International Conference on Free Electrons Laser Applications in Infrared and THz Studies of New States of Matter

Report of Contributions

Contribution ID : **1** Type : **Oral presentation**

Terahertz detectors based on Si CMOS MOSFETs for characterization of broadband and narrow radiation sources

Friday, 8 July 2022 11:10 (20)

The so-called "terahertz gap" is gradually being filled with new compact devices and effective solutions for the detection and emission of radiation. In particular, the development of field-effect-transistors (FET) is starting to play a significant role in this process [1, 2] and had demonstrated in applications together with pulse free electron lasers and gas laser [3, 4] and fast time-domain system [5]. In this report, we present the analysis of different methods which can be applied for the improvement of detector performance in wide range of frequencies. We focus on a standard Si CMOS (complementary metal-oxide-semiconductor) process technologies that can be used to produce cost-efficient THz detectors and sensors which are ready for scaling to sensor lines or arrays.

We implement different types of integrated antennas: a patch-type antenna for the front-side radiation coupling and a slot dipole antenna for the coupling with a substrate or booster lens. Furthermore, we extend our research toward the on-chip integrated amplifier. These solutions are not mutually exclusive and can be combined to achieve the best performance.

Although the best practical performance is achieved with substrate lens coupled devices, patch antenna coupling brings the advantage of a strong reduction in packaging complexity. The disadvantage of patch-antenna coupled detectors is the relatively small effective area of the antenna which limits its total efficiency in comparison to a backside-illumination solution with the slot antenna. This shortcoming can be improved by an additional dielectric lens that is attached to the top of the patch. We simulate and test the performance of detectors with dielectric lenses of different shapes: a dielectric rod, hyper-hemisphere, and aspheric curvature. Several different materials have been employed to fabricate these types of lenses, like silicon, sapphire, or various polymer materials. For example, the polyethylene hemisphere lens with 4 mm diameter improves the directivity of the patch antenna by minimum in 1.5 times with an additional advantage of an improvement in antenna efficiency.

The amplifying of the output signal – can be realized by using an integrated amplifier implemented on the same chip. Noise-optimized design and minimized distance between the detector output and amplifier input results in cost-efficient devices without the deterioration in the signal-to-noise ratio.

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Session Classification : Fri 08/07 Morning 2 / Abstract ID

Contribution ID : **2** Type : **Poster**

Cavity-mediated magnon-magnon coupling at 0.3 THz

Wednesday, 6 July 2022 09:45 (45)

In the regime of strong light-matter coupling, polariton modes are formed that are hybrid light-matter excitations sharing properties of both, an electrodynamic cavity mode and a matter mode. Recently, magnon-polaritons are intensively researched in ferromagnetic materials in the microwave range, with potential applications for quantum computing and sensors. In the recent decade, polaritons were obtained in the THz range with various excitations like, intersubband plasmons, magnetoplasmons in two-dimensional electron gases or vibrational modes of molecules. However, exploring magnetic excitations instead of dielectric transitions gives an advantage of low damping of spins. We are investigating coupling of the antiferromagnetic resonance (AFMR) with THz cavity modes. Here, we report on cavity-mediated magnon-magnon coupling in a system consisting of two parallel-plane crystals forming a Fabry-Perot type cavity. A crystal of yttrium ferrite (YFeO3) is kept at room temperature, while a crystal of hematite (alpha-Fe2O3) is fixed on a copper mirror placed on a heater. Spin dynamics in both materials are characterized by low damping. We used a monochromatic continuous-wave spectrometer operating in the range of 0.2-0.35 THz, which is based on frequency extenders to a vector network analyser. Reflection spectra measured as a function of hematite temperature show a series of cavity modes that form avoided crossings with the AFMR in the hematite crystal, frequency of which is rising with temperature. By measuring temperature-differential spectra, we reveal only cavity modes that are coupled to the AFMR in hematite. That is because the AFMR in the YFeO3 crystal does not depend on temperature of the hematite crystal, therefore modes coupled to YFeO3 do not show up in temperature-differential spectra. Contrary, differential spectra to external magnetic field reveal only cavity modes coupled to the AFMR in YFeO3 that has a frequency of about 300 GHz. Since the magnetic field is applied in a direction that does not change the AFMR in hematite, magnetic field-differential spectra do not show the modes coupled to the AFMR in hematite. Differential to a gap between the two crystals reveals the cavity modes. Under certain gap between the crystals, we can observe cavity modes that are strongly coupled to the AFMR in both crystals at the same time, which suggest that magnons in both crystal are coupled via a cavity mode.

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Session Classification : Wed 06/07 Morning1 / Abstract ID

Contribution ID : **3** Type : **Oral presentation**

The FELBE THz/IR FEL : Overview of the Facility and User Activities

The FELBE User Facility at the ELBE Center for High-Power Radiation Sources offers a pair of FELs that deliver beam to eight different user labs. The FELs are driven by a two-stage Superconducting RF (SRF) linac, which produces a quasi-CW beam (13 MHz/1 mA) at an energy of up to 36 MeV. The tuning range spanned by the two FELs extends from the mid IR to THz (5 – 250 μm). The spectral range and ultrashort pulse width ($\tau p \approx 0.7 - 25$ ps) are ideal for time-resolved measurements of many types of transient processes in low-dimensional materials [1], quantum structures [2], and correlated systems [3]. The high pulse energy can also drive nonlinear phenomena [4] and strong coupling [5] in light-matter interactions. The FELBE User Labs are equipped with instrumentation and synchronized ultrashort table-top lasers (i.e. Ti:Sa oscillators, regens, OPAs, SFG/DFG) which facilitate various classes of degenerate (single-color), and non-degenerate (two-color) pump-probe experiments. Optical cryostats and an 8 T split coil magnet are also available for low temperature and magnetic field dependent studies. Furthermore, the FELBE beamline extends into the adjacent High Field Magnet Lab (HLD) for performing magneto-optical spectroscopy measurements at fields up to 70 T [6]. The high repetition rate and tunability of the FELBE beam has uniquely enabled revolutionary methods in scattering-Scanning Nearfield Optical Microscopy (s-SNOM) to image novel light-matter interactions with resolution far below the diffraction limit [7]. Proposals for beamtime on FELBE and the other secondary sources at ELBE are invited from users twice a year.

(https://www.hzdr.de/FELBE).

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Session Classification : Tue 05/07 Morning/ Change Abstract ID

Contribution ID : **4** Type : **Poster**

Selected issues of influence irradiation on characteristics of superconducting elements in modern FEL-s facilities

Wednesday, 6 July 2022 16:50 (15)

Currently developed free electron lasers facilities more and more frequently use superconducting elements in theirs advanced constructions. Most frequent examples of these applications are the superconducting electromagnets, current leads to them and especially superconducting cavities. The same concerns the superconducting shields, as well as superconducting correction coils conducting the electron beam along the appropriate way. Beside of numerous advantages of using these new materials, there arise however then new effects, especially connected with the influence of the irradiation appearing in FEL accelerators on the current carrying properties of the unique superconducting materials. The irradiation is caused here by primary electrons beam as well as by secondary beams,composed from neutrons, gamma-rays and photons, which are created then. In the paper are discussed therefore the advantages but also problems arising, while using superconductors in modern accelerators, working in irradiation environment. It is shown in which way the irradiation effects damage the subtle structure of superconducting materials, including 2D HTc superconductors, in which columnar defects are formed. In the paper it will be analysed, in which way these structural defects influence the current carrying properties of the superconducting materials. It will be developed therefore the energetical approach to the process of capturing on the nano-defects of the magnetic pancake vortices, characteristic for HTc superconductors. Various initial positions of the captured vortices will be analysed, movement of them will lead to the potential barrier decrease. The influence of the radiational defects on the current-voltage characteristics will be investigated then and maximal current density values detected, as the function of irradiation intensity and physical parameters as magnetic field and temperature. These researches have therefore pure scientific meaning as well as can be useful for prediction of the proper work of superconducting solenoids and current leads to them in radiational environmen. Analysis can be also extended on the case of micro-cracks and dislocational defects formed during the mechanical winding of superconducting coils and arising then bending strain.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **5** Type : **Oral presentation**

Observation of Terahertz-Induced Magnetooscillations in Graphene

Thursday, 7 July 2022 17:25 (20)

Almost twenty years ago, experiments on high-mobility GaAs/AlGaAs heterostructures revealed strong magnetoresistance oscillations excited by microwave illumination [2,3]. These oscillations are 2π-periodic in $B_{\rm CR}/B \equiv \omega/\omega_c$, and thus reflect commensurability between the photon energy $\hbar\omega$ and separation $\hbar\omega_c$ between neighboring Landau levels [4]. Despite superior quality of modern graphene devices, no counterpart of such effects (apart from physically related phonon-assisted resistance oscillations [5]) has been reported so far in this class of materials.

We demonstrate the emergence of a terahertz analogue of microwave induced resistance oscillations (MIRO) [2,3]
in high-mobility multi-terminal graphene devices, termed below as THz-induced magnetooscillations (TIMO) [1]. The linear spectrum of graphene results in non-equidistant spectrum of Landau levels (LLs). The spacing between LLs at the Fermi energy depends on the carrier density n as $\hbar\omega_c = eBv_{\rm F}/\sqrt{\pi n}$. We indeed observe that the fundamental frequency of TIMO $B_{\rm CR} = B\omega/\omega_c \propto \sqrt{n}$ is controlled by n and thus can be tuned by applying the gate voltage. We also find that, in line with previous observations in other materials [4], the nodes of TIMO in graphene occur at integer $B_{\rm CR}/B = 1, 2, \ldots$.

In sharp contrast to conventional MIRO in other materials, where oscillations become strongly suppressed already at liquid helium temperature, we demonstrate that TIMO in graphene persist above the liquid nitrogen temperature. Preliminary measurements at higher THz frequencies indicate that the amplitude of TIMO at $f = 1.63$ and 2.54 THz relative to $f = 0.69$ THz is larger than expected from predicted f^{-4} scaling [4]. The above peculiarities of TIMO in graphene require further focused studies. An almost linear power dependence of the amplitude of oscillations, with a weak tendency to saturation at highest input power of 20 mW, indicates that much stronger TIMO can be induced by more powerful THz sources.

The presented observations extend the family of radiation-induced nonequilibrium effects in graphene and offer opportunities for deeper understanding of the MIRO phenomenon as well as scattering and relaxation mechanisms in this material.

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Session Classification : Thu 07/07 Afternoon 2 / Abstract ID

Contribution ID : **6** Type : **Oral presentation**

Electrically controlled THz plasmon resonances in large surface AlGaN/GaN grating-gate structures

Thursday, 7 July 2022 16:45 (20)

We report on the technology and THz spectroscopy of 2D plasmonic devices based on high density two-dimensional electron plasma in AlGaN/GaN semiconductor heterostructures. The devices were fabricated in the geometry of field effect transistor (FET). For the efficient coupling between long wavelength THz radiation and short wavelength 2D plasma waves, the special metallic, periodic grating-gate couplers were processed, replacing the usual antenna couplers used for submicron FET gates. With the developed, advanced technology it was possible to realize large surfaces of the devices (up to 4 mm2) with good gate control and negligible gate leakage currents, as proven by magnetooptics and magnetotransport studies [1].
THz plasmon resonances were studied by Fourier Transform Infrared Spectroscopy in a wide temperature range from 4.2 K to 300 K. We show that the base mode frequency of the investigated plasmon resonances lies in THz frequency range between 0.5 THz and 2.0 THz, depending on the electron plasma density and the period of the grating-gate coupler. Therefore, the plasmon frequency can be easily electrically tuned by the voltage applied to the grating-gate electrode and, in this way, changing the 2D electron density. The electrical control of the resonance frequency was realized even at room temperature. These results are promising for the development of plasmonic devices, that arouse great interest as potential resonant THz modulators, filters, detectors, and emitters with electrically controlled operating frequency.
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Session Classification : Thu 07/07 Afternoon 2 / Abstract ID

Contribution ID : **7** Type : **Oral presentation**

Temperature Dependence of Responsivity in Sub-THz band of AlGaN/GaN and Graphene Transistors

Wednesday, 6 July 2022 12:05 (20)

The temperature dependences of photo-response in sub-THz regime (0.14 THz) of AlGaN/GaN and graphene transistors were studied at temperatures from 10 to 300 K. Instead of measuring the voltage response using a lock-in amplifier, the current induced by the incoming sub-THz radiations was measured directly using the semiconductor parameters analyzer (SPA). This approach allows fast and multiple THz signal detection measurements as a function of temperature.
AlGaN/GaN heterostructures were grown by the metalorganic vapor phase epitaxy (MOVPE) method in the closed coupled showerhead 3×2 inch Aixtron reactor (Aixtron, Herzogenrath, Germany). The epi-structure consisted of a 2 nm GaN cap layer, 25 nm Al0.24Ga0.76N barrier layer, a 1.2 nm Al0.66Ga0.37N spacer, and a thick GaN buffer layer. Growth of all mentioned epilayers was done on the sapphire substrates. Graphene back gate transistors were fabricated from high-quality single layer graphene encapsulated in h-BN. The device design and high-quality graphene allowed us to achieve the electron mobility of ~3 m2/Vs at room temperature.
At all temperatures, the current response as a function of the gate voltage was in good agreement with the phenomenological expression assuming its proportionality to the first derivative of conductivity over the gate voltage.
With temperature decrease, the responsivity of both kinds of the studied devices increased and saturated at T~100K. The noise equivalent power continued to decrease with temperature decrease till the lowest measured temperature of 10K.
It was found that the enhancement in the current responsivity with temperature decrease is much steeper for graphene than that for GaN-based devices. The temperature dependence of the response was analyzed based on the model of non-resonant detection in filed effect transistors [1]. These results show an advantage of the graphene-based detectors over the GaN-based ones while operating at low temperatures.

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Session Classification : Wed 06/07 Morning 2/ change at 11 o'clock keynote1 J.M Klopf / Abstract ID

Contribution ID : **8** Type : **Oral presentation**

Investigation of electromagnetic coupling between the antenna and split-ring-based metasurface in CMOS technology

Friday, 8 July 2022 10:50 (20)

Physics of coupling of resonating structures has been investigated for many decades, yet still new effects are discovered due to the better understanding of the underlying processes and due to the shift of the focus from the classical resonators to the quantum objects, to meta-atoms and to the nanoscale in general. The well-known effect in atomic physics of the electromagnetically induced transparency was recently demonstrated with optical metamaterials stacked together. It became feasible to realize a near-field sensor based on coupled resonators for detection and spectral analysis of different 2-D materials, chemical compounds, or biological materials and structures thanks to the dramatic increase of coupled resonators' sensitivity to the changes of the electromagnetic properties of the surrounding medium. Furthermore, this concept can be efficiently implemented using the technology platform which is offered by the well-developed mainstream silicon (Si) complementary metal-oxide-semiconductor technology (CMOS). It is commercially available, reliable, and due to the extended metal stack's functionalities, providing many possibilities for designing high-frequency components. For example, 90-nm Si CMOS technology served as a platform for designing a terahertz (THz) sensor of human body-emitted radiation in a broad range of frequencies 0.1-1.5 THz. In this paper we report on the investigations of electrodynamic properties of a metasurface-coupled THz antenna with the fundamental resonance frequency of 350 GHz which is implemented in a 180-nm CMOS technology.
The structure under investigation is essentially a THz detector based on a pair of n-type CMOS transistors. The detector is equipped with a differential slot antenna with an outer diameter of 450 μm. A single split-ring resonator has a size of 65×30 μm with a gap of 10 μm. The numerical simulation of the electromagnetic properties of coupled resonators was performed by the Finite Element Method in CST Studio Suite. The experimental measurements were performed with the use of the frequency-domain terahertz platform with the CW THz source based on a photomixer of the TOPTICA's Terascan platform. When both antenna and a split-ring are placed together and their resonance is tuned to the same frequency, the electro-magnetic coupling between them results in strong shifting of peak frequencies. One peak shifts towards the lower frequencies, another towards the higher ones. 42% splitting from the initial resonance frequency was recorded. When the antenna is coupled to three split-rings the peaks shift even further from each other. If the antenna is coupled to a whole system, a metasurface of split-rings, then the 58% splitting from the resonance frequency was recorded.
Summarizing this report, we show that the efficient electromagnetic coupling between the slot antenna and the metasurface of split-ring resonators can be realized in a commercially available 180-nm CMOS technology.

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Session Classification : Fri 08/07 Morning 2 / Abstract ID

Contribution ID : **9** Type : **Oral presentation**

Detection of short-pulse terahertz radiation with field-effect transistors

Thursday, 7 July 2022 14:00 (45)

During the last decade, field-effect-transistor-based terahertz detectors (TeraFETs) have been developed to the competitive technology which enables a variety of new applications in the THz frequency range [1]. Among the achieved state-of-the-art performance [2] TeraFETs can also exhibit a strong nonlinear response to intense THz radiation pulses [3]. We show that the character of nonlinearity can be tuned by gate-to-source voltage from super-linear to saturation. We support this statement by experimental findings on TeraFETs fabricated in CMOS and GaN MMIC technologies using two different systems: a free-electron laser with ~20 ps THz pulses and a few THz cycle emission derived from a femtosecond Ti:Sapphire laser excited photoconductive emitter. Furthermore, the existence of a superlinear response regime can be supported using large-signal circuit modeling of antenna-coupled devices. This phenomenon can be employed both for THz autocorrelation measurement and to study the build-up time of rectified signal [4].

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Session Classification : Thu 07/07 Afternoon 1 / Abstract ID

Contribution ID : **10** Type : **Oral presentation**

Multichannel transmission for the future wireless THz telecommunication links

Friday, 8 July 2022 11:50 (20)

Terahertz (THz) radiation brings the attention of researchers and entrepreneurs for at least a few decades and has already found numerous applications in various areas, such as medical diagnostics, nondestructive testing, detection of dangerous materials and objects, security or telecommunication. This work focuses on the latter area of potential applications and aims at the development of the multiplexing methods for the future THz data transmission links. We propose the utilization of the properly designed THz diffractive optical elements (THz-DOEs) for manipulation of the THz waves on both sides of the data transmission link to, respectively, multiplex and demultiplex signals.
DOEs introduce defined attenuation and phase retardation distributions to the illuminating optical field. Clever adjustment of these parameters allows to reshape incoming radiation into almost arbitrarily chosen patterns. Moreover, the size of the crucial elements of such structures depends linearly on the wavelength, which in case of THz and sub-THz bands is in order of single millimeters or its fractions. Therefore, in many cases, THz-DOEs can be manufactured using relatively simple and cheap techniques, such as extrusion-based 3D printing.
In this work, we present methods of separation of THz beams propagating in the single optical channel, also with the frequency division. We have designed, optimized and manufactured THz-DOEs redirecting the incoming radiation into several focal spots. Two approaches have been investigated – single-frequency and multi-frequency operation. In the first case, a monochromatic THz beam is divided into three separate focal spots, while in the second one a polychromatic beam is redirected at an angle dependent on the frequency. All structures have been successfully verified experimentally and the obtained results comply with the theoretical simulations. Moreover, a setup demonstrating simultaneous dual-channel transmission at 300 GHz and 330 GHz has been demonstrated.

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Session Classification : Fri 08/07 Morning 2 / Abstract ID

Contribution ID : **11** Type : **Poster**

3D printable materials for use in dual band optical structures

Wednesday, 6 July 2022 17:35 (15)

Pursuit after new technical and scientific achievement is a driving force for new solutions in research equipment. Furthermore, highest ever competition is pushing time of rapid development to the limits. Evolution of science lead us to a place where two or more IR radiation wavelengths are necessary to conduct some experiments. In some cases wavelength separation is significant, mixing one from THz range and other from NIR of MIR. Working with whole IR spectrum is possible with usage of reflective optics. Inconvenience occurs when one have to work with THz range, where optical elements are significantly bigger. The 4" mirrors are standard and even 8", or bigger elements aren't uncommon. This fact may impact experimental setup layout and in cases of facilities like free electron laser, where two wavelength operation is associated with doubling beam guiding installation, simplifying even a part of it may be desirable. Guiding both THz and MIR can be done when using only reflective optics, but there is very limited Materials that can be usable for manufacturing a passive optical elements that work in both bands could lead to reduction of the number of elements. That can translate to experiment optimization, reduce cost of elements and shorter time of preparing experimental setup.

In these study selection of materials suitable for manufacturing of optical 3D structures was presented. A number of samples with different thickness was prepared and measured. The issue of the characterization of various materials in wide, optical spectral range is a common day task, unless material itself behaves differently in situations when it is homogeneous and when it is formed in the 3D printing process.

First, samples were measured in THz range with the Time domain spectroscopy (TDS) in 0.3-2.5 THz (1 mm – 150 um) frequency band. Transmission of the materials was measured and attenuation coefficients were determined. Spectral characterization of the samples in the range from 2 THz up to 1.5 um was conducted with FTIR spectroscopy. Based on this set of results influence of 3D print on the spectrum was shown. Discussion of the results includes influence of different polarization used in measurements, effects occurring with samples of different thickness and 3D printing side effects.

The objective is to enable designing of the optical elements using spectral properties of material combined with curvatures of the element. Design of optics that can work differently on two spectral bands takes advantage of implementing additional features like wavelength selectivity in THz band or different focal points.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **12** Type : **Poster**

Large inverted band-gap in strained three-layer InAs/GaInSb quantum wells

Wednesday, 6 July 2022 17:35 (15)

Quantum spin Hall insulators (QSHIs) based on HgTe and three-layer InAs/GaSb quantum wells (QWs) have comparable bulk band-gaps of about 10-18 meV. The former however features a band-gap vanishing with temperature, while the gap in InAs/GaSb QSHIs is rather temperature-independent. We report on the realization of large inverted band-gap in strained three-layer InAs/GaInSb QWs. By temperature-dependent magnetotransport measurements of gated Hall bar devices, we extract a gap as high as 45 meV. Combining local and non-local measurements, we attribute the edge conductivity observed at temperatures up to 40 K to the edge channels, of possible topological origin, with equilibration lengths of a few micrometers. Our findings pave the way toward manipulating edge transport at high temperatures in QW heterostructures.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **13** Type : **Oral presentation**

Nonlinear response of semiconductor systems under intense THz excitation

Tuesday, 5 July 2022 17:35 (20)

Intense narrowband terahertz pulses from the FELBE free-electron laser facility and a complementary table-top high-field THz source are utilized to study nonlinear excitation regimes of various degrees of freedom in semiconductors. In this talk we present several recent examples including impurity transitions in boron doped Si [1], intersubband transitions in Ge/SiGe quantum wells [2] and plasmons in InGaAs nanowires [3,4].

[1] F. Meng et al., *Phys. Rev. B* **102**, 075205 (2020).
[2] C. Ciano et al., *Optics Express* **28**, 7245 (2020).
[3] D. Lang et al., *Nanotechnology* **30**, 084003 (2019).
[4] R. Rana et al., *Nano Lett.* **20**, 3225 (2020).

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Session Classification : Tue 05/07 Afternoon 2/ Abstract ID:

Contribution ID : **14** Type : **Oral presentation**

Quantum GaAs/AlGaAs superlattice: multiphoton and high-frequency gain effects at room temperature

Wednesday, 6 July 2022 13:55 (45)

Semiconductor superlattices – artificial periodic structures consisting of ultrathin layers where by variation of their width, doping level and profile one can tailor their optical and electronic properties in a desirable way – can be found as an attractive environment to investigate various high-frequency phenomena [1,2].
In the given communication, we present the first experimental observation of the cavityless dissipative parametric generation in subcritically doped GaAs/AlGaAs quantum superlattice. The effect, theoretically predicted more than a decade ago [3, 4] and being inherent to optical systems [5], was discovered in molecular beam epitaxy grown silicon doped GaAs/AlGaAs quantum superlattice. To enable uniform electric field in the structure the superlattice was sandwiched between non-ohmic contacts – Schottky contact on the top and heterostructure underneath. The structure was then processed into mezas and placed into a waveguide for microwave excitation of 8.45 GHz pump microwave radiation for DC biased experiment at room temperature.
A spectral response associated with both the nondegenerate and degenerate parametric processes and harmonics of the pump frequency was clearly demonstrated; generation at fractional frequencies due to several multiphoton processes occurring simultaneously was revealed. It is shown that the incident transverse electromagnetic microwave is transformed into a longitudinal electrostatic wave which propagates with electron drift velocity experiencing negative absorption due to the Esaki-Tsu nonlinearity. The established slow propagating drift-relaxation mode (with velocity of about 1000 times lower than the speed of light in the material) enables to reach tremendous high-frequency gain levels of 104 cm-1, which can be extended up to THz frequencies [6].

[1] C. Waschke et al., PRL 70, 3319 (1993).
[2] A. Ignatov et al., PRL 70, 1996 (1993).
[3] T. Hyart et al., APL 89, 132105 (2006).
[4] T. Hyart et al., PRL 98, 220404 (2007).
[5] R. Byer, Journal of Nonlinear Optical Physics and Materials 6, 549-592 (1997).
[6] V. Čižas et al., Phys. Rev. Lett., in press (2022).

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Session Classification : Wed 06/07 Afternoon 1/ Abstract ID

Contribution ID : **15** Type : **Oral presentation**

Towards THz communications: channel characteristics and uncertainties

Wednesday, 6 July 2022 14:40 (20)

Future wireless technologies will require very high data rates and low latency to satisfy the nearly exponential growth of worldwide data traffic [1]. Terahertz (THz) technologies with its broad unallocated frequency band (0.1-10 THz) can be a promising potential solution. Along with extreme densification of the infrastructure and highly directional beams, it is the key enabling technology of the 6th generation (6G) wireless networks. However, due to path loss, THz communications is envisioned for only short-range wireless applications.
THz atmospheric absorption spectra are well documented and eight spectral windows with a relatively low atmospheric absorption are identified [2], but challenges due to free space losses, fog and rain have to be considered when evaluating the feasibility of THz communications at particular conditions. For example, usually events of heavy rain are taken into account as attenuation of approximately 10 dB/km [2], but due to the nature of heavy rain (high intensity, short duration), the actual values might significantly mismatch. This approach was satisfactory during the early development of the THz wireless communications technology and so-called THz technology gap (while lack of compact energy-efficient high-power THz transmitters and low-noise high-sensitivity receivers has limited the practical use of the THz band for communication systems [3]). Recent achievements in semiconductor technologies are closing the technology gap, practical applications are approaching and channel characteristics need to be assessed more carefully in order to accurately characterize possible scenarios.
The state-of-art of channel characteristics modelling is presented, as well the efforts to carry out statistical calculations. Statistical peculiarities of THz wave attenuation in heavy rain conditions in the case of short-range communications with narrow beam high-gain antennas were evaluated. Calculations were performed emulating both drop size distributions of the real rain and the laboratory-controlled rain described in literature. The results predicted a new future application possibility for such laboratory-based experiments (e.g. predict the performance of wireless THz data transmission links when the resilience margin is required). Such experiments can be employed to primarily predict the performance of data transmission links.

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[2] Nagatsuma, T. (2016); https://doi.org/10.1038/nphoton.2016.65
[3] Akyildiz, I.F. (2022); https://doi.org/10.48550/arXiv.2112.13187

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Session Classification : Wed 06/07 Afternoon 1/ Abstract ID

Contribution ID : **16** Type : **Poster**

Shielding with Graphene Epoxy Composites in the Extended THF Band from 0.25 to 4.00 THz

Wednesday, 6 July 2022 16:05 (15)

We report on THz characterization of graphene composites in the extended THF band from 0.25 to 4.00 THz. The composites, containing low percent by weight fractions (wt.%) of graphene form 0.8wt.% to 1.2wt.%, were investigated using THz- Time Domain Spectroscopy (THz-TDS). Based on the measured transmission and reflection coefficients, the shielding effectiveness parameters of reflection (SER) and transmission (SET) were calculated to determine the shielding effectiveness of absorption (SEA). The procedure comprised each of the weight fractions of graphene.
While the SER was found to be less than ~0.6 dB within the measured frequency range and for all the samples, the SET and SEA were found to be substantially higher, firmly above ~70 dB with graphene loading of 1.2wt.% at the frequency f=1.6 THz. Such unexpectedly high total shielding effectiveness resulted mostly from absorption, due to the measured low absolute values of SER.
The fact that a simple EM energy redirection via conduction-based reflection was not primary energy loss mechanism is favorable from the point of view of EMI shielding because contrary to metal-based conducting coatings or metallic nanocomposites, the graphene-based epoxy materials do not spread unwanted EM radiation from one place to another. Additionally, they have low weights.
By performing the Beer-Lambert calculations, we show that even a thin-film or a spray coating with a thickness in the few-hundred-micrometer range of lightweight, not conducting and not reflecting graphene epoxy composites can be sufficient for blocking THz radiation in many practical applications, where the shielding of EM by ~20−30 dB is typically sufficient. Thus, the fabricated composites can be successfully used as effective ultra-thin stealth materials.

[1]. Z. Barani, K. Stelmaszczyk, et al., Appl. Phys. Lett. 120, 063104 (2022)

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **17** Type : **Poster**

A simple method of evaluating dielectric properties of dielectric layers at sub-terahertz frequencies using tapered dielectric waveguides

Wednesday, 6 July 2022 17:35 (15)

The accurate knowledge of constitutive parameters of dielectric materials is demanded in numerous applications, from designing quasi-optical components, antennas and sensors to nondestructive testing. Terahertz time-domain spectroscopy (THz-TDS) is a recognized technique of the broadband material characterization, but it requires a well-adjusted measurement setup, special sample holders etc. Alternatively, the dielectric properties of materials can be evaluated using such widely used sub-THz apparatus as a vector network analyzer with frequency extenders. To this end, they must be additionally equipped with the dielectric measurement cells and corresponding software while the free-space measurements require a careful preparatory work similar to THz-TDS systems.

We propose a simple transmission-mode method of evaluating dielectric properties of thin-sheet materials utilizing a pair of metal-to dielectric waveguide transitions connected to the sub-THz frequency extenders. The dielectric sample under test is placed in the gap between two open-ended tapered dielectric waveguides (DW). The dimensions of DW, length and shape of the taper have been chosen to ensure the best operation in the near field. The main advantage of the tapered DW is an extremely low reflection from the taper both for outcoming and incident waves that makes the parasitic interference in the measurement area negligible. This allows to use simple formulas for extracting the constitutive parameters of dielectrics. Due to small dimensions of DW, the illuminated spot of the sample is even smaller than in a free-space setup with focusing lenses.

The method was tested using the frequency extenders V15VNA2-T/R (frequency range up to 75 GHz) and samples of Teflon, high-density polyethylene, high-frequency laminate RT/duroid 5870, alumina with the dielectric constant in the range 2.08 to 9.8 and thickness of 0.8 mm to 2.4 mm. The measurement error in all cases was about 1-3%.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **19** Type : **Poster**

THz spectroscopy of new materials for high frequency LTCC applications

Wednesday, 6 July 2022 17:35 (15)

The rapid development of modern 5G and 6G communication systems is connected with a increasing demand for new dielectric substrate materials, which should provide higher signal transmission speed and miniaturization as well as possibility of passive component integration. Requirements for such new materials include a low dielectric constant to minimize signal propagation delay, low dielectric losses for frequency selectivity and reduced energy consumption, and a low sintering temperature to allow the use of multi-layer LTCC/ULTCC (low/ultra-high temperature ceramic fired). With the modification of materials with a low dielectric constant, such as: silica, borosilicate glasses, cordierite, mullite, forsterite, diopside, willemite, aluminates, which have been well known for decades, less popular ceramics have recently appeared, such as: as borates, tungstates, molybdates, vanadates, and phosphates. The use of ceramic-ceramic or glass–ceramic composites is an effective way to tailor microstructure, electric, and thermal properties of functional materials for microwave substrates.
In particular, this approach enables the production of layered structures with buried passive electronic components using advanced LTCC technology, which offers relatively low cost, flexibility in design and production, a high degree of miniaturization and integration. Here, we present terahertz time domain characterization of a few selected materials including their refractive indices and the absorption coefficients. This research was funded by NATIONAL SCIENCE CENTRE, Poland, grant number 2019/35/B/ST5/02674.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **20** Type : **Poster**

Graphene/hBN - based varactor for novel sub-THz phase shifter.

Wednesday, 6 July 2022 17:35 (15)

The mm-wave and terahertz (THz) frequency ranges are gaining much attention recently due to their high applicability, which creates a need for the development of the devices operating in above-mentioned frequency ranges. One among the most important elements of such THz devices (e. g. Phase shifters) are varactors (variable capacitors), that allow tuning of the system via electrically-induced capacitance shift. In [1], the carbon nanotubes (CNTs) MicroElectroMechanical System (MEMS) varactor is described.

The device consists of series of etched trenches with metallized bottoms structuring the bottom electrode. On top of the trenches, the layer of CNTs is placed, serving as a top electrode. When voltage is applied between the top/bottom electrodes, the electrically-formed force causes the nanotube layer to bend towards the bottom electrode resulting in distance reduction that in final increases the capacitance.

However, CNTs are known from changing the capacity by themselves when exposed to various environmental conditions like temperature variation, humidity or illumination.

Here, we present the new type of the varactor fabricated upon silicon/SixNy platform with use of carbon-based metamaterials. The design of the structure is inspired by the one reported in [1]. However, in our approach, graphene (GR) is used as a top electrode, since it seems to be more stable and immune against external environment conditions. Futher stability improvement is achieved by covering GR with PMMA protective layer. To avoid shorting between GR and bottom electrode an hBN insulating layer was placed under GR.

We present the characterisation measurements of the metamaterial layers used in our device. Finally, the electrical characterisation of working device is presented including I - V and C - V characteristics, which appear to be linear. The tunability of our devices seems to be of the order of few hundred pF/V.

[1] A. A. Generalov et al., Nanotechnology 26, 045201 (2015).

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **21** Type : **Poster**

The back − gated AlGaN/GaN HEMT structure for observation of twisted plasmonic states in terahertz frequency range.

Wednesday, 6 July 2022 17:35 (15)

The Inverse Faraday Effect (IFE) is the appearance of stationary magnetic moments magnetization caused by circulary polarized ligh. Up to this moment, IFE has been mostly studied in the magnetic materials. In recent years, the IFE was predicted in the periodic lattice of metallic disks or spheres placed in the vicinity of two-dimensional electron liquid and under illumination of the external circularly polarized light. The radiation causes the DC current loops in the electron liquid, thus leading to appearance of static magnetic moments. As a result, the interaction between metal disks and two-dimensional electron liquid, the "twisted" plasmonic modes are excited what leads to the appearance of DC circulating current due to rectification. In this work, we present the basic idea of IFE. The mechanism of the effect is described and the theoretical predictions are presented. We propose GaN/AlGaN as a basic system for the experimental realization of the IFE. We present GaN/AlGaN HEMT like structure with 2-dimensional electron gas as a channel, that was made in order to observe the twisted plasmonic modes experimentally. On top of the structure, the periodic lattice of metal disks was fabricated with use of electron beam lithography. We present the theoretical predictions and the technological realization of the structure as well as its basic characterization. The frequency of the twisted plasmonic modes is expected to be in range of 0.6 - 1.2 THz thus leading to potential applications in terahertz physics and technology.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **24** Type : **Poster**

CMOS-based THz detector with on-chip amplifier for imaging applications

Friday, 8 July 2022 11:30 (20)

The non-ionizing nature of terahertz radiation together with the ability to penetrate through common packaging materials have sparked significant interest in THz non-destructive imaging applications. There is a huge need for low-cost and compact THz systems, which will grow with the further discovery of potential THz wave applications. A natural solution to this issue is the usage of mainstream semiconductor technologies, such as complementary metal-oxide-semiconductor (CMOS) lines. The understanding of device properties and the performance of CMOS-based detectors are constantly improving, resulting in high sensitivity, low noise, and broadband devices.

Mentioned detector improvement stimulates the research aimed at the readout circuits addressed to these devices. The integration between CMOS-based detector and on-chip readout electronics seems to be a natural solution. This attitude is optimal from the system performance point of view: the path between detector output and readout input is minimized. This opens up the way for the possibilities in the field of THz systems development and miniaturization.

In this study, we concentrate on a lower range of THz frequencies - the vicinity of 300 GHz. Two different types of integrated antennas have been implemented: a patch-type antenna for the front-side radiation coupling and a slot dipole antenna for the coupling with the substrate or booster lens. Furthermore, we extend our research toward the on-chip integrated amplifier. These solutions are not mutually exclusive and can be combined to achieve the best performance.
Although the best practical performance is achieved with substrate lens coupled devices, patch antenna coupling brings the advantage of a strong reduction in packaging complexity. The disadvantage of patch-antenna coupled detectors is the relatively small effective area of the antenna, which limits its total efficiency compared to a backside-illumination solution with the slot antenna. This shortcoming can be improved by an additional dielectric lens attached to the top of the patch.

The output signal amplifies can be realized by using an integrated amplifier implemented on the same chip. Noise-optimized design and minimized distance between the detector output and amplifier input results in cost-efficient devices without the deterioration in the SNR (signal-to-noise ratio). This work uses an integrated circuit based on a differential pair loaded by two resistors to achieve a voltage gain of 20V/V (26dB).

Described above solutions enable to increase of the output signal (and the practical SNR) by a total factor of approx. ~160 (at 275 GHz of radiation frequency for patch antenna detector), where the factor x8 is related to the increased effective area as well as improved efficiency of the antenna and the factor of x20 - due to the amplifier circuit.

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Session Classification : Fri 08/07 Morning 2 / Abstract ID

Contribution ID : **25** Type : **Oral presentation**

THz optics – achievements, challenges, and prospects

Tuesday, 5 July 2022 17:15 (20)

Terahertz radiation lies at the boundary of two different domains—optics and electronics. This, still not fully explored, area entwines physical phenomena describing two permeating worlds and interfering laws of optics and electronics. The fusion of two superposing physical worlds becomes an enormous challenge in designing optical elements.
All types of optical structures have been implemented for the THz waves, starting from reflective optics, going through refractive and diffractive optics, and ending on metamaterials. They all require different designing methods, manufacturing technologies and materials, and verification setups. Applicability of particular types of THz optics also strongly depends on the frequency spectrum, expected efficiency, working conditions, complexity, and price. All of these must be considered when dedicated optical elements are designed.
This work presents a variety of terahertz optical elements designed by our team. They include a variety of types, design methods (theoretical equations, backward propagation, iterative algorithms), design wavelengths (from sub-THz band to single terahertz), and applications (medical diagnostics, imaging, telecommunication). However, all these elements have one thing in common – they are dedicated to particular setups and applications, always ensuring optimized and the best possible performance in given conditions.

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Session Classification : Tue 05/07 Afternoon 2/ Abstract ID:

Contribution ID : **26** Type : **Poster**

Technology of graphene and related nanomaterials for THz application

Wednesday, 6 July 2022 17:35 (15)

Terahertz (THz) systems and technology have become of large interest over the last 20 years. However, it still needs new and innovative solutions in the field of both generation and detection of THz radiation. Despite the fact that scientists in many research centers are constantly working on the production of new THz sources and detectors based on semiconductors such as silicon, it turn out that carbon nanomaterials, including graphene and van der Waals heterostructures consisting of layered two-dimensional (2D) materials (h-BN or MoS2) are extremely promising materials for amplification and emission of THz radiation. Also, combination of 2D materials with "classical" semiconductor materials like GaN and/or GaAs can lead to the production of materials with unprecedented THz properties.
We demonstrate different methods of manufacturing nanodevices based on graphene and other 2D related materials. These methods include both the fabrication of 2D heterostructures from the micrometer scale to large surface area materials. We present step-by-step how to combine 2D materials with different materials, e.g. semiconductors, and how to fabricate matrices of THz elements (detectors, metasurfaces).
A comprehensive characterization of the basic electric and THz properties of these materials will be also presented. Preliminary results and theoretical analysis indicate the great potential of graphene-based nanostructures for terahertz applications.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **27** Type : **Oral presentation**

Spin and phonon excitations in layered antiferromagnets

Wednesday, 6 July 2022 09:00 (45)

The results of optical magneto-spectroscopy study (Raman scattering, THz absorption, high frequency magnetic resonance) of layered MnPS3 and FePS3 antiferromagnets will be presented. Attention will be focused on magneto-elastic interaction in MnPS3 [1] and appearance of magnon polarons in FePS3 [2]. Besides, the origin of a magnon gap in MnPS3 and splitting of this gap observed in both compounds, will be discussed.

1.Magnetoelastic interaction in the two-dimensional magnetic material MnPS3 studied by first principles calculations and Raman experiments
D. Vaclavkova et al., 2D Materials 7, 035030 (2020).

2.Magnon-polarons in van der Waals antiferromagnet FePS3
D. Vaclavkova et al., Phys. Rev. B 104, 134437 (2021)

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Session Classification : Wed 06/07 Morning1 / Abstract ID

Contribution ID : **28** Type : **Oral presentation**

Research potential of the PolFEL facility for THz studies.

Tuesday, 5 July 2022 16:35 (40)

Polish Free Electron Laser (PolFEL) will be an accelerator based facility, which will provide researchers THz laser pulses with constant repetition rate of 50kHz. Maximum peak energy of these THz pulse (30μJ) and pulse duration (about 30ps) for such repetition rates are usually not achievable by typical optical laser sources. This parameters of PolFEL laser THz beam give big research potential in area of THz studies. To help scientists discover this potential, experimental station will be equipped with femtosecond pulse laser system: oscillator, amplifier and two Optical Parametric Amplifiers (OPA), and two research station: pump-probe (PP) spectrometer and Scattering Nearfield Optical Microscope (SNOM). PP spectrometer with aid of two OPA will allow for time-resolved measurements of THz spectra with picosecond time resolution. Synchronization between two lasers: experimental station and photocathode laser, will allow jitter limitation between THz pulses and optical laser pulses in PP spectrometer. SNOM will allow visualization of specimen in THz beam with sub-micrometer spatial resolution. Together with AFM and FTIR module and with help of IR laser beam from OPA, SNOM will give researchers a grate multi-tool for visualization of specimen surface with sub-micron spatial resolution in spectral range from mid IR to 1THz. PolFEL facility will also provide additional space for scientists with their own equipment. PolFEL scientists and engineers will help with integration of such equipment with laser beams available in PolFEL.

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Session Classification : Tue 05/07 Afternoon 2/ Abstract ID:

Contribution ID : **29** Type : **Oral presentation**

Sub-THz Beamforming

Thursday, 7 July 2022 17:05 (20)

Intelligent (smart) or adaptive antennas are the most suitable for wireless communication, especially for fifth generation and higher communication systems. The key property of intelligent technology is the ability to respond automatically by changing an appropriate radiation pattern. Phase-array based smart antennas are used as the main beamforming structure. The development and application of the phase-array in THz frequency range is very problematic. A TIME–MODULATED antenna array (TMAA) can be used as a cheaper alternative.
TMAA is based on periodical ON/OFF switching of signals received/transmitted from/to each antenna array element; hence, continuous wave signals are modulated to pulsed RF signals. The spectrum of a signal after time–modulation is composed of a carrier component and harmonic components (sidebands). When a TMAA is used to receive a signal at the carrier frequency f0, and the switching frequency fp ≪ f0, sideband components will appear in the receiver. The carrier component can be used for sidelobe reduction, while siedebands are suitable for beam–scanning. The advantage of TMAAs lies in beamforming, which is achieved with switches instead of phase–shifters. RF switches based on semiconductors can be low–cost and high power handling components operating in high frequency range. This advantage might be a key factor enabling TMAAs to be a low–cost solution applicable to future intelligent antenna systems for mm–wave communication. RF switches, which use a combination of graphene and two-dimensional high-density electron gas (2DEG) in the AlGaN/GaN system, were proposed and studied. The switches were integrated into the coplanar waveguide, which allows them to be used in any system without the use of, e.g., bonding, flip-chip and other technologies and avoiding the matching problems. The use of such a switch can provide up to 20 MHz of bandwidth in time-modulated systems, which is an outstanding result for such systems.

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Session Classification : Thu 07/07 Afternoon 2 / Abstract ID

Contribution ID : **30** Type : **Oral presentation**

Measurements of Electromagnetic Properties of Low-loss Dielectrics in the mm-Wave and sub-THz Bands

Friday, 8 July 2022 09:20 (20)

Low-loss materials find multiple applications in the modern electronics industry with dielectric-based substrates used in printed circuit boards (PCB's) being a prominent example. Others include ceramic materials and plastics employed in packages for integrated circuits or supportive and protection structures for integrated antennas. There is a strong interest in efficient and easy-to-use methods to characterize all such materials at higher frequencies for dielectric constant (Dk) and dielectric loss (Df).

The main goal of this paper is to present a novel approach to material measurements at the mm-wave band based on high-Q Fabry-Perot resonators, which has been found efficient up to the frequency of 120 GHz. The upper limit is a result of available coaxial transmission lines employed to excite the resonator loaded with a sample under test and is expected to rise when new types of the lines (of smaller diameters) are offered.

In order to overcome this limitation we have attempted to combine the dedicated Fabry-Perot resonator with sub-THz spectrometers operating in either time- or frequency-domain. As a result, low-loss materials can be efficiently characterized in a ultra-broad frequency band extending from ca. 10 GHz up to hundreds of GHz employing, first, the mm-wave set-up based on a resonator and a vector network analyser (VNA) and, then, a sub-THz set-up with a spectrometer as a source of test signals. The effort will be divided into two tasks aimed at obtaining a set of numerical and mechanical models of structures with couplings, which provide as weak loss of cavity's Q-factor as possible.

The results in form of Dk and Df data on some dielectric materials measured up to the sub-THz bands will be presented.

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Presenter(s) : Dr KOPYT, Pawel (Warsaw Univ. of Technology)

Session Classification : Fri 08/07 Morning 1 / Abstract ID

Contribution ID : **31** Type : **Oral presentation**

Understanding the microscopic origin of Terahertz conductance in strained polycrystalline graphene

Thursday, 7 July 2022 09:45 (45)

The conductivity of polycrystalline graphene in the THz range is relevant for many applications. However, a full understanding of the underlying physics has not yet been achieved, due to the lack of reliable models of carrier transport in polycrystalline nanomaterials. In this work, we relate the structural deformation in strained graphene with the deviation from the Drude conductance. To this end, THz time-domain spectroscopy has been performed as function of the graphene deformation to extract the frequency dependence of the permittivity. Experimental findings are interpreted, for the first time, by means of a fully atomistic model that provides a novel microscopic interpretation of the observed Drude-Smith behavior.
Experimentally we have studied a thin polymer membrane, on top of which a graphene monolayer has been transferred. The sample is mounted on a mandrel with four clamps; by operating on the mandrel tightening mechanism, the sample can be strained. The sample is then analyzed with two spectrometers: a THz-TDS instrument, operating in the 0.3-2 THz spectral range, a FTIR instrument, operating either in the FIR (2-10 THz) or in the MIR (10-100 THz) spectral ranges depending on the employed beam-splitter and detector. The strain strongly affects the 0.3-2 THz region, while the 10-100 THz region is almost unaffected.
To interpret the observed spectra, we calculated by means of the multilayer scattering matrix method the trasmittance. The SM method employed here is the last "PPML" package available online from some of the authors[1]; its main input are the thicknesses of the layers and the conductivity of graphene. After an unsuccessful attempt to describe the graphene conductivity through a Drude model, we applied the Drude-Smith model, in its recent revision by Cocker et al.[2] This model quantifies the conductivity of a multi-domain conductor, a situation that may well describe our large-size poly-crystalline graphene sample. With this model we obtained a good agreement with experiments. We supported such explanation by a comparison with atomistic simulations relying on the wFQ approach[3], allowing a direct comparison with experimental results. In this scenario, the atomistic nature of wFQ is suitable for the description of cracks, bond elongations and the mutual motion of grain boundaries. Thus, wFQ can indeed model complex carriers transport in strained graphene. The physical parameters returned by wFQ are exploited to better interpret the meaning of Drude-Smith parameters, for which a microscopic interpretation is then given.

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Session Classification : Thu 07/07 Morning 1 / Abstract ID

Contribution ID : **32** Type : **Poster**

Tunable CNT Surfaces for THz Wave Applications

Wednesday, 6 July 2022 17:35 (15)

The research and development in the frequency region of 0.1-1.0 THz is extremely significant for the wide range of applications, such as telecommunication and imaging systems, material spectroscopy, medical imaging and treatments, etc. Despite the problems in technology and high prices for basic components (phase shifters, directional couplers, etc.), the THz systems offer higher date rates for telecommunication, high spatial resolution in the visualization of objects, small size of antennas and other elements. The state-of-the-art of the THz devices reveals serious problems with radiation sources with continuous wave semiconductor-based source, electronically tunable phase shifters, etc.
Carbon nanotubes (CNT) offer unique properties due to their natural small dimensions and outstanding electrical properties. Their tunability properties makes them very attractive in application to the THz system. Integration of CNTs with the dielectric rod waveguide (DRW) technology transferred from cellulose membranes onto other substrates (sapphire DRW, optical glass, polished silicon) by direct dry transfer enables a novel technology platform for tunable THz systems.
Phase shifter can be developed by introducing the optically controlled varactor to the DRW. The phase change of 10-20 deg with almost negligible change in attenuation less than 0.1 dB can be achieved in the frequency range of 75-500 GHz. Besides, DRWs have no cut-off frequency enabling broad band operation.
The effect of the dielectric constant tuning of single-walled carbon nanotubes under light illumination is observed in the very wide frequency range of 0.1–1 THz. The optical absorption spectrum is not uniform and it consists of several absorption peaks related to electron transitions. Therefore, the change of capacity and resistance under different light wavelength illumination is different at different wavelengths.
The losses are attributed to the electromagnetic absorption by the CNT layers with differences stemming from variations in nanotube densities and total lengths of the transferred samples on the DRWs. The increased absorbance at lower frequencies has also been previously observed for CNTs.
Carbon based nanomaterials are perspective materials for very wide applications in millimeter wave and THz frequency range. Phase shifter based on DRW loaded with CNT layer is a perspective candidate for ultra-wide band device application. The ultra-wide band optically controlled CNT-based phase shifter can enable THz beam steering.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **33** Type : **Oral presentation**

Nonlinear ultrafast studies at TeraFERMI beamline

Tuesday, 5 July 2022 13:30 (45)

TeraFERMI is a beamline built up in 2015 at the Free Electron Laser (FEL) FERMI at Elettra in Trieste (Italy). FERMI is a seeded FEL that works in a single pass-single bunch mode at 10 or 50 Hz, covering the spectral range from 100 to 4 nm. TeraFERMI is based on a Coherent Transition Radiation source that provides high intense THz electric field in the multi MV/cm range. Such a THz electric field can push nonlinear materials well into their nonlinear regime. The beamline experimental setup fulfils the capability to address nonlinear regime by measuring the fluence-dependent transmission/reflection spectra or the pump-probe response, in both the single-colour (THz pump - THz probe) and the two-colours (THz pump - IR probe) configuration, even in extreme conditions (low temperature). Condensed matter is widely investigated at TeraFERMI: Two-dimensional materials, Dirac materials, semiconductors, oxides and superconductors are only some examples. Biochemical samples, like water, can also be studied at the beamlime. Here, we will focus mainly on a study carried on a topological insulator, a particular type of Dirac materials. Topological insulators, indeed, show nonlinear THz behaviour similar to the case of graphene, thanks to the linear dispersion of their surface Dirac massless carriers. In particular, we show the nonlinear response of the Dirac plasmon of topological insulator Bi2Se3 thin films.

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Session Classification : Tue 05/07 Afternoon 1/ Abstract ID

Contribution ID : **34** Type : **Oral presentation**

Auger scattering in massless Dirac and Kane materials

Wednesday, 6 July 2022 11:00 (45)

We present an overview that sheds light into the carrier dynamics of in Landau-quantized Dirac and Kane systems, namely graphene and mercury cadmium telluride (MCT). The non-equidistant Landau-ladder makes these materials highly attractive for realizing the old dream of the semiconductor physics community to fabricate a Landau-level laser. For a recent review on this topic, see Ref. [1]. In such a laser, stimulated emission is achieved between a pair of Landau levels and the emission wavelength can be tuned by the strength of the magnetic field. In graphene, we found evidence for strong Auger scattering for the lowest allowed transitions $LL_{-1} \rightarrow LL_0$ and $LL_0 \rightarrow LL_1$ [2]. These energetically degenerate transitions can be distinguished by applying circularly polarized radiation of opposite polarization. In this configuration, Auger scattering can cause depletion of the LL0 level even though it is optically pumped at the same time. Recently, we have investigated the $LL_{-2} \rightarrow LL_1$ and $LL_{-1} \rightarrow LL_2$ transition under strong optical pumping. This transition is a candidate for the lasing transition for a Landau-level laser. We observed non-equilibrium carrier distributions by selective pumping before thermalization occurred. MCT, on the other hand, is even more attractive because of much longer relaxation times [3]. They are on the ns scale while in graphene thermalization occurs on a timescale of a few ps. The reason for the longer timescale is the different Landau ladder due to spin splitting.

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Physics **11**, (2015).
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Session Classification : Wed 06/07 Morning 2/ change at 11 o'clock keynote1 J.M Klopf / Abstract ID

Contribution ID : **35** Type : **Oral presentation**

Infrared free electron lasers in (bio)analytical chemistry

The four FELs at the HFML-FELIX user facility (FELIX-1, FELIX-2, FELICE and FLARE) each produce their own range of wavelengths and together they provide a tuning range between 3 and 1500 micrometer (0.2-110 THz). FELICE is a unique FEL beamline dedicated to intra-cavity experiments: the intensity at the point of the experiments is 50 to 100 times higher compared to the conventional user stations. The 20 end stations provide a variety of experimental setups including mass spectrometers, pump-probe setups, synchronized laser (ns, ps, fs), cryostats etc. Additionally, the FEL beamlines are coupled to the magnets of the High Field Magnet Laboratory (HFML) providing continuous magnetic fields up to 38 Tesla (soon 45 Tesla). Research projects at FELIX include systems such as (bio)molecules, clusters and complexes, as well as semiconductors, metals and magnetic materials.
The high power IR FELs are very well suited for (bio)analytical chemistry applications. Infrared ion spectroscopy (IRIS), combining the individual analytical strengths of mass spectrometry and infrared spectroscopy, is a powerful tool for small-molecule identification in a wide range of analytical applications including metabolomics, forensics, environmental science, amongst others. At FELIX, four commercial state-of-the-art analytical mass spectrometers have been connected to the FEL beamline in order to record the IR spectra of mass-to-charge selected ions. IR spectra measured for analyte compounds provide a signature that can be matched to reference spectra, either measured from standards or predicted using quantum-chemical calculations. In combination with chromatographic separation, infrared spectroscopy of mass-selected ions provides a promising new route for the identification of the molecular structures of unknown m/z peaks in complex mixture analysis. Using currently existing experimental protocols in our laboratory an IR spectrum can routinely be measured from sub-picograms samples.
At FELIX, analytical infrared ion spectroscopy is used to elucidate the three-dimensional structure of molecules, to discover new biomarkers for metabolic diseases (in collaboration with medical institutes), to identify novel psychoactive drugs (with the forensic laboratory of the Dutch police), to identify metabolic or chemical derivatives of drugs and chemicals (for pharmaceutical and chemical companies), and to identify micro-pollutants in environmental samples (for knowledge institutes and companies).
This lecture provides of an overview of the FELIX user facility, followed by a tutorial of infrared ion spectroscopy with a focus on the applications and the opportunities to provide a commercial service for industry.

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Session Classification : Tue 05/07 Afternoon 1/ Abstract ID

Contribution ID : **36** Type : **Oral presentation**

Nonlinear terahertz spectroscopy on liquid water

Thursday, 7 July 2022 14:45 (45)

Water is one of the most studied and least understood liquids[1]. While several anomalies in the thermodynamic, macroscopic properties of water are well documented[2], on the microscopic scale this special liquid is characterized by a dynamic, tetrahedral network of hydrogen bonded (HB) molecules rearranging on the picosecond timescale[3]. Thus, terahertz (THz) spectroscopy is uniquely suited to probe the dynamics of the HB water network.

The first results detailing the nonlinear response of water in the THz frequency range are recent, and the molecular interpretation is a matter of ongoing discussion. Tcypkin et al.[4,5], Ghalgaoui et al.[6], and Novelli et al.[7–10] all found that the third-order nonlinear response of water in the THz range has a similar magnitude, but proposed different explanations. The transient response of liquid water was assigned to cascaded second-order anharmonicity of the intramolecular O–H stretching modes[4]; to the field-induced irreversible ionization of water molecules[6]; or to the resonant excitation of molecular reorientations[8].

We performed a series of non-linear experiments at ~1 and 12.3 THz on liquid water at user facilities[7–10]. By comparing results obtained on a static sample and a free-flowing water jet at 12.3 THz, we were able to disentangle the distinct contributions by thermal, acoustic, and non-linear optical effects[9]. Recently, we showed that the non-linear response of water at ~1 THz depends weakly on the temperature of the bulk liquid[10]. Based on these observations, we suggest that the THz fields could be reorienting the hydrogen-bonded water molecules in the liquid phase, as originally proposed in ref.[8].

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Session Classification : Thu 07/07 Afternoon 1 / Abstract ID

Contribution ID : **37** Type : **Oral presentation**

Detecting trace amount of contamination or additives in commercial-grade gasolines by means of THz-TDS time-of-flight spectroscopy

Friday, 8 July 2022 10:00 (20)

Terahertz Time-Domain Spectroscopy (THz-TDS) has recently become an attractive analytical technique in gas, liquid or solid state phase which uses ultra-short bursts of terahertz radiation for probing of the medium properties. We show that straight forward and fast determination of propagation times of THz pulses transmitted through gasoline samples is adequate to detect small, a few hundred ppm fractions (percent by weight %wt.) of water and other contamination in commercial-grade gasoline.
A series of measurements conducted to examine time-profiles of picosecond THz pulses, i.e. their peak amplitude time-positions and delays, was used to investigate compositional change in gasoline. More precisely, the Time-of-Flights (TOFs) of the pulses passing through pure gasoline samples were compared with those transmitted through gasoline mixtures containing de-ionized water and isopropanol at calibrated weight fractions. It was found that the difference between the TOFs expressed as a function of admixture concentration has a universal linear character, independently of admixture type.
In_order to explain this linear dependence, the obtained results were compared with the Gladstone-Dale mixing rule, which presumes that refractive index of a pseudo binary mixture can be expressed as a weighted sum of refractive indices of solvent and dissolved substance with the weights given by mass fractions of the two constituents. We show that when applying this simple model an excellent agreement between measurements and theoretical calculations is obtained, proving good solubility of dissolved substance in gasoline, when the assumption on pseudo binary mixture of gasoline is fulfilled [1].

[1]. K. Stelmaszczyk, E. Karpierz-Marczewska, et al., Appl. Sci. 12, 1629, 2022

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Session Classification : Fri 08/07 Morning 1 / Abstract ID

Contribution ID : **38** Type : **Poster**

Terahertz Time-Domain Spectroscopy for artworks analysis

Wednesday, 6 July 2022 15:50 (15)

In recent years, terahertz (THz) techniques have been used in many fields of applications, most of all in space, telecommunication and security industry. However, the number of projects connecting THz technologies with Science and Culture is constantly increasing and the conservation and restoration of art, e.g. paintings or sculptures, belongs to the most evolving areas in this domain.
The conventional spectroscopic and imaging techniques for the analysis of art pieces comprise: X-ray, Ultraviolet (UV), Infrared (IR) and laser spectroscopy, but even if well established, they may have negative impact on the objects under analysis due to high energies of photons. Only IR reflectography is considered as safe method, but in many cases it is simply not sufficient. THz imaging is a non-invasive and safe technique which extends spectral bands of X-ray and IR spectroscopies to lower and less invasive photon energies. Several years ago, it was proposed for the study of artworks and research in the Uffizi Gallery in Florence and recent developments in THz technology, in particular time domain techniques, enable easier and more effective usage of THz radiation in the field of art conservation.
The best established and most promising THz time domain technique is known as Terahertz Time Domain Spectroscopy (THz-TDS). It can be used to characterize and identify various materials in the THz wavelength range, basing on the intensity of the wave passing through the sample or the wave reflected from it. In addition, the measurement of the phase of the THz wave makes it possible to study the parameters characterizing macroscopic electromagnetic properties of materials, as extension to typical molecular absorption spectra.
Inspired by successful applications of THz techniques in the Uffizi Gallery in Florence, the Louvre in Paris or museums in Milan, we decided at CENTERA to prepare THz-TDS experiments, which provide new information about the internal physical structure of paintings or frescos such as canvases, paper and even dry plaster. THz waves have good penetration depths in all these materials (~1 cm) and with broad spectral bandwidth of ps THz pulses (0.1 - 10 THz), it is be possible to identify the substances that the paint consists of basing on the registration of THz absorption spectra. As a result, one can learn about such properties of the analysed pieces of arts such as the depths of subsequent paint layers or pigments.
During investigations a specially prepared picture has been used. It was prepared using two types of paints: oil and acrylic, covering its selected areas with different amount of varnish (different layer thickness). Then the whole painting was painted over with white paint. Two dimensional (x-y) scans of the entire painting were made with THz-TDS spectrometer in both transmission and reflection modes with the resolution better than 1 mm. The obtained results will be presented on the poster.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **39** Type : **Oral presentation**

Pressure tuning of THz cyclotron resonance in HgCdTe alloys

Wednesday, 6 July 2022 11:45 (20)

The main inspiration of the current work was the results previously obtained by the part of the co-authors in MCT samples by temperature-dependent THz magnetospectroscopy [1]. The latter revealed the evolution of the energy band-gap with temperature vanishing at a certain temperature. It was shown that although the fermions in MCT alloys are represented by the admixture between the Dirac and spin-1 particles [2], they indeed support the pseudo-relativistic description involving the particle rest-mass and Fermi velocity. This work focuses on the band-gap evolution of Hg1-xCdxTe epitaxial alloys with cadmium content (x) and the hydrostatic pressure (p) probed by THz magnetospectroscopy. We study three MCT samples with different cadmium content x = 0.15, 0.16 and 0.17. THz magnetospectroscopy of the sample with x = 0.15 was performed in the pressure cell in the range of p from 0 to 3.83 kbar.
The THz magnetospectroscopy was performed at 2 K using thinned Allan-Bradley carbon resistor as a bolometer. As a source of THz radiation, the far-infrared molecular laser and Virginia diodes (VDI) source operating at 0.63 THz, 1.61 THz, 1.84 THz, 2.52 THz, 3.11 THz, and 4.25 THz were used. To create hydrostatic pressure in the pressure cell a mixture of transformer oil and kerosene was used. The fitting analysis agrees with experimental results and pseudo-relativistic description with Fermi velocity c = 1.0·106 m/s independent of hydrostatic pressure p and Cd content x.
We have investigated THz magnetospectroscopy of pseudo-relativistic fermions in Hg1-xCdxTe alloys with different cadmium content. The measured transmission spectra have featured resonant absorption lines corresponding to the optical transition between Landau levels of pseudo-relativistic fermions. Analysis of experimental data within the pseudo-relativistic description [1] allowed us to determine the rest mass m and Fermi velocity c of pseudo-relativistic fermions. The band-gaps Eg = 2mc^2 are in good agreement with the previously measured dependence on Cd content. The values of c are shown to be independent of Cd content and hydrostatic pressure.

This research was partially supported by the Foundation for Polish Science through a TEAM/2016-3/25 and by CENTERA Laboratories in the frame the International Research Agendas program for the Foundation for Polish Sciences co-financed by the European Union under the European Regional Development Fund (No. MAB/2018/9). It was also supported by the Terahertz Occitanie Platform, by CNRS through IRP.

Reference:
[1] F. Teppe et al. "Temperature-driven massless Kane fermions in HgCdTe crystals" Nature Comm. 7, 12576 (2016).
[2] S.S. Krishtopenko et al. "Hybridization of topological surface states with a flat band" J. Phys.: Condens. Matter 32, 165501 (2020).

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Session Classification : Wed 06/07 Morning 2/ change at 11 o'clock keynote1 J.M Klopf / Abstract ID

Contribution ID : **40** Type : **Poster**

Mobility Spectrum Analysis for Electric Charge Carriers in HgCdTe/HgTe/HgCdTe Quantum Well with Inverted Bands Order Close to Topological Transition

Wednesday, 6 July 2022 17:35 (15)

Based on the experimental small-field magnetotransport measurements performed for 7.1 nm-width HgCdTe/HgTe/HgCdTe quantum well with inverted band structure order, we will present results of the mobility spectra analysis in dependence on both the gate voltage (charge carrier concentration) and temperature.
We will discuss these data from the point of view of the band structure picture and possible scattering mechnisms of various types of carries in the system.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **41** Type : **Oral presentation**

Graphene plasmonics: THz nonlinearities beyond thermal effects

Thursday, 7 July 2022 11:00 (45)

Graphene is a very versatile material for optoelectronics or nonlinear optics in a large spectral range, in particular for THz radiation. One drawback is the low interaction volume between THz radiation and the single atomic layer, which limits the light matter interaction at elevated photon frequencies. During the recent years it has been shown that patterning graphene into plasmonic structures, e.g. ribbons or disks, can shift the rather strong optical response of free charge carriers at low frequencies to a more confined plasmonic resonance at higher frequencies. The size of the structure, in combination with the carrier density, determines the plasmon frequency, that can be tailored in a wide range. Beyond the linear absorption, the nonlinear optical properties are enhanced by about two orders of magnitude under resonance compared to unpatterned graphene. Here we present a set of studies that quantify the thermal effect when the structures are excited with strong laser pulses: the charge carriers are heated efficiently, as their specific heat is rather low, which leads to a decreased chemical potential and therewith a reduced plasmon frequency. Compared to thermal nonlinearities in conventional materials, thermal nonlinearities in graphene are very fast as the hot charge carriers cool down within several tens of picoseconds. Polarization-resolved pump-probe measurements on graphene disks revealed nonlinear absorption beyond thermal effects, i.e. plasmonic nonlinearities: thermal and nonthermal effect can be distinguished by using cross- and co-polarized pump-probe measurements. Numerical simulations considering thermal as well as plasmonic nonlinearities, match the observed signals well, giving a complete picture of the nonlinear processes in graphene plasmons.

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Session Classification : Thu 07/07 Morning 2 / Abstract ID

Contribution ID : **42** Type : **Poster**

FinFET and EdgeFET for THz detectors

Wednesday, 6 July 2022 17:35 (15)

We report on the investigations of FinFET and EdeFET AlGaN/GaN field effect transistors as THz detectors. Both devices we fabricated in the same technological runs on the base of the two-dimensional electron gas (2DEG) AlGaN/GaN epitaxial structures and then investigated towards THz detection. Design of a new FET dubbed EdgeFET is based on two lateral Schottky barrier gates on the sides of 2DEG channel, which is the significant difference to FinFET. This side gate configuration allowed us to electrically control the conductivity of the channel by changing its width while keeping the carrier density and mobility virtually unchanged. Electrical parameters and photoresponse of EdgeFET will be discussed and compared to the standard FinFET device. For understanding the transistor pinch-off process of the EdgeFET channel, we proposed a gradual channel model. Contrary to FinFET this kind of EdgeFET allowed us to efficiently control the current flow in the 2DEG conduction channel. Moreover, due to depletion, regions at a certain range of reverse biasing form a nanowire, which is beneficial for the adjustable resonant THz detection. Our studies of DC characteristics and photoresponse in the sub-terahertz frequency confirm the validity of the approach.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **43** Type : **Poster**

Magnetospectroscopy of a CdTe/ $Cd_{0.8}Mg_{0.2}Te$ quantum well

Wednesday, 6 July 2022 17:35 (15)

We present results of magnetotransport and magnetospectroscopic studies on a single CdTe quantum well (QW) with $Cd_{0.8}Mg_{0.2}Te$ barriers modulation-doped with Iodine donors. Experiments were carried out at temperatures of about 1.8 K as a function of magnetic field up to 10 T and included measurements of: transport, THz transmission, photoluminescence, optically detected cyclotron resonance (ODCR) and reflectivity in the visible range.

Transport measurements determined concentration of a two-dimensional electron gas (2DEG) in the CdTe QW to be 3.3×10^{11} cm^{-2} in the darkness 3.4×10^{11} cm^{-2} after over the barrier illumination. These values were used to establish the filling factors in the analysis of optical spectra. THz transmission measurements allowed us to determine the effective mass of electrons which was to be $(0.1020 \pm 0.0006)m_e$, consistent with earlier studies on CdTe QWs. Magnetoluminescence spectra showed the Fermi-edge-singularity shape that is characteristic for the case of QWs with such a high 2DEG concentration and allowed us to observe a band-to-band recombination between Landau levels in the conduction and valence bands. Combined with the determined mass of the free electron, this allowed us to determine the mass of the hole involved in the luminescence process. ODCR spectra showed that heating of 2DEG by absorption of a THz radiation leads to redistribution of electrons between all observable Landau levels, not just those adjacent to the Fermi energy. Reflectivity measurements revealed the presence of multiple resonances and provided valuable information about the energetical structure of levels of the QW under the influence of the internal electric field.

In conclcusion, we have shown on the example of CdTe/$Cd_{0.8}Mg_{0.2}Te$ QW that the combination of magnetotransport with THz and VIS magnetospectroscopy allows for a thorough characterization of the structure of quantum levels in a two-dimensional system. The comprehensive procedure applied in our study show the way to plan and carry out experiments on less known semiconductor objects.

This research was partially supported by the Polish National Science Centre grant UMO-2019/33/B/ST7/02858.

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Session Classification : Wed 06/07 Poster Session/ ID:

Contribution ID : **55** Type : **Oral presentation**

THz magnetism - terra incognita beyond the conventional approximations

Thursday, 7 July 2022 09:00 (45)

Antiferromagnets are ideal candidates to reach THz landmark in data storage with no additional energy costs. However, the lack of a net magnetization in these materials requires exceedingly high magnetic fields to manipulate their spins, hindering not only applications, but even fundamental studies on writing bits on antiferromagnets. Here we propose an approach to empower THz control of antiferromagnetic order_by pushing antiferromagnet out of equilibrium through generation of coherent magnonic state. We will show that an antiferromagnet out of equilibrium is practically a different material. Generation of coherent magnonic states in antiferromagnets substantially modifies the susceptibility of antiferromagnetic spins to THz magnetic fields and facilitates energy transfer between otherwise noninteracting phononic and magnonic modes [1,2]. In this case, the generated impact on spins goes far beyond trivial superposition of excitations and can facilitate conceptually new ways for controlling antiferromagnetism. The proposed theoretical description suggests that spin dynamics in antiferromagnets is intrinsically non-linear and once coherent magnonic state is induced, additional channels of energy transfer between otherwise orthogonal modes open up.
[1] E. A. Mashkovich, K. Grishunin, R. Dubrovin, R. V. Pisarev, A. K. Zvezdin and A. V. Kimel, THz light driven coupling of antiferromagnetic spins to lattice, Science 374, 1608-1611 (2021).
[2] Th. Blank et al (in preparation)

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Session Classification : Thu 07/07 Morning 1 / Abstract ID

Contribution ID : **56** Type : **Oral presentation**

Ultra-wideband graphene-based THz absorbers

Friday, 8 July 2022 09:40 (20)

Historically, terahertz science and technology has been restricted to specialized applications such as radio astronomy due to various technological challenges. Hollow rectangular waveguides are the primary transmission line medium in many terahertz systems due to their mechanical stability, low electromagnetic losses, enclosed nature, and compatibility with active circuit elements. Electromagnetic wave devices such as circulators, couplers and power dividers require that one or more of their ports be terminated to eliminate unwanted signals and ensure correct operation. Waveguide terminations are often realized by short-circuited waveguide sections that present low reflection and absorb the incident energy due to the presence of an absorbing material inside the waveguide. We proposed a new kind of ultra-wideband THz absorber which can be directly integrated into a standard metallic waveguide, allowing it to be used in conventional THz systems. In_order to analyze the electromagnetic properties of the absorbing materials in the frequency range from 67 GHz to 500 GHz, the absorbing material has to be embedded inside a waveguide. At the sub-millimeter frequencies, these dimensions get too small to insert any absorbing material; therefore, we use vacuum filtration to directly deposit the absorber material inside a specialized waveguide cassette. This cassette can then be integrated with a waveguide system for material characterization. The integration method developed here is easily scalable to different frequency ranges and waveguide geometries and requires only standard laboratory equipment and techniques, making it viable for high-volume production. In addition, by utilizing the same method with precision silicon micromachined components, our approach could be used to develop compact, low-cost THz waveguide absorbers of complex geometry. In this study, graphene augmented inorganic nanofibers (GAIN) were used as waveguide embedded absorbers. The measured insertion loss between 67 GHz to 110 GHz is greater than 20 dB and exceeds 40 dB at frequencies above 400 GHz. The reflection coefficient of the samples measured below 200 GHz is in excess of −10 dB, indicating that much of the incident energy is reflected by the step change in impedance at the material's interface at these frequencies. The short electrical length of the samples at these frequencies leads to a relatively low insertion loss, despite the material's high reflectivity. Above 200 GHz, the GAIN samples exhibit a reflection coefficient below −10 dB.

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Session Classification : Fri 08/07 Morning 1 / Abstract ID

Contribution ID : **57** Type : **Oral presentation**

PolFEL project: towards the construction of the Polish THz/IR/VUV Free Electron Laser

Tuesday, 5 July 2022 16:15 (20)

The idea of building a 4th generation accelerator based light source at NCBJ has been developed for almost 20 years. The concept came to reality in 2018 after receiving the funding for the construction of the Polish Free Electron Laser – PolFEL (or formally, its first stage). The PolFEL device will be driven with an RF continuous-wave superconducting linac, including a superconducting injector furnished with an in house developed lead film superconducting photocathode. The linac will be split into three branches feeding the undulator chains dedicated to THz, IR and UV/VUV coherent electromagnetic radiation emission, respectively. In effect, PolFEL will provide a wide range of light with wavelengths from 0.6 mm down to 60 nm. In addition, the facility will be furnished with a station generating short X-ray pulses in the inverse Compton scattering process. In the presentation, we will describe the PolFEL facility and its research capabilities in more details. The current status of the project and its timetable will be also presented. Finally, we will indicate the plans for further extension of the facility in the second stage the preparation for which should start right after the completion of the current stage.

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Session Classification : Tue 05/07 Afternoon 2/ Abstract ID:

Contribution ID : **58** Type : **Oral presentation**

Current status of Chemical Infrared Imaging (CIRI / SOLAIR) beamline in Solaris

Tuesday, 5 July 2022 17:55 (20)

The Chemical Infrared Imaging (CIRI) /Solaris Advanced InfraRed beamline (SOLAIR) is currently under construction. The large radiation extraction from a bending magnet will allow to collect a very wide wavelength range (0.4 - 500 µm), covering the near (NIR),_mid (MIR) and the far (FIR) infrared spectral range. The extraction of infrared range of synchrotron radiation will be achieved using a flat and slotted mirror (M1), which will be located inside the dipole chamber located at the bending magnet in the storage ring.

The presentation will showcase the current status of the project along with the expected IR beam parameters. It will also highlight microscopic techniques (FT-IR, s-SNOM and PTIR) planned to be used at the beamline with potential applications.

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Session Classification : Tue 05/07 Afternoon 2/ Abstract ID:

Contribution ID : **59** Type : **Oral presentation**

Superradiant terahertz facilities for high field Terahertz Science – the first 2 decades

Tuesday, 5 July 2022 15:30 (45)

Ultrashort flashes of THz light with low photon energies of a few meV, but strong electric or magnetic field transients have in the past two decades been increasingly employed to prepare various fascinating nonequilibrium states in matter. Superradiant Terahertz radiation from linear accelerators, first demonstrated in 2001 at Jefferson lab [1], is the working principle of a new class of sources for high-field THz pulses which turned out to be ideally suited to perform experiments of this type. Over the past 20 years several superradiant THz facilities have been commissioned (see e.g. [2]) from facilities operating parasitically at the linac of soft X-ray free electron lasers [3,4] to dedicated compact facilities operating at high repetition rates based on superconducting linac technology [5]. This talk will give an overview of these developments and will discuss some of the scientific highlight experiments. An outlook into proposed next generation facilities is given which will include facilities at hard X-ray free electron lasers [6,7] and dedicated multi-user facilities. In addition, emerging new experimental opportunities are presented.

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[2] M. Gensch et al, SUPER-RADIANT LINAC-BASED THz SOURCES IN 2013, proceed. Of FEL 2013, New York, WEIBNO01 (2013).
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[7] Z. Zhang et al, A high-power, high-repetition-rate THz source for pump–probe experiments at Linac Coherent Light Source II, J. Synch. Rad. 27, 890 (2020).

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Session Classification : Tue 05/07 Afternoon 2/ Abstract ID:

Contribution ID : **60** Type : **Oral presentation**

Amplification of THz Radiation by Strong Interaction of Drifting Electrons with Plasmons in Graphene and GaN

Thursday, 7 July 2022 11:45 (45)

More than 40 years ago, a new direction in physics opened up with the arrival of plasma-wave electronics. The possibility that the plasma waves could propagate faster than electrons fascinated all. Therefore, it was initially expected that plasmonic devices, including detectors and generators of electromagnetic radiation, would be able to work effectively in the very high frequencies - terahertz (THz) range, inaccessible to standard electronic devices. However, numerous experimental attempts to realize the amplifiers or emitters failed: the intensity of radiation turned out to be too small, plasma resonances too broad, or devices operated only at cryogenic temperatures.
We demonstrate – for the first time- experimentally strong interaction of resonant plasmons in Graphene with drifting electrons leading to THz radiation amplification with a gain going up to 9%. The results are interpreted using a dissipative plasmonics crystal model, which captures some trends and basic physics of the amplification phenomena but is far from being completed [1] .
We will present challenges of both experimental and theoretical research on the strong plasmons-drifting electrons- THz light interaction in Dirac matter - that were recently (2022) recognized as an important research direction by EU commission - awarding ERC -Advanced grant –"TERAPLASM" that will be realized by CENTERA laboratory – UNIPRESS-PAN in consortium with CEZAMAT – Technical University of Warsaw and in collaboration with teams from Japan France Germany

[1] Boubanga-Tombet S, Knap W, Yadav D, Satou A, But DB, Popov VV, Gorbenko IV, Kachorovskii V, Otsuji T: Room-Temperature Amplification of THz Radiation by Grating-Gate Graphene Structures. Phys Rev X 2020; 10((3): 031004. [DOI: 10.1103/PhysRevX.10.031004]

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Session Classification : Thu 07/07 Morning 2 / Abstract ID

Contribution ID : **61** Type : **Oral presentation**

Terahertz spectroscopy of two-dimensional plasmons in grating-gated AlGaN/GaN heterostructures

Wednesday, 6 July 2022 15:00 (20)

High electron mobility and temperature stability of III-nitride heterostructures serve as a base for the development of tunable frequency THz emitters. Some THz emission results of the 2D plasmons in nitride high electron mobility transistor (HEMT) structures have been previously reported, but they are still far from commercially viable devices. It is worth noting that the graphene-based plasmonic metamaterial for THz laser transistors was proposed recently. Nevertheless, the III-nitride heterostructures as promising plasmonic material were confirmed too by demonstrating possibility of the 2D plasmon excitation up to room temperatures.
In this work, we report on the emission and transmission spectra of the 2D plasmons excited in THz range in grating-gated AlGaN/GaN HEMT structures at the 80 K temperature. The plasmonic samples were fabricated by positioning the periodic metal stripes on top surface of heterostructures over an area of about 2 × 2 mm2. Three gate-gratings were prepared in the same process on the 10x10 mm2 sample to minimize fabrication uncertainties and ensure the uniformity of material parameters over the different gratings. The periods of the gratings with filling factor of 50 % were selected to be 600 nm, 800 nm, and 1000 nm enabling the excitation of fundamental plasmon modes in the frequency range of 1 3 THz in wide temperature range. In this work the symmetric 800 nm period gratings were investigated in order to find optimal conditions for excitation of 2D plasmons under electrical excitation. The ohmic source, S, and drain, D, contacts to the conductive 2DEG channel were developed outside of the grating, the wave vector of which was oriented perpendicularly to the contacts as described elsewhere. The resonance position and intensity were found to be related to the grating period and the bias voltage applied to the transistor terminals. Moreover, the Rabi splitting of 2D plasmon resonance was observed in the emission spectra demonstrating the splitting values to be up to 400 GHz which was considerably larger than previously reported for the plasmonic samples developed of similar III-nitride heterostructures.
This work received funding from the Research Council of Lithuania (Lietuvos mokslo taryba) through project "Hybrid plasmonic components for THz range (T-HP)" under Grant No. 01.2.2-LMT-K-718-03-0096 and was supported by CENTERA Laboratories in frame of the International Research Agendas program for the Foundation for Polish Sciences co-financed by the European Union under the European Regional Development Fund (No. MAB/2018/9).

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Session Classification : Wed 06/07 Afternoon 1/ Abstract ID

Contribution ID : **62** Type : **Oral presentation**

Free Electron Lasers: Past, Present and Future Challenges

Tuesday, 5 July 2022 10:15 (60)

Session Classification : Tutorial by Gian Piero Gallerano and Manfred Helm