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Book of Abstracts

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Session I

Chip-scale Terahertz quantum cascade lasers frequency combs: recent advances and applications in near-field nanoscopy

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Optical frequency combs (FCs), that establish a rigid phase-coherent link between the microwave and optical domains of the electromagnetic spectrum, are emerging as a key high-precision tools for the development of quantum technology platforms. These include potential applications for communication, computation, information, sensing and metrology, and can extend from the near-infrared with micro-resonator combs, up to the technologically attractive terahertz (THz) frequency range, where powerful and miniaturized quantum cascade laser (QCL) can spontaneously generate stable FCs. In this talk I'll review our recent advances in the development of stable THz QCL FCs and harmonic frequency combs with record optical power/mode and record dynamic range and I'll discuss their application potential in the fascinating area of near-field nanoscopy.

Optical beatnote detection of a portable THz QCL comb by direct microwave mixing onto a Hot-electron bolometer

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Frequency combs based on quantum cascade lasers [1] have gained attention as efficient, compact on-chip sources in the Mid-IR and THz regions. THz comb devices, thanks to their broadband double-metal waveguides, can provide wide coherent bandwidths covering more than 1 THz [2,3]. The full potential of frequency combs can be exploited by coupling them to high performance fast detectors capable of high frequency detection (>15 GHz) [4] in a dual comb scheme [1] or in SWIFT spectroscopy [5], where the THz signal is demodulated at the repetition rate (i.e. intermodal spacing) of the comb by measuring the optical beatnote. Hot Electron Bolometers are extremely sensitive detectors, and they are vastly employed in astronomical observations to map THz lines with a very high spectral resolution [6]. At the same time, such devices feature an intrinsically wide electrical bandwidth, making them appealing for applications in the THz range where the quest for high-speed detectors has been boosted by renewed interest in the field of ultrafast THz physics and frequency comb technology.
We present optical beatnote detection from a narrow, planarized THz QCL comb [7] operating at 80 K in a small nitrogen-cooled dewar. The 21.6 GHz comb beatnote is detected by downconversion, directly mixing free-space signals from the QCL and a microwave synthesizer onto an NbN HEB optimized for RF frequencies and downconverting it to a >3 GHz bandwidth. In Fig.1the RF signal at 840 MHz measured from the bolometer results from the mixing of the carrier wave at 20.8 GHz and the optical beatnote of the QCL that is then equal to 21.640 GHz. The setup constitutes a very convenient platform for the study of QCL-based optical frequency combs and a building block for compact, portable frequency comb fast spectrometers.

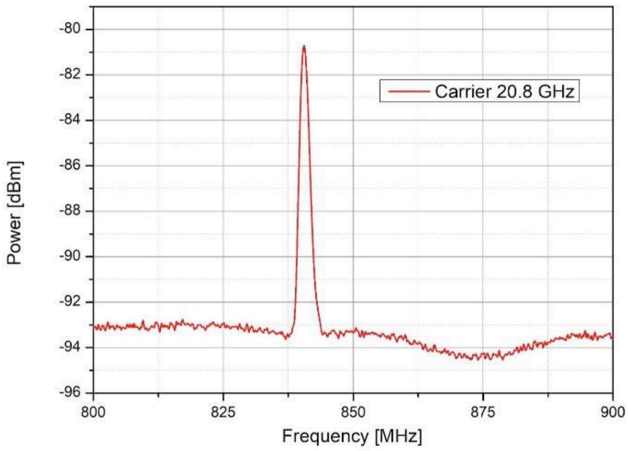

Figure 1: The RF signal measured from the bolometer results from the mixing of the carrier wave at 20.8 GHz and the optical beatnote of the QCL

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High repetition rate THz generation by cavity enhanced optical rectification in GaP

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We report on the experimental characterization of a GaP nonlinear crystal inserted within an enhancement resonator pumped by high-repetition rate near-infrared pulses for the generation of milliwatt-level THz radiation.Terahertz (THz) radiation exhibits properties of great interest and potential applications in several scientific fields. For example, THz waves (in the spectral range between 0.1 and 30 THz) find direct applications in spectroscopy of innovative materials, time-domain quantum optics, and biological sensing [1]. However, THz science remains challenging because of the lack of suitable sources and detectors. To fill this technological gap, various techniques have been explored over the years. For instance, quantum cascade lasers and photoconductive antennas are well-established methods to generate THz radiation [2]. Recently, frequency down-conversion of near-infrared light in nonlinear crystals emerged as a powerful alternative to more traditional methods. In particular, optical rectification schemes based on ytterbium (Yb) ultrafast lasers are now considered extremely promising [3]. Moreover, the use of an enhancement resonator able to store the infrared pulses from the Yb laser source boosts the power that can be used for optical rectification [4]. However, high-average power leads to a high thermal load for the nonlinear crystal. In addition, spatial deformation of the resonant mode can occur when the crystal is under stress inside the cavity, causing power losses and THz power drops. A crystal widely used is Gallium Phosphide (GaP) [5]. Recently, Hekmat et al. [6] published an extensive study on the behavior of this crystal when used for single pass optical rectification in the presence of high power. In this work, we propose a preliminary study in a slightly different regime of operation for GaP crystals, exploiting an enhancement resonator to achieve an average power > 300 W. This offers the chance to investigate the material properties at very high power together with the possibility of understanding the effect of GaP-induced mode deformation inside an enhancement cavity. We propose an experimental setup based on a amplified Yb fiber mode-locking laser (spectral width ~ 7 nm around 1035 nm) with a repetition rate of nearly 100 MHz, with maximum power of 60 W, and a pulse length of 370 fs. The amplified pulses are boosted to nearly 300 W using an enhancement cavity inside which optical rectification in a GaP crystal takes place. This way, modal instabilities and high-power-induced effects on GaP are observable and characterizable together with the THz generation efficiency. Even if modal instabilities partially limit the maximum gain achievable with the enhancement cavity, the comprehension of the phenomenon will soon allow the implementation of mitigation strategies to fully exploit the advantage of optical rectification in an enhancement cavity for the high repetition rate and the milliwatt level average power THz generation, opening the way to promising applications in the THz region. The experimental setup for intracavity THz generation is shown in Figure 1a. A Yb mode-locked fiber laser produces pulses at 1035 nm with a 92.857-MHz repetition rate. A high-power fiber amplifier raises the average power to a maximum of 60 W. Chirped volume Bragg gratings are used to stretch and recompress the pulse length to 370 fs. Then the laser pulses are coupled to an enhancement cavity, where they interact with an AR-coated GaP crystal to produce THz waves via optical rectification. Initial tests have been performed with a 2-mm tick crystal, but we plan to compare the performances with 1-mm and 0.5-mm crystals. The interaction area is ~ 1 mm^2. The cavity design recalls the one already exploited for previous studies with different applications that can be found in Refs. [7,8]. As a difference, the finesse is lowered by the presence of the GaP crystal (losses ~ 10%), increased group delay dispersion, and low reflectivity of the input coupler (84%). The resonant mode is monitored with a CCD camera outside the cavity. We estimate a maximum gain factor of 14. This way, at the interaction point with the GaP, powers > 300 W can be reached. In Figure 1b we show the generated THz power in single pass configuration (GaP outside the cavity) and using the enhancement cavity. The cavity power gain is also shown. For a given laser power, the enhancement cavity boosts the power on the GaP and the generated THz. On the other hand, for an increasing incident power, the cavity gain decreases. This is a symptom of a laser-cavity decoupling, mainly due to modal degeneration and thermal lensing caused by local changes in the refractive index in the GaP. Then, the enhancement cavity fundamental mode overlaps with higher-order modes, and losses rise. The mode change with power is shown in the insets of Fig. 1b.

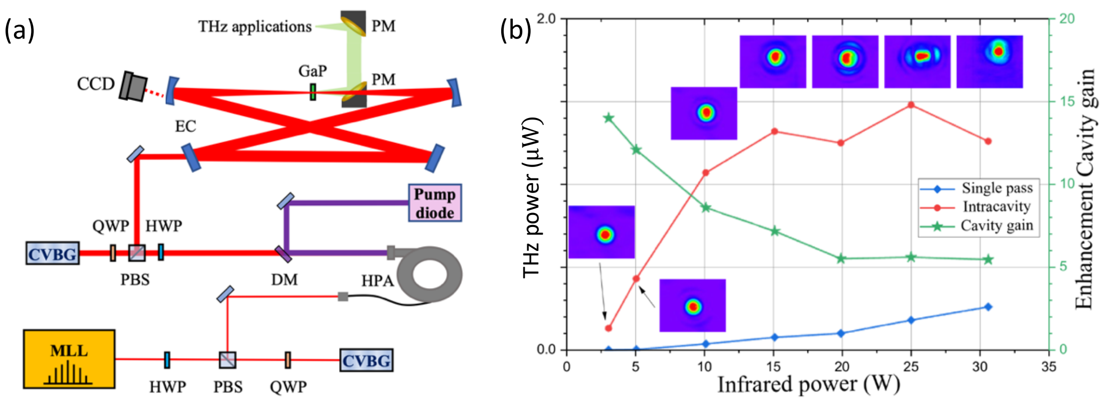

Fig. 1. Panel (a): Experimental setup. MLL: mode-locked laser, HWP/QWP: half /quarter waveplate, CVBG: chirped volume Bragg grating, HPA: high power amplifier, DM: dichroic mirror, EC: enhancement cavity, PM: parabolic mirrors. Panel (b): Generated THz power in single pass configuration and with an enhancement resonator (left axis) and cavity gain (right axis) as a function of infrared laser power. Cavity modes acquired with CCD camera are shown for each power.

In Fig. 2 a comparison between the cavity modes at intracavity power of 3 W, 109 W, and 345 W is presented. For power higher than 100 W (Figs. 2b and 2c), the fundamental mode is clearly superimposed with larger modes. Analyzing the mode images acquired with the CCD camera it is possible to extract quantitative information on the GaP behavior at different powers and temperatures. The results of such analysis will be presented at the MICS 2023 Conference in Vienna, together with THz generation data at maximum power and a comparison among different GaP thicknesses. To mitigate the mode instabilities of GaP, we propose to introduce a telescope with variable convergence inside the cavity, that might compensate for the thermal lensing effects of the GaP. At the moment, only preliminary tests with the intracavity telescope have been done.

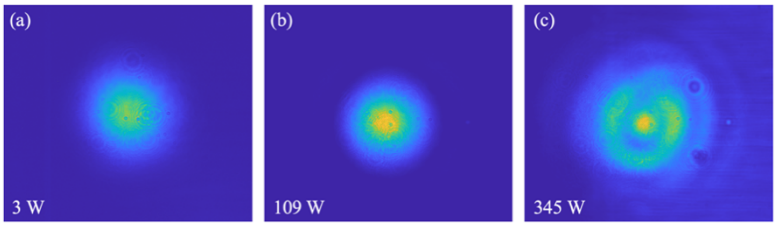

Fig. 2. Cavity modes at different powers on the GaP: (a) 3 W, (b) 109 W, and (c) 345 W.

We proposed a simple experimental setup for the generation of THz pulses with a high repetition rate via optical rectification of a Yb mode-locked laser in a GaP crystal inside an enhancement cavity. We showed that the use of an enhancement resonator can boost the generation efficiency although some drawbacks coming from the high average power arise. We investigated the behavior of the GaP crystal at high power, to suggest mitigation strategies and further increase the efficiency of THz generation of the setup.

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THz amplitude modulation by organic-based metadevices

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THz radiation, in the region between 0.1 and 10 THz, has attracted a lot of interest in the last years due to its peculiar interaction properties with matter and the possibility of applying it both in telecommunications and sensing devices [1]. One of the current subjects of active investigation in this field is the enhancement and optimization of the interaction between THz radiation and materials for application in these fields.
In this framework, metasurfaces have been proposed for this purpose [2]. Metasurfaces are materials engineered in such a way as to express peculiar electromagnetic properties in a specific range of frequencies of the electromagnetic spectrum. In particular, it is possible to design metamaterials that can strongly interact with THz pulses to tune their frequency, amplitude, and phase. We studied an innovative metadevice configuration that mixes the flexible properties of Split-Ring resonator-based metasurfaces with the dynamic tuning capabilities of organic semiconductors to achieve an electrically tunable metadevice [3]. This peculiar approach has been already demonstrated for microwaves [4] but there is yet no direct application in the THz spectral region. In particular, thanks to this device, we were able to obtain modulation depth of the THz amplitude in the order of 65% at a frequency of around 0.7 THz, as shown in Figure 1.

These performances are comparable to other state-of-the-art devices [5] but with the increased benefit of requiring a very low driving electric field, in the order of 1V. This capability comes from the use of so-called Organic Mixed Ion-Electron Conductors (OMIECs), a class of semiconductors whose permeability to charge carriers can be tuned by applying an external electric field, effectively changing the semiconductor conductivity.
Furthermore, we tested the effectiveness of applying different manufacturing methods to produce these metadevices, shifting towards a more scalable and cheaper approach exploiting ink-jet printing for both the metasurface and the organic semiconductor. This work opens the way to the exploitation of OMIECs-based modulating devices for applications in telecommunications and sensing. Moreover, other fields like electronics or bioelectronics could benefit from the further development of the capabilities and properties of organic semiconductors.

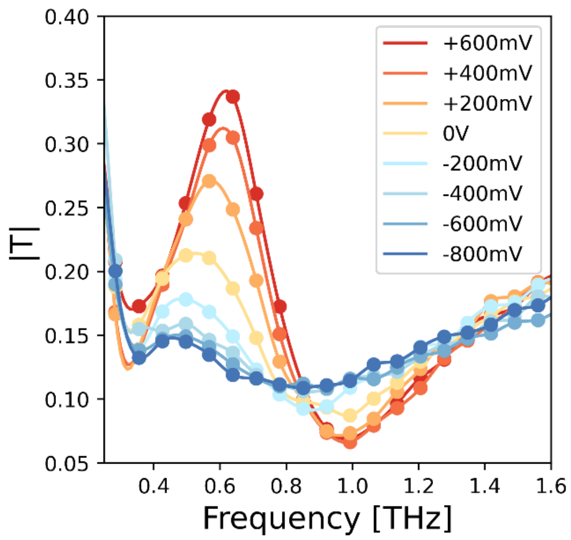

Figure 1. Absolute value of THz transmission across the metadevice as a function of the external driving potential.

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Infrared Plasmons in Quantum Materials

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Surface plasmons, the collective oscillations of electrons in metals and doped semiconductors, show outstanding electromagnetic (EM) properties spanning from a reduced wavelength in comparison to that of an exciting electromagnetic field, an extreme electric field enhancement several orders of magnitude larger than the incident field, to several nonlinear effects like harmonic generation and optical rectification. Although conventional metals, like gold and silver, are usually used in plasmonics, non-conventional and exotics materials now on the scientific edge, providing additional properties like plasmon tunability due to their extreme sensitivity to external parameters like doping, temperature, and electric and magnetic fields. In this work we present the generation of surface plasmon polariton in two quantum materials, patterned in the form of micro-ribbon arrays: the ultrahigh conductive $PdCoO_2$ oxide and the Wey-II semimetal $PtTe_2$. $PdCoO_2$ layered delafossite is the most conductive compound among metallic-oxides, with a room-temperature resistivity of nearly 2 $\mu\Omega cm$, corresponding to a mean free path of about 600Å[1]. These values represent a record considering that the charge density of $PdCoO_2$ is three times lower than copper [1]. $PtTe_2$ is a Weyl semimetal, with topological nontrivial properties and the highest room-temperature electrical conductivity among metallic Transition Metal Dichalcogenides [2]. By changing the width W and period $2W$ of the ribbon arrays, we select suitable values of the plasmon wavevector q, experimentally sampling the surface plasmon dispersion (see Fig.1 for $PdCoO_2$) in the mid-infrared electromagnetic region. Near the ribbon edge, we observe a strong field enhancement due to the plasmon confinement, indicating both materials as a promising infrared plasmonic candidates [3,4].

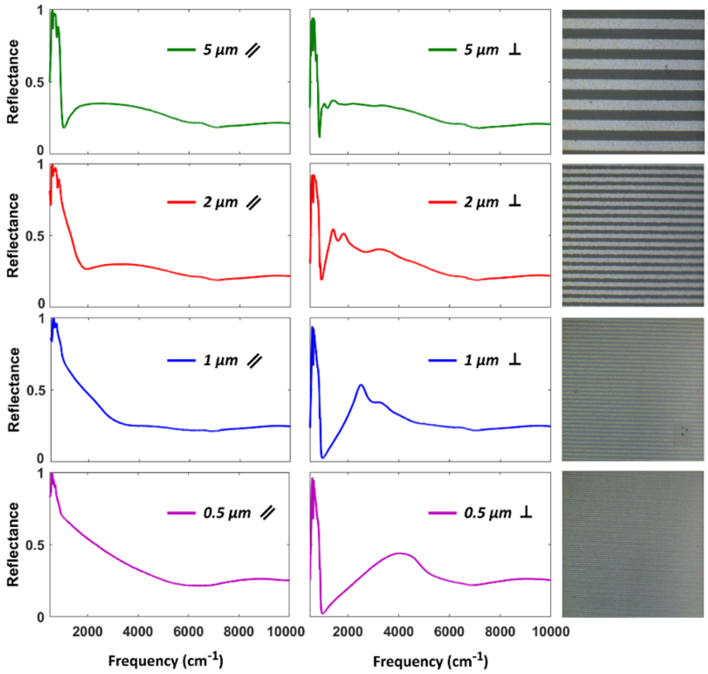

Figure 1. Reflectance of the four patterned films of $PdCoO_2$, with the radiation electric field parallel to the ribbons (left column) and perpendicular to the ribbons (right column). On the right are displayed the optical microscope images of the $PdCoO_2$ patterned films with different widths W and periods 2W.

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Session II

Terahertz Spectroscopy and Topological Quantum Materials

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Quantum materials and terahertz radiation present a mutual interplay. On one hand, linear terahertz spectroscopy allows to study the unconventional excitations of quantum materials and nonlinear and time-resolved spectroscopy their temporal evolution. On the other hand, quantum materials can be used to produce and manipulate terahertz radiation, opening up the possibility of developing new devices and applications.
In this talk, I will review our recent results on the investigation of topological quantum materials through linear and pump-probe terahertz spectroscopy and their use for generating terahertz radiation with unconventional properties.

Optical Permittivity and Permeability in the THz Band from Independent Measurements of Normal Transmission and Reflection

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An accurate retrieval procedure has been developed in order to extract both the dielectric and magnetic response of thin and thick samples in the THz band. Differently from a previous approach [1], the exact expressions of the complex reflection $\tilde{R}$ and transmission $\tilde{T}$ of the THz beam normally impinging on the sample surface are used. The core of the methodology consists in the independent employment of the experimental $\tilde{R}$ and $\tilde{T}$ values, processed by a total variation technique [2] to retrieve the complex impedance $\tilde{z}$ and refractive index $\tilde{n}$, namely $\tilde{z}_R$, $\tilde{z}_T$, $\tilde{n}_R$, $\tilde{n}_T$. From here the dielectric function $\tilde{\varepsilon}$ and permeability $\tilde{\mu}$ are obtained through $\tilde{\varepsilon}_i = \tilde{n}_i \tilde{z}_i$, $\tilde{\mu}_i = \tilde{n}_i / \tilde{z}_i$ $(i = R, T)$ to achieve $\tilde{\varepsilon}_R$, $\tilde{\varepsilon}_T$, $\tilde{\mu}_R$, $\tilde{\mu}_T$. The technique is applied to a thin film of $BiFeO_3$ showing a small but finite magnetization and a phononic resonance at about 2 THz [3]. The $BiFeO_3$ films have been grown on quartz, following a procedure similar to that previously optimized for the deposition on Si (100) substrate [4]. In particular, the films have been deposited in the temperature range 600–800 °C for 60 min using the $Bi(phenyl)_3$ and $Fe(tmhd)_3$ (phenyl = $-C_6H_5$, H-tmhd = 2,2,6,6-tetramethyl-3,5-heptandione), as precursors. The X-ray diffraction patterns, recorded in grazing incidence mode (0.8°), have confirmed the formation of pure, polycrystalline $BiFeO_3$ films, while the field emission scanning electron microscopy image indicates the presence of grains of about 500-600 nm.

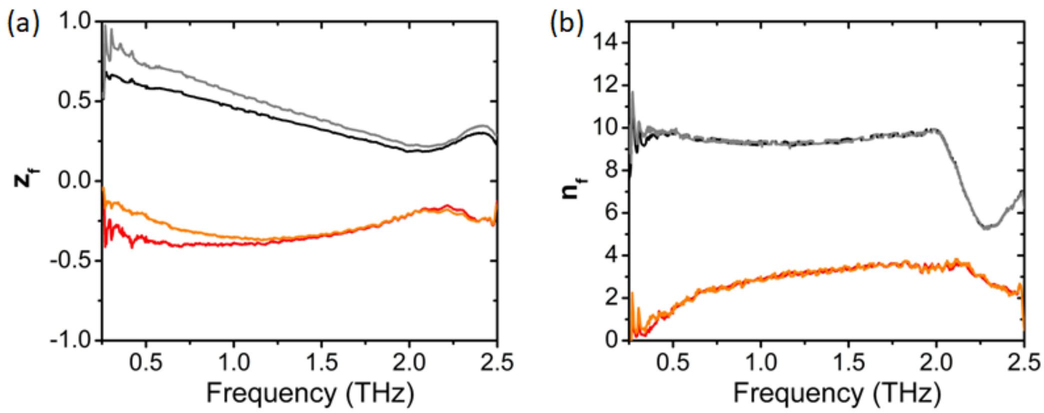

Figure 1: (a) Normalized complex impedance and (b) complex refractive index of a $BiFeO_3$ film.

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Polarimetry of Terahertz Pulses from two-color plasma

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Terahertz (THz) generation by two-color plasma has garnered attention for its capacity of providing intense and ultra-broadband THz pulses. Like any form of electromagnetic radiation, controlling wave polarization is crucial for a wide range of applications [1]. However, accurately characterizing and selectively controlling the polarization of broadband THz pulses remains challenging due to limitations in efficient optics.

On the detection side, THz air-biased coherent detection has emerged as a promising solution, employing heterodyne detection and second-harmonic generation (SHG) induced by THz radiation [2]. Nevertheless, recent research has revealed that the laser-induced air plasma in this technique can exhibit birefringence, introducing systematic errors in polarization-state determination [3]. In a recent publication [4], we have proposed a simplified approach that uses a weak probe beam and avoids high-voltage DC bias fields. Unlike the terahertz air-biased coherent detection scheme, our approach provides a unipolar, intensity-proportional signal for SHG. Therefore, we have named this technique THz Unipolar Polarimetry (TUP). In Fig. 1a an example of TUP measurement is shown. In this presentation we will demonstrate the absence of induced birefringence in air in this experimental approach, ensuring accurate measurements of the polarization state of ultra-wideband THz pulses. Regarding the control, we act on the two-colors process by varying the fundamental wave (FW) chirp and the phase difference between the FW and the second-harmonic wave (SHW). These parameters are key factors in controlling different properties of the generated THz pulses: temporal shape, energy, and the polarization state. Specifically, our findings indicate that an elliptical THz polarization can be achieved under conditions where the chirp is optimized for maximum generation efficiency. Furthermore, under these optimized conditions, we observed that as the phase difference between the FW and SHW is increased, the polarization axis of the ellipse undergoes counterclockwise rotation. Nevertheless, measurements conducted with chirp values falling outside the optimal range result in the loss of ellipticity in THz radiation, revealing polarization structures reminiscent of a 'flower' shape. In Fig. 1b we display an example of these measurements.

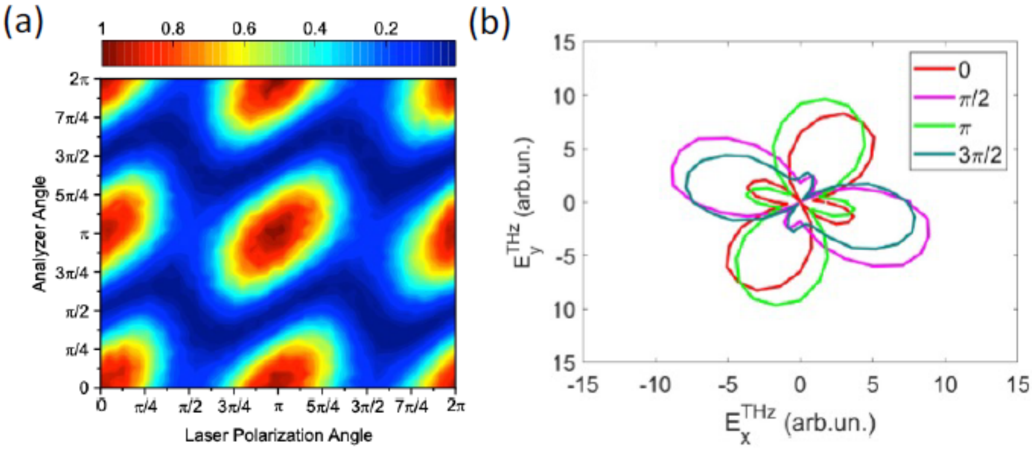

Figure 1. (a) Example of a TUP measurement. (b) Example of polarization measurement for a given chirp at different value of phase delay between the FW and SHW.

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Session III

Ultrafast THz spectroscopy of extended systems

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In this presentation, I will discuss the use of THz ultrafast spectroscopy to investigate extended systems. Optical Pump – THz Probe spectroscopy (OPTPs) has been extensively used to investigate the carrier and lattice ultrafast dynamics in bulk and low-dimensional semiconductors and topological matter [1-5]. Free carriers, electron-phonon related phenomena, and low-energy collective oscillations of conduction charges show their fingerprint in the THz spectral range. Moreover, by lying close to the Fermi level, the charge carriers photoexcited by THz waves are closely connected to DC transport. Time domain detection allows the direct observation of the amplitude and phase of the THz pulse that has interacted with the material. From this information, the complex dielectric function of the material or its complex conductivity can be directly obtained, without the need for Kramers-Kronig relations.
I will introduce different schemes for the generation and detection of THz pulses, the experimental configurations for measuring the charge-carriers dynamics, and the procedures routinely exploited to retrieve the pump-induced optical conductivity in the frequency domain from the THz fields acquired in the time domain. In this respect, I will go through some technical details that are usually barely mentioned in the literature.
I will then give an overview of our recent results concerning the presence of large polaron and exciton in 3D and 2D perovskites, the coupling of native electron doping with far-infrared phonons in Sn-based perovskites and the ultrafast carrier dynamics in the $HgPSe_3$ layered semiconductor [6-9].

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Terahertz electric-field driven dynamical multiferroicity in $SrTiO_3$

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The emergence of collective order in matter is among the most fundamental and intriguing phenomena in physics. In recent years, the ultrafast dynamical control and creation of novel ordered states of matter, not accessible in thermodynamic equilibrium, is receiving much attention. Among those, the theoretical concept of dynamical multiferroicity has been introduced to describe the emergence of magnetization by means of a time-dependent electric polarization in non-ferromagnetic materials [1,2]. In simple terms, a large amplitude coherent rotating motion of the ions in a crystal induces a magnetic moment along the axis of rotation, as schematically shown in Figure 1. However, the experimental verification of this effect is still lacking.
With our work [3], we provide the first evidence of room temperature magnetization in the archetypal paraelectric perovskite $SrTiO_3$ due to dynamical multiferroicity. To achieve it, we resonantly drive the infrared-active soft phonon mode with intense circularly polarized terahertz electric field, and detect a large magneto-optical Kerr effect. A simple model, which includes two coupled nonlinear oscillators whose forces and couplings are derived from ab-initio calculations using self-consistent phonon theory at finite temperature [4], qualitatively reproduces our experimental observations in the time and frequency domains. A quantitatively correct magnitude of the effect is obtained when one also considers the phonon analogue of the reciprocal of the Einstein - de Haas effect, also called the Barnett effect, where the total angular momentum is transferred from the coherent phonon motion to the electrons. Our findings show a new path for designing ultrafast magnetic switches by means of coherent control of lattice vibrations with light.

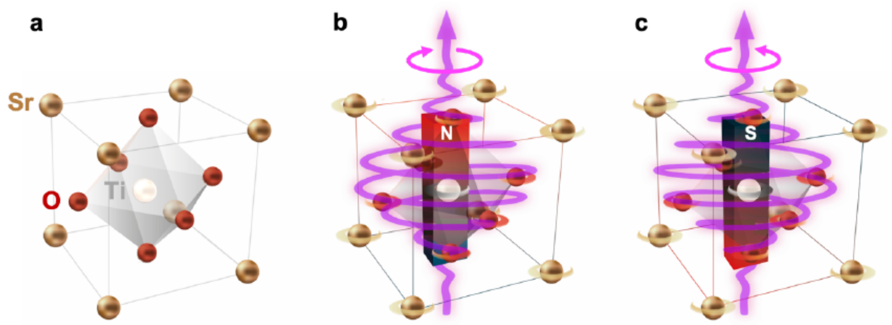

Figure 1. (a) $SrTiO_3$ unit cell in the absence of a terahertz electric field. When a circularly polarized terahertz field pulse drives a circular atomic motion, dynamical multiferroicity is expected to create a net magnetic moment in the unit cell, with (b) a north pole up for a pulse which is left-handed and (c) a south pole up for a pulse which is right-handed.

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THz Optics for Beam Tailoring by Form-Birefringence

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We present the recent advances achieved on the design, fabrication, and experimental validation of THz all-dielectric optical devices for beam tailoring and phase front shaping. There is a growing interest on optical components and devices for THz beam tailoring and controlled manipulation over its amplitude, phase and polarization states for probing and controlling a variety of complex phenomena[1]. Advanced electromagnetic field profiles can be attained under the controlled manipulation of spatial amplitude and/or phase over the plane of incidence. Some examples include plasmonic structures using graphene-based hybrid waveguides, axially symmetric wave plates using liquid crystals or intrinsically birefringent crystals and optical elements using periodically structured dielectric interfaces. The birefringence associated with the use of periodic structures is called "form birefringence" and has been widely applied to realize various THz optical components and devices [2]. We first realized a $\lambda/4$ plate as the main design element (Figure 1.a). The form-birefringence concept and its possible adaptation to additive manufacturing techniques were analytically evaluated and experimentally measured by THz time domain spectroscopy and polarization-sensitive imaging techniques. The full position-dependent electric field spatial maps and the corresponding polarization distribution maps were acquired. Then, we adapted this concept to realize a large surface area phase shifter plate (Figure 1.b) consisting of two wave plate zones coupled in a perpendicular orientation and enabling the creation of quasi-ideal phase retardation in between the two planes with a good uniformity [3]. Finally, we realized a q-plate (Figure 1.c) consisting of space-variant slabs enabling the realization of radial and azimuthal vector beams at discrete frequency intervals [4].

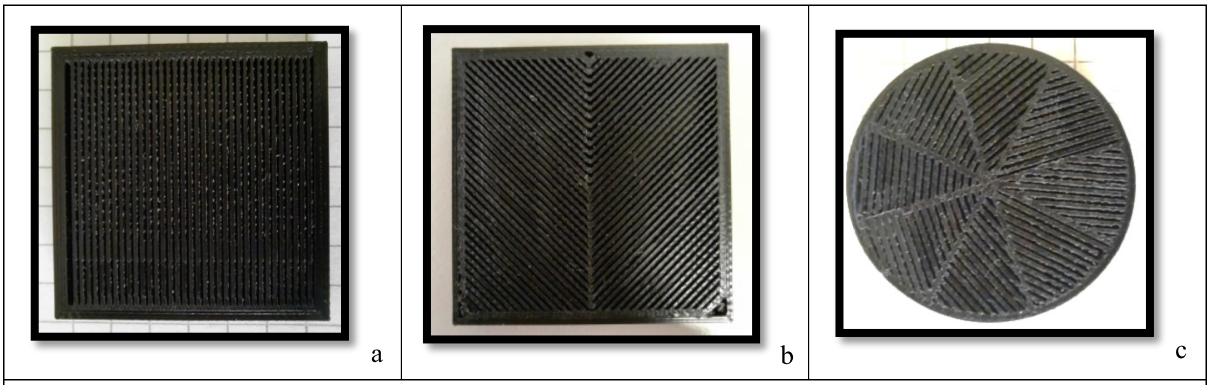

Figure 1. The realized THz Optical devices a) $\lambda/4$ wave plate b) Phase Shifter plate c) q-Plate

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Terahertz imaging super-resolution

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Spatial resolution is the ability to distinguish the details of a physical object that an optical instrument can reproduce in an image. However, because of the wave nature of light, resolution is limited by diffraction, which hampers attempts to overcome the Abbe's limit [1]. This limit, the diffraction limit, defines the minimum distance between two features that can be resolved with a certain contrast by optical instruments and is a physical limit. It is expressed by the formula $dx = 2\,\lambda/(n\,\mathrm{NA}^2)$, where dx represents the smallest resolved feature in the lateral direction, meanwhile n is the refractive index of the medium between the objective lens and the sample, λ is the wavelength of radiation used, NA is the numerical aperture of the optical system.
The acquired image is always a blurred representation of the actual object under investigation. The so-called Point Spread Function (PSF) describes this blurring: the response of a camera system to a point source or an impulse. Indeed, for each single point in the object, the minimal size of its focal spot is never infinitely small, and the lateral and axial extents of the intensity distribution in the focal region represent the three-dimensional diffraction pattern of light emitted and transmitted to the image plane through a high Numerical Aperture (NA) objective. Moreover, since the image formation process is linear, the acquired image is a focused image, the sample, convolved with the PSF, i.e.: image = sample ⊗ PSF.
Methods such as super resolution can be utilized to alleviate the impact of a wide Point Spread Function (PSF), and they are particularly useful in the THz range where diffraction can significantly degrade imaging quality for details smaller than the order of millimeters. The exploration and advancement of super-resolution imaging have been ongoing since the 1980s and 1990s. Numerous optical imaging techniques, including both near-field (Fresnel regime) and far-field (Fraunhofer regime) approaches, have been devised, with the far-field methods based on structured-illumination gaining significant popularity in biological samples, primarily owing to their application of fluorescent dyes [2,3].
This work aims to develop a far-field super-resolution THz imaging system utilizing a freestanding knife-edge [4] within a confocal configuration, in transmission or reflection mode, of a THz-time domain spectroscopy (THz-TDS) system [5]. The intended application is for the examination of small-scale graphic details in planar samples, such as documents on paper substrates, typically featuring signs with lateral dimensions below 1 mm [6].
The THz super resolution set-up was implemented on a Menlo Systems (Germany) TERA K15 THz-TDS system [7]. The knife-edge was realized by a blade, which was put close to the object plane by distances shorter than that of THz wavelength. In practical terms, the conversion of evanescent-wave intensity scattered by the blade edge into newly formed propagating waves, enabling the reconstruction of super-resolved images in the far-field, involves subtracting the total far-field power collected at each blade position x from that collected at the previous position $x - dx$ for each pixel in the image. In Fig. 1 it is shown the improvement in spatial resolution of a sharp metallic edge imaged in transmission mode at 0.3 THz due to the knife-edge technique. The maximum slope of each profile was calculated between 0.1 and 0.9 of the maximum intensity finding that without the blade amounted to 0.44/mm, whereas with the blade, the slope reached 1/mm, with an enhancement of 2.3 times.
Super-risolution was also achieved in reflection mode in the THz imaging of graphic signs realized by several compounds on paper and on a real medieval manuscript.

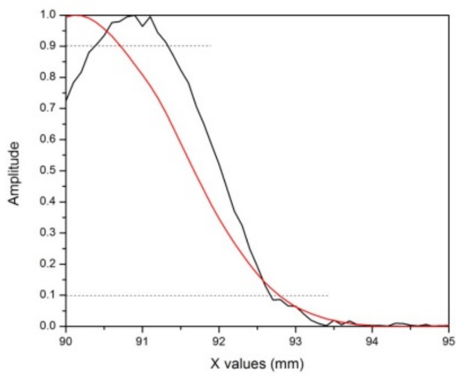

Figure 1. Intensity profiles along X of a sharp metallic edge imaged by using the THz-TDS transmission setup at 0.3 THz with (black curve) and without (red curve) the blade.

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Exploiting THz imaging to map plastic foam density

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Plastic foams are widely used materials made by mixing polymers with a gas [1]. Their mechanical and physical properties are governed mainly by the density, so it is important to assess this feature to check the accuracy of the production process. However, while simple in principle, density measurements are not straightforward in practice, especially when objects have a non-uniform density. Therefore, there is a huge interest towards the development of effective, possibly low-cost methodologies to accurately measure the foam density and its spatial distribution.
Starting from the observation that the molecular mixture constituting the foam appears electrically homogeneous at THz wavelengths, this communication proposes an approach based on the use of time of flight (ToF) [2] to reconstruct the foam density spatial map. The approach is applicable to samples whose thickness and electromagnetic parameters are such that the impinging THz wave reaches a metal substrate behind the sample and neglects the possibly dispersive behavior of the material under test. It provides 2D maps that describe the spatial variability of the thickness and the effective refractive index of the sample under test, which embeds the changes of the material refractive index along the wave propagation path. The same idea was previously exploited for the characterization of magnetic scaffolds [3].
To enable the evaluation of the density, a set of uniform propylene foam samples having well-known density were first realized and characterized by means of the proposed approach to build a refractive index-density calibration curve. For a generic object under test, this curve is used to turn the estimated effective refractive index into a map of the density.
The characterization of the sample depicted in Figure 1a is shown as an example of the proposed approach. According to the production process procedure, this sample is expected to be uniform, with density $\rho = 214$ kg/m^3; determined by weighting the sample. Figure 1b shows the estimated thickness map, which is confirmed to be of about 8 mm, without relevant geometrical changes. Figure 1c reports the average sample refractive index map, which is then turned into the spatial density map in Figure 1d by using the calibration curve. As can be seen, the THz inspection reveals that, contrary to expectations, the actual density of the plastic foam sample is not uniform, due to some flaws occurring during the sample-production process. More examples and details will be given at the conference.

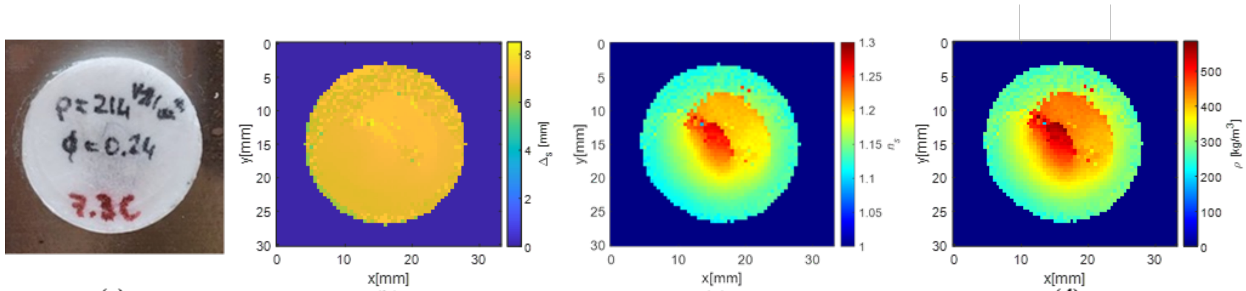

Figure 1. THz imaging of a PP foam: a) image of the sample; b) estimated thickness; c) estimated average refractive index; d) reconstructed foam density map.

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Terahertz imaging for the detection of cimiciato-infected hazelnuts.

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In recent years, hazelnut cultivation is becoming increasingly important in terms of areas invested and crops expected. Among the various quality defects, one of the most detrimental alterations to hazelnut quality is "cimiciato" defect, which is caused by a group of insects belonging to the families of *Coreidae* and *Pentatomidae*. Nowadays no reliable automatic method to discriminate between healthy and cimiciato hazelnuts exists and the food industry still relies on manual visual inspection of shelled nuts. The aim of this work was to validate a continuous-wave terahertz transmission imaging system to discriminate cimiciato-infected hazelnuts by a non-invasive method that can, potentially, be implemented in a real-time approach. Carrying low-energy photons, THz radiation is unable to induce ionization processes, which means that it is a perfectly safe radiation for biological tissues. The trial was conducted on a sample of 150 hazelnuts. We set up a classification model and to assess its performance we used a validation sample of 50 hazelnuts. We plotted the distributions of the healthy and injured samples and fitted the two curves with a polynomial function. The data from each unknown nut was added as a new data point to each of the two distributions, and the minimum distance between this new point and the fitting function was calculated. The new data point was, then, assigned to the distribution with the lower distance and the correct/incorrect attribution was evaluated by visual inspection of the nuts. The procedure was able to correctly identify 100% of cimiciato hazelnuts in the mixed population with still a 25% false negative rate. The developed method is simple, requires a low-cost apparatus and can potentially be implemented in real time, therefore, it can be of great interest for the food industry.

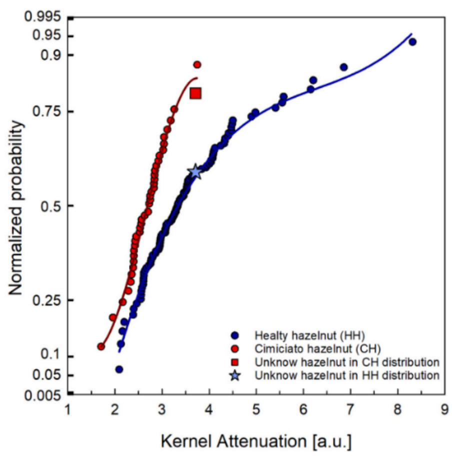

Figure 1: Probability plot of the two different distributions of healthy hazelnuts (HH) and cimiciato hazelnuts (CH) with the fit superimposed and an example of placing an unknown hazelnut in the HH (star) and CH (square) distributions.

Session IV

Micro-thermo-mechanical THz detectors

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Thermomechanical bolometers based on high-quality mechanical resonators are a promising technology for broadband light detection. Further functionalities can be added by controlling the absorption spectrum of the devices. To this end, we embedded (almost-) 2D layers, minimally impacting the mechanical quality while, at the same time, offering strong absorbance. Further layer patterning could grant resonant absorption, for hyperspectral imaging or polarization sensitive detection. Transduction is usually performed through optical probing of the mechanical resonance, but direct electrical output can also be obtained through magnetic flux modulation, provided the mechanical object contains an inductive element. The concept is particularly useful in array read-out, where many elements with different mechanical frequencies can be easily addressed in parallel.

Metamaterial quasi-optical components for astronomical instrumentation at millimetre and sub-millimetre wavelengths

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We report on the development of novel optical components based on metamaterials, carried out in the last years, for mm and sub-mm astronomical instrumentation. Using the mesh-filter technology, we have realized transmissive and reflective half-wave plates, flat lenses, anti-reflection coatings, absorbers, etc. The metal-mesh technology, based on copper grids embedded within polypropylene layers, gives the possibility to accurately and arbitrarily manipulate the radiation across surfaces and allows in principle to replace any classical optical component with a mesh-equivalent one. The devices mentioned above can find applications in other fields such as telecommunications and security. The technology itself can be pushed further to realise novel/exotic metamaterials with properties of interest for theoretical studies. In addition, the realisation of these metamaterials can be extended into the Silicon technology, with all the advantages associated with it.

THz wave for Cultural Heritage @ IREA-CNR

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Nowadays, Teraherz (THz) waves are receiving huge attention in the frame of cultural heritage [1], [2]. THz imaging and spectroscopy are, indeed, useful tools for gathering high-resolution (of the order of mm) information about construction modality, preparing drawings and author's re-paintings, conservation state of artworks as well as to identify previous restoration actions, mainly of paintings and frescos.
THz time-domain systems are part of the imaging/mapping technological tools of the Italian node of the European research infrastructure for heritage science (E-RIHS.it) [3].
Since 2014, research activities regarding the design of strategies for improving the imaging capabilities of THz waves and their application in artworks surveys are carried out at the Institute for Electromagnetic Sensing of the Environment, National Research Council of Italy (IREA-CNR) [4].
This communication aims at providing a critical overview of the THz potentialities and describing the main challenges for a reliable and accurate data interpretation; finally, some results mainly regarding majolica and ancient decorated mortar specimens will be presented, even with the aim to point out the developed strategies to solve issues in data acquisition and processing [5], [6].

Acknowledgement

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Terahertz Technologies as New Frontiers for Pathogenic Microorganism Sensing: Drawbacks, Potentialities and Applications

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The rapid and accurate identification of pathogenic microorganisms is a topic of great relevance due to its notable importance in all areas related to human life, health and public safety, as also highlighted by recent events linked to the SARS-CoV-2 pandemic.
In the field of public health, the need for deployable tools for adequate, rapid and effective recognition on a large scale is of particular importance for the prevention and treatment of serious infectious diseases, and at the same time to prepare effective medical treatments and clinical therapies. Furthermore, in the field of food quality, food and water are potential sources of bacterial proliferation due to incorrect packaging and storage procedures, so accurate controls are necessary to guarantee product safety.
Currently, gold standards include conventional techniques based primarily on cell culture methods and molecular and/or biochemical recognitions, particularly for microbial pathogens, and molecular and immunological techniques for viral pathogens. They present some drawbacks regarding sensitivity, safety, laboriousness, long-term collection and analysis of data [1-4]. Therefore, since these methods are still limited, it is necessary to find new, precise and highly sensitive alternative solutions. Numerous biosensor platforms have been suggested to address these shortcomings, using electrical, mechanical, optical, and plasmonic approaches. They are all promising applications suitable for laboratory and clinical/medical investigations, with high potential for compact, portable, real-time and label-free detection. Among these different kinds of approaches, biosensor platforms based on optical sensing have gained considerable attention, such as THz spectroscopy, also in combination with THz nano- and metamaterials.
Despite the extensive and well-established attention paid to the microwave, infrared and visible regions, the small THz gap between microwave and infrared (0.1-10 THz, 3-330 cm^{-1}, 30 - 3000 μm) has long been ignored due to its technological difficulties in generation and detection. In recent years, the THz region has undergone a technological renaissance driven by improvements in sources, detector responses and the availability of new materials with a strong THz response [2,4-19]; promoting and accelerating the diffusion of THz technologies in several fields of scientific application, including pathogenic microorganism sensing [1,2,4,18,20].

In the context of biomedical and biochemical applications, THz radiation (4 meV @ 1 THz) is largely interesting because its low photonic energy (incapable of heating materials or inducing the ionization of atoms/molecules), provides non-destructive and non-ionizing detection, in contrast to other optical techniques, including ultraviolet or X-rays, where high-energy photons (>>eV) cause direct biological damage on the sample [18,21]. Furthermore, rotational and vibrational molecular modes and intermolecular vibrations, such as hydrogen bonds, typically dominate the THz frequency region [1,18]. Therefore, THz techniques directly identify the spectral properties of the material and offer chemical specificity to imaging experiments [18,19], which can be performed efficiently in label-free and non-contact modes. On the other hand, high sensitivity to water and low spatial resolution (around 100 μm) are the main disadvantages of THz radiation. The extreme sensitivity of THz radiation to polar molecules, specifically water, restricts the THz waves penetrability from tens to hundred microns in hydrated samples, preventing wide technological spread in biological fields [1,2,4,18,20]. Referring to THz spectroscopy, many layouts and materials are used for THz signal collection, showing high performance in terms of the signal-to-noise ratio (SNR) and coherent detection mode.

Interestingly, we used our transmission-mode THz time-domain spectroscopy (THz-TDS) system, detailed in Figure 1, to evaluate the response of bio-signatures of the desert cyanobacterium Chroococcidiopsis (CCMEE 057), subjected to strong ionizing ion irradiation during the STARLIFE irradiation campaign. In this application, we studied the dielectric properties of dried films of cyanobacteria, previously exposed to increasing doses of X-rays. By measuring both the amplitudes and phases of THz electric fields transmitted through the microbial samples, we extracted dielectric properties, including absorbance and refractive index of microbial films, using effective medium theory, specifically the Bruggeman model.

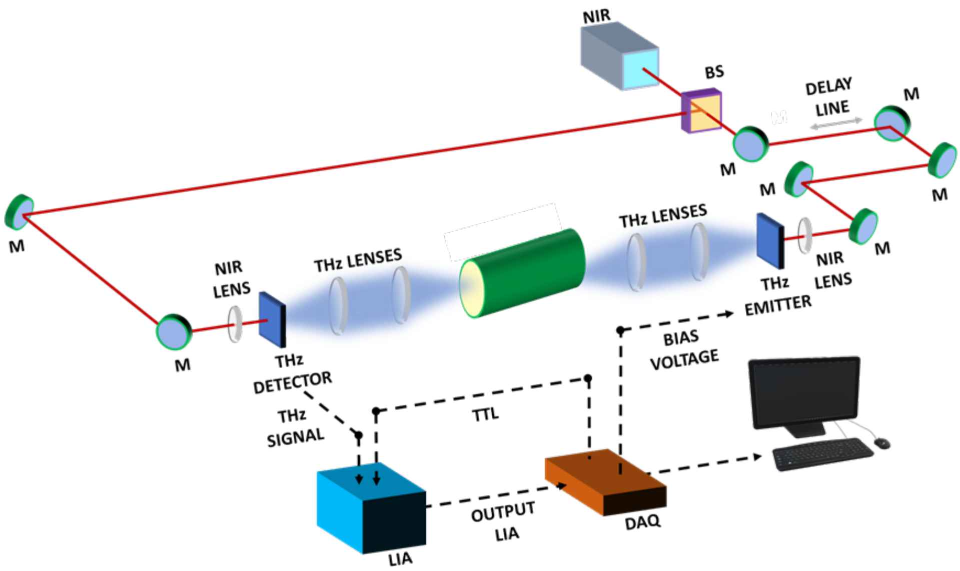

Figure 1. Schematic layout of THz-TDS setup in transmission mode based on switched photoconductive antennas (PCAs), available at Dept. of Physics, Sapienza University. A femtosecond near-IR (NIR) laser beam is divided in two parts by a beam splitter. Some mirrors (M) convey the laser beams to the THz emitter and receiver, where they are focused by a NIR lens. Here the THz beam is produced and detected, respectively. A stack of transparent THz lenses collimates and focuses THz radiation along the path and a sample holder is inserted into the THz propagation region. The acquisition chain consists of a Lock-in amplifier (LIA), a data acquisition card (DAQ) and a personal computer for data collection and analysis. The optical delay line is used to sample the THz pulse in the time domain.[10]

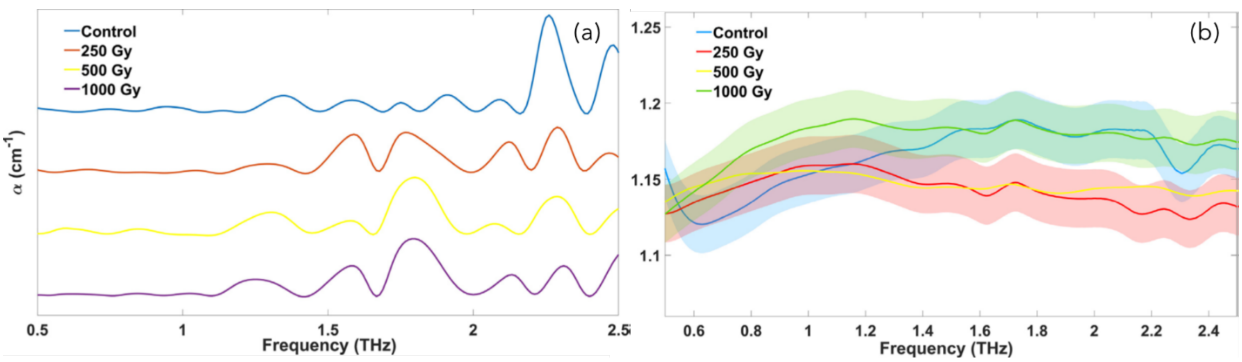

Figure 2. (a) THz absorption spectra and (b) refractive indices of dried CCMEE 057 films on Si substrate obtained from the Bruggeman model exposed to increasing X - rays doses, during the STARLIFE campaign. The spectral range is 0.5–2.5 THz.[20]

More extensive researches should be performed, previous results [2,4, 22], suggest that a direct microorganism THz detection is very difficult due to the virus low THz absorption coefficient and, in various cases, the absence of specific THz spectral features. Thus, THz spectroscopy can be used to study the optical properties, such as the refractive index and absorption coefficient, of different types of pathogens, the THz wavelength is much larger than the particle size of microorganisms. This results in very low spatial resolution and reduced sensitivity. However, incredible advances in the field of optics make it possible to maximize the interaction between radiation and biomaterial using plasmonic biosensors and metamaterials.

Meta- and nanomaterials, operating in the THz region, represent an attractive alternative and provide great potential for high-speed, on-site and label-free point-of-care virus detection [2,4]. Some previously examined plasmonic platforms, such as planar metal-dielectric biosensors, require simple and intelligent fabrication techniques to achieve low LODs. We explored pioneering studies on THz virus detection and reported technological efforts in THz metamaterial optical biosensors, highlighting the flexibility of a variety of geometric structures, their sensitivity, and LODs for various microorganism [2,4]. However, the strong potential of THz-

based pathogens detection is still in the early stages of development and far from clinical use. However, recent technological improvements in the manufacturing and miniaturization of THz layouts promise to improve the performance of meta- and nano-sensors, achieving higher sensitivities than traditional/conventional devices, and even enabling remote localization and control.
Finally, recent applications of machine learning have achieved great acclaim in several scientific fields, including sensor design, where the behavior of integrated metamaterial systems has been explored.
Deep learning methods have also been successfully used to predict potential correlations between plasmonic geometric structures, their optical parameters, and the resulting resonance spectra. Research based on new photonic materials, such as topological insulators and quantum photonics devices, offers promising ideas for THz biosensing.
In this continuously evolving framework, we are exploring the emerging and challenging technology of THz radiation and its solutions and applications for high-sensitivity detection.

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THz dynamics of aqueous binary mixtures at a mesoscopic level

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We report a study at a mesoscopic level on the THz dynamics of three aliphatic alcohols (2-propanol, methanol, and ethanol), one diol (ethylene glycol), and the corresponding water solutions at room temperature, using a time domain ellipsometer. The dielectric response of the pure liquids is nicely fitted using a generalized Debye-Lorentz model, which considers hydrogen-bond rupture and reformation dynamics, the motion of the alkyl chains and of the H-bonded OH groups, and the presence of molecular vibrations [1]. For the binary mixtures, we focus on the properties of the water-rich region, finding an anomalous behavior in the absorption properties at very low solute molar concentrations (X_M). These results, first observed in the THz region, are in line with previous findings (mostly from thermodynamic measurements) and can be explained by considering the amphiphilic nature of the alcohol molecules. Figure 1 (i) presents the frequency dependent dielectric properties of (a) 2-propanol, (b) methanol, (c) ethanol, and (d) ethane-1,2-diol in the THz region achieved by a customized THz time-domain spectroscopic ellipsometer [2] and the corresponding fitting curves based on an effective Debye model [3], showing an excellent agreement. However, this model fails to reproduce the experimental results when an alcohol-water binary mixture is considered, especially for small (0-5 %) alcohol molar fraction X_M. To better highlight the molecular dynamics of the solute at very low X_M, we display in Fig.1 (ii) the deviation of the experimental results from the expected Debye behavior ($\Delta k = k_{exp} - k_{Debye}$).

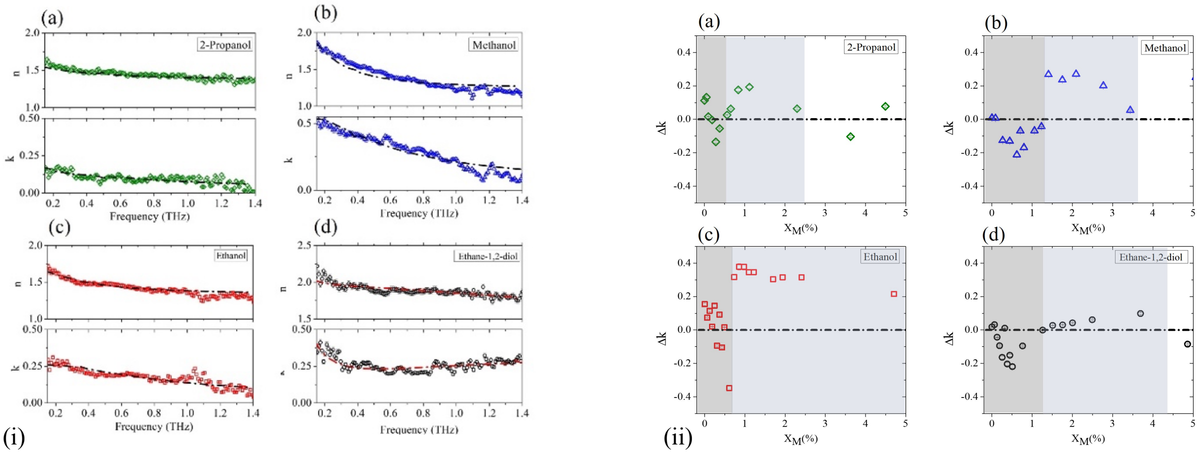

Figure 1. (i) The experimental complex refractive index n + ik vs frequency (solid points) for (a) 2-propanol, (b) methanol, (c) ethanol, and (d) ethane-1,2-diol, and the corresponding fit (dot-dashed line) to the generalized Debye model. (ii) Deviation Δk (frequency averaged) between the experimental data and the prediction of the Debye model for aqueous binary mixtures based on (a) 2-propanol, (b) methanol, (c) ethanol, and (d) ethane-1,2-diol, measured at low solute molar fraction.

Results show that the mixtures behave completely out of the Debye prediction, which can be explained by the complex dynamics occurring in aqueous binary mixtures due to the competing, hydrophobic and hydrophilic, behavior of the alcohol. In the water-rich region (very scarce solute molecules), we measure a sudden drop in absorption properties of water, the dominant mechanism appearing to be the destruction of existing H-bonds between water molecules, since the hydrophobic behavior of the alcohol plays the main role. As the solute molar concentrations becomes higher, we first observe an increase in the absorption properties of the mixture, due to the formation of water clusters around alcohol molecules, followed by a Debye-like decay by increasing the alcohol concentration.

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Session V

THz-photonics by all-dielectric phonon-polariton nonlinear nanoantennas

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The THz spectrum offers the potential of a plethora of applications, ranging from the imaging through non transparent media to wireless-over-fiber communications and THz-photonics. The latter framework would greatly benefit from the development of optical-to-THz wavelength converters. Exploiting Difference Frequency Generation in a nonlinear all dielectric nanoantenna, we propose a compact solution to this problem. The approach is completely transparent with respect to the modulation format and can be easily integrated in a metasurface platform for simultaneous frequency and spatial moulding of THz beams.

Keywords: *photonic metasurfaces, THz photonics*

The terahertz (THz) region of the electromagnetic spectrum has gained increasing attention in the last decades and today it is one of the fundamental emerging branches of research for the broad photonics community.

Astrophysics, communications, imaging, spectroscopy, biotechnology and security are among the huge plethora of applications where THz technology can provide ground-breaking devices and systems, also thanks to the particular features of a wide range of media in the THz spectral range [1, 2, 3]. Noteworthy, metasurfaces are today identified as the framework where all the above approaches can be conveniently unified to provide a compact and integrable solution to a variety of different beam forming needs. For example, in Fig. 1 the THz surface wave is beam formed into the far-field (FF) THz radiation by a modulated THz metasurface, providing gain and directionality. Recently, in order to get the highest performance per unit volume via resonant, nanoscale, compact platforms, THz generation by optical rectification in plasmonic Split-Ring Resonators (SRRs) has been reported [4]; the THz signal is produced from nanoscale SRRs by exciting magnetic-dipole modes in the infrared regime. A thorough study of THz pulse generation using a 40 nm thin metasurface based on plasmonic SRRs excited with a laser oscillator emitting nanojoule femtosecond pulses has been reported, measuring a conversion efficiency as high as that of a 0.1 mm thick ZnTe crystal. Despite these pioneering results, a breakthrough in the field demands for a substantial improvement of the conversion efficiency at the nanoscale. One promising alternative to plasmonic THz emitters is represented by all-dielectric THz antennas. As schematically depicted in Fig. 1, exploiting DFG driven by second-order nonlinearities in a nonlinear all dielectric nanoantenna, we have proposed this wavelength converter in [5, 6]. As a prototype example, for an AlGaAs nanoantenna, we calculate a strong conversion efficiency around 11 THz for an optimized structure. Moreover, we also stress that the same approach can be applied also using different materials with second-order nonlinearity, such as $LiNbO_3$, to access different spectral regions [7].

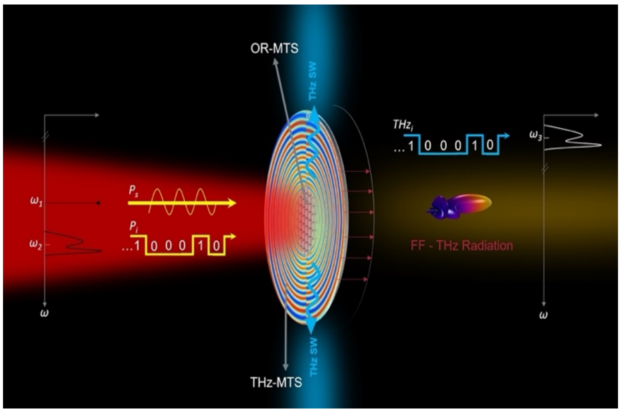

Figure 1: The wavelength converter: the information message, with power Pi, mixes with the incident signal, power Ps, both in the IR region. DFG in the all-dielectric nanoantennas emitting the THz information signal, THz, to produce a THz surface wave (SW) which propagates in the surrounding THz metasurface where it is converted into the desired THz radiation in the far-field (FF).

Let us imagine a scenario in which a dielectric metasurface generates a THz signal through DFG process when excited with pumps in the infrared regime, see Fig. 1. To demonstrate this statement, we aim to exploit nonlinear

DFG process in an all-dielectric nanoantenna of AlGaAs crystalline structure. Indeed, starting from two intense laser beams in the infra-red, the DFG nonlinear generated field can have a frequency of few THz, thus laying within the THz gap window. Although there exist other compounds that possess zincblende structure, the choice of AlGaAs is rather advantageous for our purpose, due to its low loss and dispersion in the optical region, high refractive index, large nonlinear susceptibility of the second-order as well as a well-established fabrication techniques.

Let us consider an AlGaAs nanocylinder free-standing in air, with radius r equal to 200 nm and height h of 400 nm. The geometrical parameters of the nanodisk are selected in order to fulfill a magnetic dipolar resonance around the fundamental wavelength. We consider two incident pump beams that excite the proposed nanodisk in the infra-red range. Thus, two spectrally close components of the input optical pulses are mixed via the DFG process, so that the terahertz component is generated. The role of localized surface phonon-polaritons (SPhP) can be investigated by resorting to a reduced quasi-static model of the THz generation process.

A fair qualitative agreement with the extinction efficiency evaluated from FEM numerical analysis (blue trace in Fig. 2) is retrieved. Note that if one considers non-resonant extinction from the Rayleigh background, the estimated DFG efficiency would drop by almost two orders of magnitude on the efficiency peaks (red curve in Fig. 2). This ascertains the key role of SPhP in the THz generation from all-dielectric nonlinear nanoantennas. Lastly, to further highlight the potential of the proposed structure for THz applications, we perform a comparison with state-of-the-art configurations, based on a plasmonic structure. We consider an isolated gold split-ring resonator with similar geometrical parameters as the one reported in [4]. Such THz generation efficiency simulations retrieve 7 orders of magnitude lower than what is attained with the proposed single AlGaAs nanopillars. Hence, using high-refractive index dielectric materials not only strongly enhances the DFG process thanks to the bulk nonlinear coefficient and THz SPhP oscillations, but also provides, from a simple cylindrical geometry of the antenna, a configuration of the nonlinear radiation pattern that is suitable for launching surface waves in THz metasurfaces.

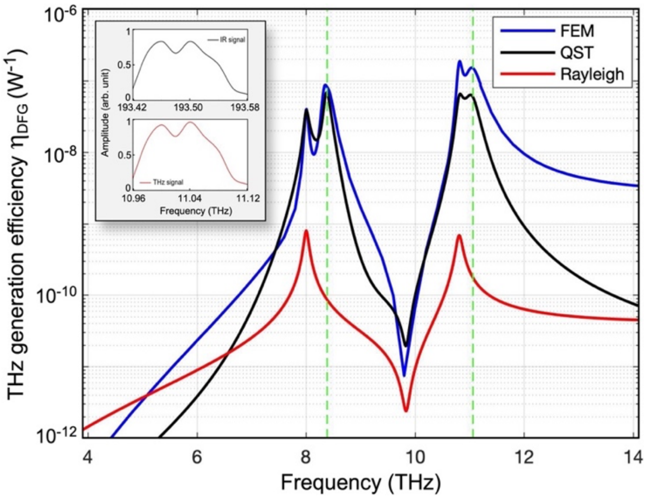

Figure 2: Conversion efficiency for THz generation by DFG in the proposed AlGaAs nanoantenna, evaluated from FEM numerical analysis (blue), and reduced model with (black) or without (red) contribution from phonon permittivity. The inset shows the negligible spectral distorsion introduced by the proposed

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The beam alignment problem in THz wireless networks

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Terahertz (THz)-band communications are a key enabler for ultrahigh bandwidth and ultralow latency communication paradigms. When integrated with other THz-band applications, such as localization, sensing, and imaging, THz technologies may lead to the deployment of intelligent wireless communication systems. However, communications at THz are quite challenging due to the severe attenuation of signal power caused by high diffraction and penetration losses, as well as atmospheric absorption. To compensate for the severe path loss, high-directional beamforming with large antenna gains both at the transmitter and at the receiver is mandatory. Designing such a highly directional beamforming requires an initial beam alignment procedure prior to data transmission, in order to maintain a desired signal-to-noise ratio (SNR) level. However, fast and accurate acquisition of beam directions is quite challenging for THz-band communications due to the very low SNR available before properly aligning the beams with the dominant signal propagation paths. In this paper, we develop a receiver-assisted beam-alignment algorithm by which the receiver and the transmitter collaborate to identify the angle-of-arrivals and angle-of-departures associated with the strongest paths of the THz channel.

The THz Spectral Range: a Window of Opportunities

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We are witnessing impressive progress in THz technologies, mostly driven by the promise of brand new application areas and different ways to interact with matter or to transmit information. Such progress is also related to the under-exploitation of a significant part of the electromagnetic spectrum represented by the far-infrared/THz region that borders with microwaves around 300 GHz and with mid-infrared, around 10 THz or even higher frequencies [1,2]. On the other hand, the potential role of novel photonics tools in the THz range is still to be unveiled but many important applications have already shown its importance. Indeed, material transparency/opacity to THz frequencies is different form nearby mid-IR and can provide better resolved information than lower frequency microwaves/RF [3]. Moreover, for transmission of information THz frequencies are the logical continuation of moving to higher and higher frequencies to get carriers able to carry more and more data [4]. In terms of interaction with matter, THz photons are the key to excite the rotational degrees of freedom of a large part of molecules, enabling metrological measurements to unveil new physics or also to control molecules in view of the most demanding applications on the horizon, like ultracold molecules for quantum simulation, sensing or computing [5,6]. In these really exciting and thrilling times for THz science and technology, it is crucial to invent proper instruments and techniques for unveiling the basical physical mechanisms of new devices, to get reliable measurements of relevant parameters and to sharpen the tools for specific and demanding applications. This has been the mainstream of our group in Firenze in the last 35 years and we will review the latest achievements related to state-of-the-art techniques and applications. In particular, efforts have been directed to setting up an heterodyne technique to characterize the newly generated comb patterns, also in QCLs [7,8] and to demonstrate full phaselocking of THz QCL combs [9,10]. More recently, we are further sharpening our photonic techniques to better understand the role of novel architectures and materials in modifying QCL emission [11]. In view of extending the generation domain of THz sources beyond the 5 THz transparency limit of semiconductors routinely used for QCLs fabrication, we demonstrated all telecom-wavelength pumped cw THz generation with simultaneous high resolution and broadband coverage up to about 7.5 THz [12,13]. Finally, we will show novel applications that are emerging from such impressive THz progress, e.g. a novel communication system at THz frequencies [14].

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Session VI

Terahertz saturable absorption from relativistic high-temperature thermodynamics in black phosphorus

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Black phosphorus is a unique two-dimensional (2D) material (Figure 1) with a tunable infrared band gap and anisotropic conduction properties [1]. Black phosphorus also displays the occurrence of a pressure-induced topological Lifshitz transition turning the material from a narrow gap semiconductor to a massless Dirac metal due to a nonavoided band crossing [2]. We investigate the ambient pressure nonlinear terahertz (THz) electrodynamics of black phosphorus along the more conducting armchair direction and found that its THz saturable-absorption properties can be understood within a thermodynamic model by assuming a fast thermalization of the electron bath [3]. While black phosphorus does not display the presence of massless fermions at ambient pressure and temperature the material's anomalous THz nonlinear properties can be accounted for by a relativistic massive Dirac dispersion, provided that the Fermi temperature is low enough. This suggests that an optimal tuning of the Fermi level could be a strategy to engineer a strong THz nonlinear response in other massive Dirac materials, such as transition-metal dichalcogenides or high-temperature superconductors.

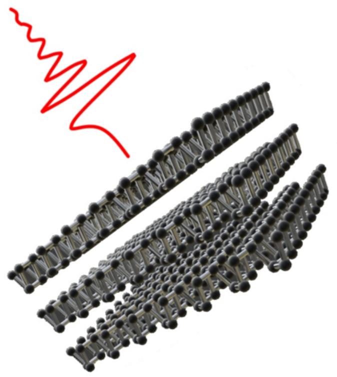

Figure 1. Sketch of black phosphorus' crystal structure

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Underway Projects for Innovative THz/IR Sources based on Particle Accelerators: SISSI 2.0 and SABINA

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Terahertz/Infrared (THz/IR) radiation and technologies have found incredible development in the last few decades due to their applications in many different fields, ranging from indoor and outdoor communication, security, environmental monitoring, biological research, medical applications and finally as a spectroscopic investigation tool in condensed matter [1]. However, many of these applications requires increasingly high-power sources and demands for the possibility to manipulate radiation features such as pulse time duration, frequency spectrum and polarization. One of the most efficient ways of generating THz/IR radiation fulfilling these requirements is to use relativistic electrons accelerated in storage rings, where synchrotron radiation can be generated by means of bending magnets or specific Insertion Devices (IDs), or by accelerating electrons in LINACs, where the development of FEL technologies allows for coherent and monochromatic radiation to be produced.
Few projects are currently underway for the realization or the upgrade of innovative THz/IR sources based on particle acceleration, some of them involving two of the most important research facilities in Italy, i.e. the third-generation synchrotron Elettra in Trieste and the SPARC_LAB linear accelerator in Frascati.
Elettra 2.0 is a major upgrade of the Elettra facility towards what is called the ‘ultimate’ light source, which will allow both horizontal and vertical emittance to be greatly reduced in order to guarantee a substantial increase in brilliance and coherence for the emitted radiation. The main work on the structure consists in the upgrade of the magnetic optics without changing the basic features of the accelerator [2] and it will involve all the beamlines, including SISSI (Synchrotron Infrared Source for Spectroscopy and Imaging), which is the line dedicated to the collection of THz/IR radiation emitted by magnetic dipoles. The SISSI 2.0 Project is included in this major upgrade and aims to characterize the radiation produced by this beamline focusing on the interference effects and on the emergence of new edge radiation contributions caused by the complex magnetic structure of the new multi-bend achromats. In addition, the project involves the reorganization of the extraction beamline for the transport of radiation to an external user facility.
The same spirit of innovation is embodied by the SABINA project, which aims to make some major upgrades in the SPARC_LAB structure with the practical goal of realizing a FEL beamline operating as a user facility and producing quasi-monochromatic radiation over a wide spectral range from 3 THz up to 30 THz, with time duration pulses on the order of ps and energies in the mJ range. The core of the beamline consists of a series of three undulators based on the APPLE-X design that allows the emission of high intensity synchrotron radiation and the manipulation of high electric fields (~10 MV/cm) by controlling their polarizations (linear, circular and elliptical). The beamline also includes the transport of the produced radiation to an ‘open to user’ laboratory which will be equipped with the appropriate optical set-up necessary to perform a wide variety of scientific experiments concerning nonlinear and time-resolved optical spectroscopy.

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The LNF IR-THz beamline @ DAϕNE: experimental set-ups and perspectives

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The INFN-LNF DAϕNE storage ring produces a powerful source of Synchrotron Radiation in the THz range [1]. The brilliance of SR in the THz domain is up to three orders of magnitude with respect to conventional sources (i.e. mercury lamps), as shown in Figure 1, and the flux increases with the electron current stored. These aspects permit to perform experiments in several field from material science to biology and chemistry and offer the possibility to analyze samples in solid, liquid and gas phases [2-8]. Experimental set-ups available at SINBAD beamline and applications are presented. Moreover, perspectives of the Terahertz (THz) technology applied on cultural heritage field will be described [9,10].

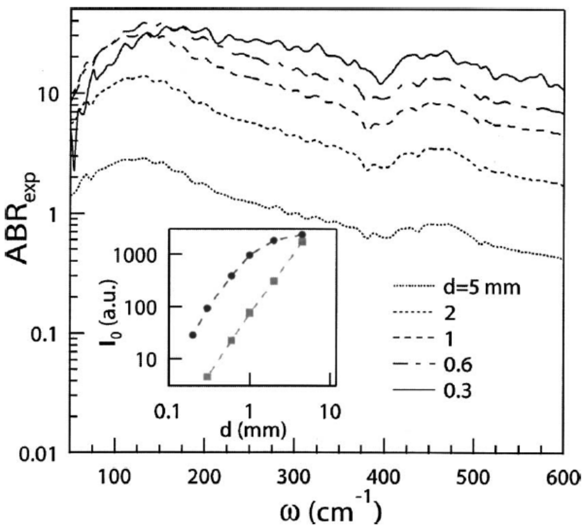

Figure 1. Actual Brilliance Ratio (ABR) between the intensity of SR-SINBAD and a mercury lamp [1].

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Material Characterizations in the Sub-THz Region for Particle Accelerators

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Coatings play a crucial role for the functionality of vacuum chambers in particle accelerators, serving dual purposes by efficiently facilitating pumping and mitigating electron cloud effects. However, their impact on the surface resistance of chamber walls raises concerns, potentially influencing machine performances and imposing limitations on achievable energies and currents. Therefore, an electromagnetic characterization is essential for a comprehensive study of accelerator structures, particularly in the context of the next generation of particle accelerators where the demand for extremely short bunches accentuates the importance of assessing material responses in the sub-THz region.
In this presentation, we focus on the electromagnetic characterization of three different types of Non-Evaporable Getters (NEG) coatings. Specifically, we examine the CERN standard, a densified film using HiPIMS, and porous, high-pressure coated. NEG coatings are particularly utilized to achieve conditions of ultra-high vacuum. Additionally, we explore the characterization of Amorphous Carbon (a-C), necessitating a modification of the setup. a-C is primarily employed for mitigating the electron cloud effect. We will showcase the electromagnetic characterization of these coating materials using a time-domain method based on THz waveguide spectroscopy. This advanced methodology allows for a comprehensive exploration of the electromagnetic properties of coatings, providing valuable insights into their behavior within the sub-THz frequency range. The findings contribute to a deeper understanding of the intricate interactions between coatings and accelerator structures, with the aim of optimizing performance and efficiency in the evolving landscape of particle acceleration technologies.