domain imaging.

In recent years, additive manufacturing has proven to be a flexible technique for the manufacturing of three-dimensional objects, including polymer-based materials [1]. The identification and authentication of individual objects via a digital fingerprint is expected to gain significance and will be important for smart production lines and fields like certification, anti-counterfeiting, and logistics [2]. In this work, the digital code is embedded underneath the surface of the object using a selective laser sintering process [3]. Several objects with different code structures were manufactured by partially melting the plastic powder and leaving inclusions full of powder inside the object. We identify code structures within these objects by exploiting the refractive index difference between the powder and solid material using terahertz frequency-domain imaging. The frequency-domain spectroscopy system employed is a fast-sweeping cw-terahertz spectrometer (T-Sweeper, HHI) [4]. The goals are: i) validating the measuring principle, and ii) testing different scanning methods (stage-scanning and beam-scanning).

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P.02 Fabrication and Calibration of Chromium-Based Filters for Applications in the Terahertz Range

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Absorbers and beamsplitters are important basic components to realize accurate experiments in the terahertz range (0.3 THz to 10 THz). Major problems in this field are high costs for the devices, while at the same time, many solutions are based on a dielectric material (such as undoped silicon) of a non-negligible thickness (>100 µm), which causes the transmission spectrum to be frequency-dependent due to Fabry-Perot -etalon modulations. To overcome the addressed challenges, an „in-house" development was initiated to realize components providing constant transmission over a wide frequency range.

One method of creating filters, respectively beam splitters, free from Fabry-Perot effects in the terahertz frequency range is to use ultrathin metal films on membranes of organic polymers of a few micrometer thickness. Here, they were realized by thermal evaporation of a chromium layer onto a 4 µm thick polypropylene foil. The decision to use polypropylene was made because this material exhibits low absorption in the terahertz range. Chromium, on the other hand, has a good adhesion to polypropylene. Filters were produced with circular or elliptical outer shape, the latter is useful for beam splitters as they have a circular cross-section area when positioned under an angle of 45°.

To determine the appropriate thickness of the metal film, we performed an experimental study to quantitatively determine the power transmission as a function of the chromium layer thickness. We fabricated six samples with varying layer thicknesses (50 nm to 120 nm) determined by the deposition rate given by the evaporation system. For the measurement of the terahertz power- transmission, the samples were mounted in a Toptica TeraScan 1550 spectroscopy system with an intermediate focus, and illuminated under an incidence angle of 0° by the system's continuous-wave (CW) radiation generated in a photomixer emitter. The frequency covered a range from 0.2 THz to 1 THz. The transmitted radiation was detected using either an in-house built TeraFET terahertz power detector or a photomixer-based terahertz field detector (Toptica TeraScan 1550 receiver).

We found repeatable transmission for a given chromium thickness . For interferometric experiments, a filter providing 50 % transmission is important. In our experiments, we found that this ratio is reached for a thickness of 115 nm. As the stated thickness is not consistent with literature values (between 6 nm to 7.5 nm [1] on silicon wafers), we are in the process of performing thickness measurements using an atomic-force microscope (AFM) and a Dektak profilometer.

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P.03 Metamaterial-based Passive Phase Modulators for THz Frequencies

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For several types of applications of terahertz radiation, phase modulators are important beam-control components. In fact, they represent a current research hotspot. For free-space applications, one finds both reflective and transmissive devices, and passive phase shifters as well as active phase modulators which are digitally controllable. This work, representing a research project towards a B.Sc. degree, investigates the design and fabrication of a passive free-space phase shifter for 600 GHz to be used in transmission mode. It is realized in the form of a 2D metasurface on a 4-µm-thick Mylar foil as a flexible substrate. With CST Microwave Studio simulations, I investigated metasurfaces with various metallic split-ring-type unit cells, assuming the conductivity of the metal patterns to be that of gold. The final target structure exhibits a high transmittance at 600 GHz and adds a phase shift to the beam, which depends on the polarization of the incident electric field. By rotating the polarization of the incident field from 0° to 90°, the phase shift changes from -3° to -41° while maintaining a power transmittance of more than 60%. The 2D metamaterial was fabricated using optical lithography and thermal metal evaporation. After attachment of the Mylar foil to a carrier wafer, lithography was performed with a negative photoresist. Deposition of chromium as an adhesion layer and of a 200-nm-thick gold layer was followed by a wet-chemical lift-off process. The final object is a flexible metamaterial. In a next step, we plan to develop phase masks with various degrees of phase shift at different locations on the metamaterial. In the poster presentation, I will discuss our goal to incorporate such phase-shift masks into a Fourier imaging system in order to achieve imaging with super-resolution.

P.04 Integrating High Frequency THz Source with Active Shot-To-Shot Jitter Correction for High Resolution Optical Probe – THz Pump Experiments

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To efficiently drive many material eigenmodes, such as phonons (up to 40 THz) or intramolecular vibrations (0.1-100 THz) [1] one requires high-field narrowband terahertz (THz) pulses. Most conventional table-top high-power terahertz sources result in broadband THz pulses and are optimal for these applications [2].

Difference frequency mixing (DFG) of near-infrared pulses in GaSe crystal provides a compact and straightforward method for generating narrowband sub-picosecond high-field pulses [3]. The pump pulses are commonly generated by a dual optical parametric amplifier (OPA), driven with Ti:Sa regenerative amplifier output. The generated THz pulses are intrinsically phase stable with a tunable central frequency ranging from 10 to 70 THz and a small bandwidth, making them well-suited for resonantly driving lattice dynamics [4].

The stability and sensitivity of ultrafast detection schemes can be improved by utilizing the seed oscillator of the Ti:Sa amplifier for probing [4]. However, this subjects measurements to short time delay fluctuations between the amplified and seed pulses, which arise from optical path length fluctuations inside the amplifier. The resulting temporal jitter, typically within the range of 10-20 fs, poses a significant obstacle, making the measurement of high-frequency dynamics with high resolution unattainable.

Here we present a DFG high frequency THz source combined with a shot-to-shot jitter correction scheme based on the cross-correlation of the seed and amplifier pulses inside a beta barium borate (BBO) crystal [5]. The spectrum of the generated sum frequency (SFG) signal carries the relative timing of the pulses. This time shift can be extracted at the 1 kHz repetition rate of the Ti:Sa regenerative amplifier and used to actively correct the recorded THz transients and recover the loss of temporal resolution.

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P.05 Room-Temperature Highly-Sensitive Terahertz Detectors based on Graphene FETs

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For the detection of THz radiation, Terahertz field-effect transistors (TeraFETs) have been researched over the last decade and three technologies, i. e. silicon, III-V and low-dimensional material has been emerged. A low-dimension FET is the Graphene FET (GFET) which is a field-effect transistor with a Graphene channel. In this letter, we present a GFET with a single layer Graphene encapsulated between two flakes of hexagonal Boron-Nitrid (h-BN) which was fabricated with the dry-transfer method and E-beam lithography. The h-BN serves as a dielectric and a protection layer for the Graphene. We characterize the antenna by measuring the responsibility in dependence of the gate voltage for several frequencies (0.2 THz to 1 THz) of a Bow-tie antenna with a silicon-lens. The graphene is swiped by a local inverted back-gate, i.e. a gate contact underneath the heterostructure. We find good agreement of the resonance according to our expected best performance CST impedance simulations. We calculate the optical NEP values for the given THz frequencies and find a minimum NEPmin = 65 pW/$\sqrt{\text{Hz}}$ at 350 GHz for our designed antenna, way lower than state-of-the art GFETs.

P.06 Time-Domain Spectroscopy for Space Exploration at Terahertz Energy Scales

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In recent years, short pulse lasers have made massive progress and space-ready femtosecond laser systems are under development [1,2]. As we discuss, time-domain spectroscopy techniques to identify planetary minerals by their spectroscopic fingerprints in the infrared and terahertz frequency range can have technological advantages over conventional spectroscopic techniques such as Fourier-Transform Infrared or Raman spectroscopy. The advantages are compactness, the possibility to replace bulky optical components by electro-optic/acousto-optic photonic techniques and the potential to be chip-integrable. Here we show our progress enroute to a THz Time-Domain spectroscopy set-up qualified for space applications and operational over bandwidth of 30 THz with a resolution of better than 100 GHz [3].

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P.07 Terahertz Upconversion With Nonlinear Organic Crystals

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Generating and detecting terahertz radiation remains a complex task due to the low photon energy. To simplify detection, researchers have explored nonlinear conversion methods to transfer information to other spectral ranges [1]. One promising approach is upconversion of terahertz radiation using ultrashort pulse lasers, which has a significantly higher photon yield than comparable processes [2]. Compared to conventional time-domain spectroscopy, the spectral bandwidth of this method is more limited [3]. However, organic crystals exhibit significantly larger bandwidths [4].

In our experiment, we used various organic crystals, including DAST, DSTMS, and OH1, as nonlinear media. To utilize this process for organic crystals, a pump laser in the near-infrared range at 1550 nm is required, along with a camera based on an InGaAs sensor. The pump wavelength is spectrally very close to the signal wavelength, only 8 nm apart. To minimize residual radiation from the pump, two filter sections are employed. These narrow the beam spectrally before upconversion and filter out the pump wavelength after upconversion, allowing for the separation of the signal radiation.

With this approach, we successfully detected signal photons generated by upconversion in organic crystals. Here we show our latest results, applying this novel detection scheme.

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P.08 Characterization of Silicon With TDS Over a Wide Resistivity Range

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Silicon is one of the most important semiconductors used in many applications that are essential to modern electronics. One of its main characteristics is the resistivity which is usually measured by the four-point probe method requiring to contact the sample with the measuring tip [1]. This, however, always contains the danger of affecting the material under test. A fast and non-contact measurement technique based on terahertz time-domain spectroscopy is already well established in the characterization of dielectrics [2], but its potential to characterize semiconductors is not fully utilized, yet.

Therefore, this potential is investigated by simulations as well as measurements of single-layer silicon wafers and simulations of two-layer silicon samples with TDS. As will be shown, the resistivity characterization is possible over a wide range for single-layer samples, while it is more complicated and restricted to specific cases for two-layer samples.

For the evaluation of the single-layer samples, we show two different approaches to evaluate the samples [3]. One of them is an analytical approach and one is a simulation approach. Comparing the results, the advantages and disadvantages of each of them are analyzed over the wide resistivity range.

Finally, using an X-Y-scan of measurements across whole wafers allows to image the spatial resistivity distribution and to detect possible inhomogeneities in the samples. In combination with recently shown advances in measuring speed [4], this shows the potential of TDS to possibly become competitive with established measurement techniques in the semiconductor industry.

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