

TER DAYS

MILANO 2026

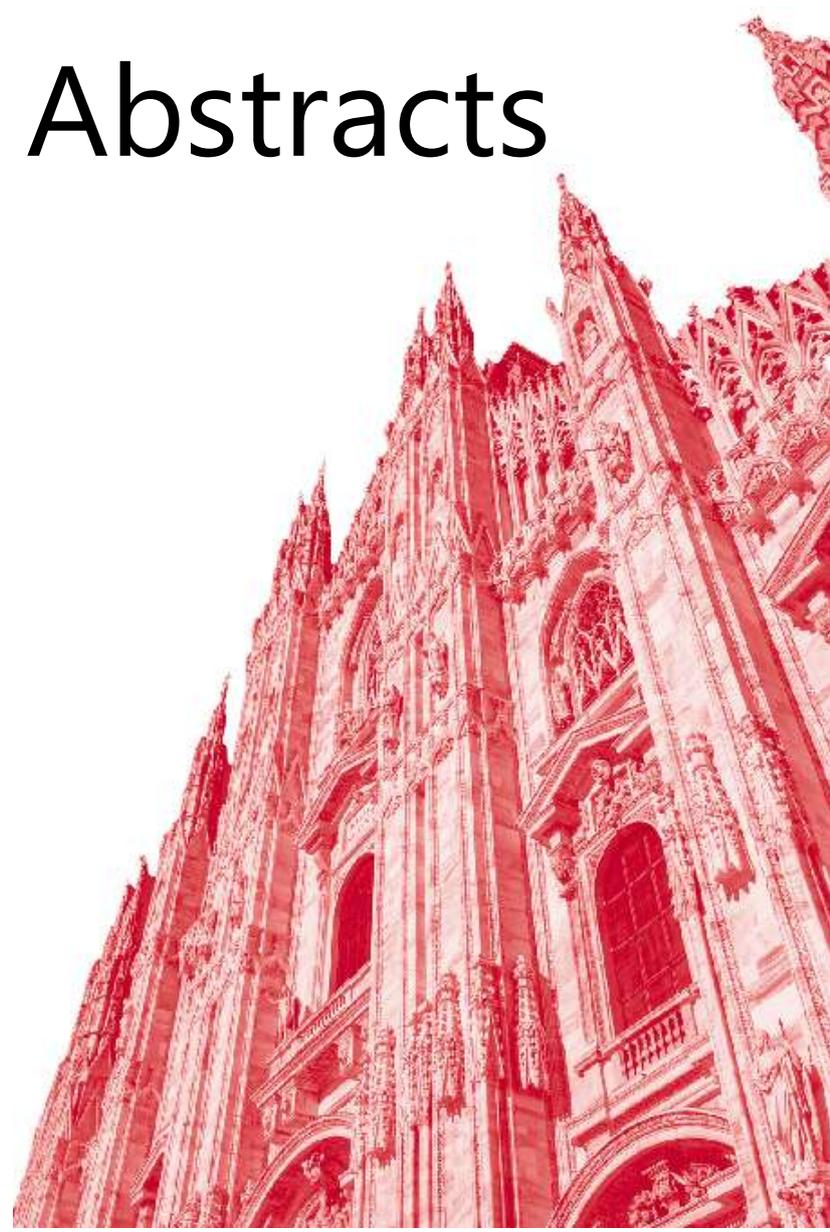
29-30 JANUARY 2026

POLITECNICO DI MILANO

Book of Abstracts



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TERADAYS

MILANO 2026

Welcome to the 4th edition of the **Teradays!**

The electromagnetic spectral region between 0.1 and 10 THz is rapidly becoming a frontier for both fundamental research and transformative applications.

Teradays 2026 aims to bring together scientists and industry to discuss the latest advances in this rich spectral band. The conference will focus on the role of millimeter and sub-millimeter waves in telecommunications, on THz technology (sources, detectors, and components), THz spectroscopy and materials science, and THz imaging, with an emphasis on bridging academic research and industrial development. The program includes invited and contributed oral presentations, networking opportunities, and a social dinner.

This 4th edition is held on January 29–30, 2026, in Milan, at the **Politecnico di Milano**, in collaboration with the Institute of Photonics and Nanotechnologies of the National Research Council (**CNR-IFN**) and the National Institute for Nuclear Physics (**INFN**).

The organizing committee thanks the sponsors who supported the event.



Quantum Design
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Scientific and Organizing committees

Scientific Committee

- Prof. Antonello Andreone – Department of Physics, University of Naples "Federico II"
- Dr. Gianluca Galzerano – Institute for Photonics and Nanotechnologies, National Research Council (IFN – CNR)
- Prof. Stefano Lupi – Department of Physics, Sapienza University

Organizing Committee

- Dr. Gianluca Galzerano – Institute for Photonics and Nanotechnologies, National Research Council (IFN – CNR)
- Dr. Dario Giannotti – Department of Physics, Politecnico di Milano
- Dr. Francesco Canella – Institute for Photonics and Nanotechnologies, National Research Council (IFN – CNR)
- Dr. Eugenio Cinquanta – Institute for Photonics and Nanotechnologies, National Research Council (IFN – CNR)
- Dr. Eva Pogna – Institute for Photonics and Nanotechnologies, National Research Council (IFN – CNR)
- Ms. Stefania Mosca – Department of Physics, Politecnico di Milano

Scientific program

Thursday 29 January

08:45 – 09:15 **Registrations**

09:15 – 09:30 **Welcome (INF and Department Director)**

I Section: THz Technologies

Chair G. Galzerano

09:30 – 10:00 **Martin Kock (Invited):** *Devices to guide and manipulate THz waves*

10:00 – 10:20 **Andrea Perucchi:** *Advanced Nonlinear THz Spectroscopies at the TeraFERMI Beamline*

10:20 – 10:40 **Lorenzo Mosesso:** *Design and Optimization of the THz/IR Beamline SISSI 2.0 at the Elettra Synchrotron Facility*

10:40 – 11:00 **Ilaria Balossino:** *Advancing SABINA: Installation, Commissioning Plan, and Early THz Diagnostics*

11:00 – 11:20

Coffee Break

II Section: THz Spectroscopy

Chair: E. Cinquanta

11:20 – 11:40 **Zahra Mazaheri:** *Terahertz ATR Spectroscopy to Sense Acetone in Water: Toward Biomarker and Contaminant Monitoring*

11:40 – 12:00 **Walter Fuscaldo:** *Electromagnetic Modeling for Material and Metasurface Characterization through Terahertz Time-Domain*

12:00 – 12:20 **Camilla Merola:** *More than meets the eye: depth-resolved THz chemical mapping of multilayered samples*

12:20 – 12:40 **Riccardo Piccoli:** *Self-Referenced THz Time-Domain Spectroscopy for Reflection Measurements*

12:40 – 13:00 **Gian Paolo Papari:** *Enhanced THz Permeability in Non-Magnetic Drude Conductors*

13:00 – 14:30

Lunch

III Section: THz Generation

Chair: S. Lupi

14:30 – 15:00

Giacomo Scalari (Invited): *On-chip Coherent THz photonics with frequency combs*

15:00 – 15:20

Domenico Paparo: *Production and Modulation of Fully Circular Ultrabroadband THz Radiation Using Two-Color Plasma Generation*

15:20 – 15:40

Luca Carletti: *THz Generation via LSPPh-Enhanced Optical Rectification in LiNbO₃ Metasurfaces*

15:40 – 16:00

Dario Giannotti: *Generation of Few-Cycle THz Pulses in DSTMS Driven by an 8.3-MHz Amplified Mamyshev Oscillator*

16:00 – 16:20

Coffee Break

IV Section: THz Materials

Chair: F. Canella

16:20 – 16:40

Michele Celebrano: *THz Field Induced Second Harmonic Generation in Epsilon Near Zero Indium Tin Oxide Thin Films*

16:40 – 17:00

Paola Di Pietro: *Terahertz driven nanosecond dynamics of oxygen defect state in anatase TiO₂*

17:00 – 17:20

Luciana Di Gaspare: *SiGe on Si material platform for THz applications*

17:20 – 17:40

Can Koral: *Dielectric Relaxation Dynamics in Silver Nanoparticle-Doped Chitosan Films*

17:40 – 18:00

Giulia Folpini: *Doping density and carrier-phonon coupling in tin based perovskites*

18:00 – 18:30

Sponsor Talk by Bruker Italia

19:30

Social Dinner (*La Dogana del Buongusto*)

Friday 30 January

V Section: THz Imaging Chair A. Andreone

- 09:00 – 09:30 **Romain Peretti (Invited)**: *Λ -photonic for Terahertz Light - Matter interactions enhancement: from broadband concentration to near-field imaging*
- 09:30 – 09:50 **Fulvia Gennari**: *Crack Detection in Pompeii wall paintings using Terahertz Imaging*
- 09:50 – 10:10 **Alessandra Toncelli**: *Probing Ozone Exposure Effects on Different plant species with THz Imaging*
- 10:10 – 10:30 **Valentina Di Sarno**: *Terahertz Spectroscopic Imaging and Unsupervised Analysis for Multidomain Non-Destructive Diagnostics*
- 10:30 – 10:50 **Mauro Missori**: *Recent Advances in Terahertz Spectroscopy and Imaging for Materials and Cultural Heritage Studies*

10:50 – 11:20

Coffee break

VI Section: THz for ICT Chair D. Giannotti

- 11:20 – 11:40 **Alessia Sorgi**: *Demonstration of a Transportable QCL-Based Free-Space link for Reliable THz Communications*
- 11:40 – 12:00 **Junaid Yaseen**: *Tailoring sub-THz Beams by Liquid Crystal Assisted Reconfigurable Intelligent Surfaces*
- 12:00 – 12:20 **Alessandra Contestabile**: *Photonics at Space-Time Interfaces for Advanced THz-Wave Manipulations*
- 12:20 – 12:40 **Guido Gentili**: *Modeling of electromagnetic wave propagation in semimetals*
- 12:40 – 13:00 **Unai Arregui-Leon**: *Nonlinear phonon-polaritonic flat-optics for temporal edge detection in the THz*

13:00 – 14:20

Lunch

VII Section: THz Spectroscopy

Chair: G. Galzerano

- 14:20 – 14:40 Umar Farooq: *Temperature-dependent birefringence behavior of NdGaO probed by terahertz spectroscopy*
- 14:40 – 15:10 Marco Ballabio: *Unveiling the Semiconducting Properties in Four Different Metal Triphenylenehexathiol-based Metal-Organic Frameworks* 0
- 15:10 – 15:30 Salvatore Macis: *Transient Terahertz Polaron Conductivity of Magnetite*
- 15:20 – 15:40 Candida Moffa: *Advancing atmospheric pollution monitoring with airborne THz spectrometer*
- 15:40 – 16:00 Federico Grandi: *Lattice dynamics and carrier transport in HgPSe*

16:00 – 17:00

Closing Remarks and Visit to the Polytechnic and INF-CNR laboratories

Invited Speakers

Prof. Dr. Giacomo Scalari (ETH Zürich, Institute for Quantum Electronics – Switzerland)



Giacomo Scalari is an Adjunct Professor and Senior Scientist at ETH Zürich's Institute for Quantum Electronics, active in the Quantum Opto-Electronics group. He earned his Physics diploma from the University of Pisa (1999) and completed a PhD in 2005 on magneto-spectroscopy and the development of terahertz quantum cascade lasers (THz QCLs). He joined ETH Zürich in 2007 and became a permanent senior scientist in 2011. His research spans THz QCLs (including frequency combs), ultrastrong light-matter coupling in the THz, and THz superconducting metamaterials.

Prof. Dr. Romain Peretti (IEMN-CNRS, Université de Lille – France)



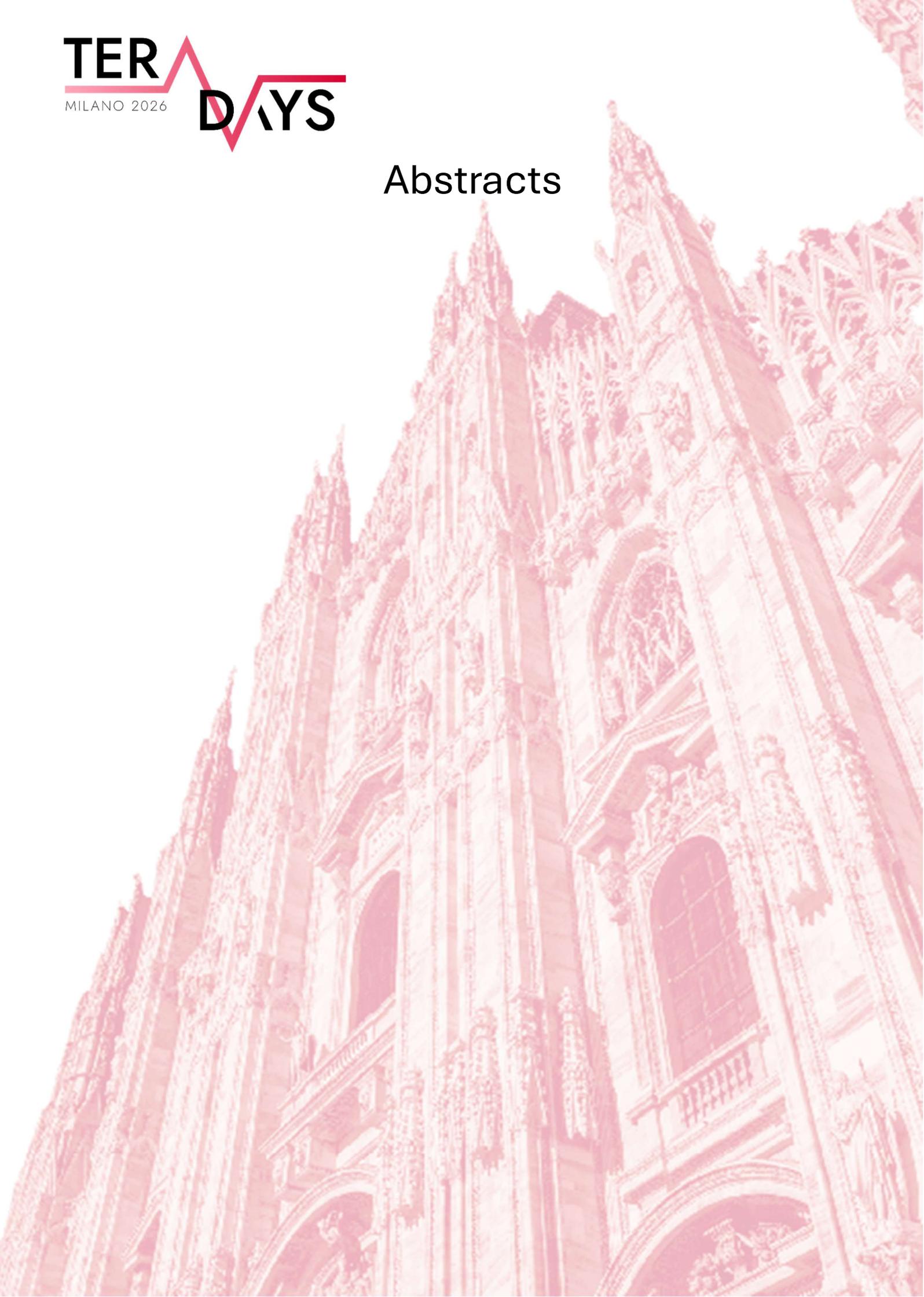
Romain Peretti is a CNRS research fellow (chargé de recherche) at the IEMN laboratory (CNRS / Université de Lille / UPHF). He specializes in terahertz biophotonics, developing THz tools and measurement techniques for applications in biology and medicine. His work investigates how THz electromagnetic waves interact with biologically relevant molecules in solid, liquid, and gas phases, with a strong emphasis on THz spectroscopy approaches to protein structure and dynamics and on exploring THz-based diagnostic perspectives.

Prof. Dr. Martin Koch (Philipps-Universität Marburg, Department of Physics Germany)



Martin Koch is Professor of Physics at Philipps-Universität Marburg, where he leads research in semiconductor photonics and terahertz science. His interests include THz systems and applications, ultrafast/semiconductor spectroscopy, and related photonic technologies. He serves as Editor-in-Chief of the Journal of Infrared, Millimeter, and Terahertz Waves and has received several distinctions, including the Kaiser-Friedrich Research Prize (2003), the IPB Patent Award (2009), and the IRMMW-THz Society Exceptional Service Award (2019).

Abstracts



Devices to guide and manipulate THz waves

Martin Koch

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Abstract: In this presentation, we will discuss a whole range of quasi-optical components that have been developed over the last 15 years by the Marburg Semiconductor Photonics Group.

Spectroscopy using terahertz waves and THz communication technology have developed significantly in recent decades. Considerable progress has been made. This applies in particular to the development of powerful THz sources and THz detectors. Since THz radiation can be regarded as long-waved light, THz systems also require a whole range of quasi-optical components. This includes lenses, prisms, diffraction gratings, polarizers, and so on. These components are commercially available in the optical spectral range from many companies. In the THz range, they had to be or still have to be developed. Over the past 15 years, the working group in Marburg has presented several such components that can be used to guide or manipulate THz beams. In the talk we will present several of these components.

First, we will discuss low-cost THz lenses and transmission blaze gratings. These devices can be easily produced by compression molding [1,2]. Alternatively, these optical components can also be fabricated by 3D printing [3,4]. As 3D printing is a very powerful technique it also allows for the fabrication of waveguides or even couplers for THz frequencies [5,6]. Moreover, we will present a prism. Nearly all dielectric materials do not show dispersion in the THz range. Hence, the concept for prisms, which is based on the dispersion of glass in the visible spectral range, cannot be used for THz frequencies. We therefore use a different physical principle: our prisms are based the well known waveguide dispersion [7]. Often, one wants to manipulate the state of the polarization of THz waves. Wave plates are ideal components for this purpose. We will present a wave plate easily made of a stack of ordinary white copy paper [8]. The working mechanism of this component is form birefringence. Its design frequency can be adjusted by varying the thickness of paper stripes. Of course, there are alternative ways to produce components based on form birefringence, for example waveplates can be fabricated out of fused silica using a process known as selective laser-induced etching [9]. Finally, we present a THz lens with a variable focus containing a terahertz-transparent liquid [10]. By injecting and draining an oil, which is transparent at THz frequencies into the lens one can vary the lens curvature. This in turn leads to a shorter or longer focal length.

Contacts:

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Advanced Nonlinear THz Spectroscopies at the TeraFERMI Beamline

Andrea Perucchi

Elettra - Sincrotrone Trieste S.C.p.A., S.S. 14 km 163.5 in AREA Science Park, 34012 Trieste, Italy

Abstract: TeraFERMI is a THz beamline delivering high fields for nonlinear spectroscopy. We review existing set-ups and introduce new single-shot diagnostics enabling pulse-resolved studies.

TeraFERMI is the dedicated THz beamline of the FERMI Free-Electron-Laser facility [1], delivering broadband ultrashort pulses with peak electric fields exceeding 5 MV/cm and magnetic fields in the Tesla range. These extreme field strengths enable access to nonlinear THz spectroscopy and a wide variety of strong-field pump–probe experiments. The beamline supports multiple experimental configurations, including fluence-dependent THz spectroscopy [2,3], THz-pump/THz-probe, and THz-pump/IR-probe [4] schemes. More recently, its capabilities have been expanded to include THz-pump/SHG-probe and THz-pump/supercontinuum-probe methodologies, further broadening the range of accessible light–matter interaction regimes.

Current developments at TeraFERMI focus on the implementation of single-shot spectroscopy techniques. This diagnostic approach retrieves THz electric-field waveforms on a single-pulse basis by exploiting polarization diversity in electro-optic crystals [5]. An earlier prototype of this instrument was successfully tested at TeraFERMI [6]; it is now being deployed as a permanent installation, enabling real-time monitoring and analysis of THz waveforms. Single-shot detection is especially advantageous for investigating nonlinear processes such as THz harmonics generation, where FEL-based THz sources exhibit significant shot-to-shot variations in pulse energy and spectral content. Conventional averaging can obscure essential non-perturbative features, whereas single-shot measurements provide a statistical ensemble from which scaling laws, fluctuation-driven behavior, and strong-field responses can be extracted more efficiently. These advances position TeraFERMI as a versatile platform for exploring emergent regimes of ultrafast, non-perturbative THz light–matter interactions in quantum materials.



Fig.1 | Overview of the TeraFERMI laboratory

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Design and Optimization of the THz/IR Beamline SISSI 2.0 at the Elettra Synchrotron Facility

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Abstract: The optical layout of the future THz/IR beamline SISSI 2.0 at the upgraded Elettra 2.0 is presented. The design of the optics has been developed through numerical simulations to characterize the synchrotron radiation emitted by the new Diffraction Limited Storage Ring

Synchrotrons are storage rings designed to produce high-brightness radiation over a broad frequency range from the Infrared (IR) to the X-rays. In the third generation of these machines, the introduction of Insertion Devices (IDs), alongside with the more conventional bending magnets, have ensured the possibility of generating radiation with extraordinary properties, providing access to a great variety of experimental techniques and paving the way for new science and technological innovations. Elettra is one of the first European third-generation light sources in the soft X-ray, featuring a 259.2 m storage ring, operation energies of 2 and 2.4 GeV, and 28 beamlines available to external users. A major upgrade is currently underway at the facility for the realization of the new Diffraction-Limited Storage Ring (DLSR) Elettra 2.0. This upgrade is intended to reduce the horizontal emittance of the particle beam by an order of magnitude, reaching the amazing target of 212 pm·rad, which will allow to deliver radiation with improved brightness and with an almost full degree of transverse coherence up to 0.5 keV. The main work on the structure consists in the upgrade of the magnetic optics, which will be replaced with a new modified multi-bend achromat lattice type with reverse bends and longitudinal gradient dipoles named S6BA-E (symmetric six bend achromat enhanced), without changing the basic features of the accelerator [1,2].

This upgrade will involve all the beamlines and specifically SISSI (Synchrotron Infrared Source for Spectroscopy and Imaging), which is dedicated to the collection of Terahertz/Infrared (THz/IR) radiation emitted by magnetic dipoles from a wide vertical angle, difficult to achieve in DLSR accelerators. In the early 2000, SISSI has been planned and developed through the collaboration between the Department of Physics of Sapienza, IOM-CNR Institute and Elettra Synchrotron. Nowadays, through the same collaboration, the SISSI 2.0 project is devoted to the design and commissioning of an upgraded beamline which is intended to transport the THz/IR radiation emitted from the new source up to a laboratory dedicated to optical and IR micro-spectroscopy experiments. The future beamline, which is presented in Fig.1 is based, in its preliminary version, on three main sections dedicated respectively to the following tasks:

- Aberration correction and beam focalization
- Beam reshaping and beam collimation

- Beam-spot size reduction through a telescope

To achieve these goals, the beamline is equipped with a sophisticated sequence of twelve mirrors, including non-conventional optical components such as a conical mirror. This optical layout has been specifically designed to deliver optimal beam characteristics at the experimental hall, enabling the ambitious scientific program envisioned for SISSI 2.0. In particular, it will support advanced IR sub-diffraction nano-spectroscopy experiments with improved signal-to-noise ratio and enhanced long-term stability.

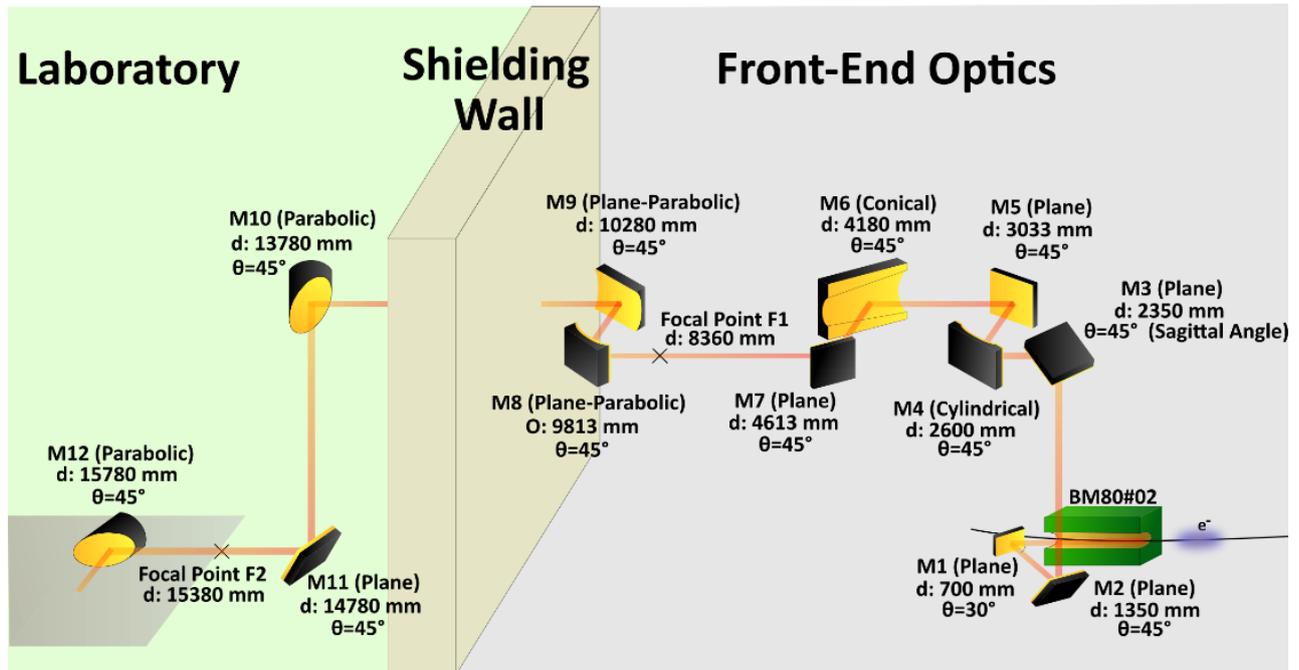


Figure 1 | SISSI 2.0 beamline design

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Advancing SABINA: Installation, Commissioning Plan, and Early THz Diagnostics

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3) ENEA - Centro Ricerche Frascati, Via Enrico Fermi, 45 00044 Frascati (Roma)

Abstract: SABINA addresses the challenge of delivering high-intensity, tunable-polarization THz/MIR FEL radiation. The beamline and APPLE-X undulators are installed and characterized. In 2026, commissioning will validate beam transport, assess undulator performance, and enable first THz measurements for simulation benchmarking and optimization.

SABINA (Source of Advanced Beam Imaging for Novel Applications) [1] is the new THz and MIR Free-Electron Laser currently under installation at the SPARC_LAB facility of INFN-LNF [2].

The facility is designed to generate high-intensity, short-pulse radiation with tunable polarization in the THz and MIR spectral ranges. The electron beam provided by SPARC_LAB, operating in the 30–100 MeV energy range, will drive a Self-Amplified Spontaneous Emission (SASE) process across up to three APPLE-X undulators [3], delivering quasi-monochromatic radiation in the spectral range from 3 to 30 THz with milliJoule-level energies and picosecond pulse durations.

The project is finally transitioning from concept to reality: the full electron beam line - including the dogleg transport system and the APPLE-X undulator chain - is now installed and undergoing final technical validation.

In recent months, significant effort has been devoted to instrumenting the electron beam line and designing the radiation transport line. The undulators have been precisely mechanically aligned, magnetically characterized [4], and integrated into the control system through coordinated operations among experts in several fields. This ensures the flexibility required for variable-polarization operation for an efficient user facility.

SABINA is therefore entering a decisive phase, moving from construction to beam commissioning. The first electron beam on the SABINA's line is scheduled for the early

months of 2026 and will proceed through a stepwise program. The initial stage will concentrate on driving the beam through the full dogleg to verify optics, stability, and transport efficiency. Moreover, a thorough performance analysis of the undulators will be performed to match the simulations with the real conditions and at different beam energies.

In parallel, a temporary diagnostic station for the first detection of THz radiation will be installed downstream of the undulators. This temporary setup will enable early photon-beam characterization while the permanent photon-transport line to the future user area is in installation phase.

The contribution will present the status of SABINA, detailing the implemented beamline, the progress on the undulator system, the planned commissioning strategy, and the expected timeline for the 2026 experimental campaign. Preliminary planning for the first THz measurements - targeted to benchmark simulations and guide final optimization - will also be discussed.

Contacts:

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Acknowledgements:

SABINA is a project co-funded by Regione Lazio with the "Research infrastructures" public call within the POR-FESR 2014-2020 program.

This work is supported by NextGeneration EU- Italian National Recovery and Resilience Plan, Mission 4 -Component 2 - Investment 3.1. - Project name: Rome Technopole, CUP: I93C21000150006.

Terahertz ATR Spectroscopy to Sense Acetone in Water: Toward Biomarker and Contaminant Monitoring

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In this study, Attenuated Total Reflection (ATR) is combined with the Terahertz Time-Domain Spectroscopy (TDS) technique to provide a reliable method for measuring volatile organic compounds (VOCs). Acetone in water solution over the full concentration range (0-100%) was investigated. The complex function of the compound for different molar fractions was studied as a function of frequency and the intermolecular dynamics of the aqueous binary mixture analyzed using a double Cole-Cole (DCC) model.

Acetone, the smallest ketone, has high environmental and biomedical impacts, as it is highly used in laboratories and industries, as well as being a metabolic byproduct in humans [1]. Therefore, detection of acetone and understanding its dynamics with the environment is essential. Acetone is only a hydrogen-bond acceptor (aprotic molecule) that can disrupt the existing O–H network of water, which leads to a sudden change in the dielectric response of pure water, even in small amounts. The terahertz (THz) band, which is highly sensitive to molecular relaxation and hydrogen-bond dynamics, makes spectroscopic techniques a powerful detection tool for such dynamics [3]. Using an ATR optomechanical design, with a sealed pool for the liquids as a sample holder at the top of a highly resistivity silicon, provides an opportunity to measure highly volatile compounds like acetone with high accuracy.

This study aims to investigate the intermolecular dynamics of the acetone aqueous solutions with different concentrations using THZ-ATR method. Measurements are carried out by using s-polarized THz pulses incident above the critical angle to the ATR prism at room temperature (T~25°C). The evanescent field interaction with the mixtures is probed, and real ($\epsilon_1(\omega)$) and imaginary ($\epsilon_2(\omega)$) parts of the dielectric response are retrieved at a frequency range of 0.2 to 1.6 THz. The experimentally achieved data were then fitted to the double Cole-Cole model (Eq. 1), showing a good agreement between model and experiment. Samples with different molar fractions ($X_M\%$) were prepared in sealed conditions at room temperature to avoid acetone evaporation.

The double Cole-Cole model of dielectric response is [2]

$$\tilde{\epsilon}(\omega) = \epsilon_{\infty} + \frac{\Delta\epsilon_1}{1+(i\omega\tau_1)^{1-\alpha_1}} + \frac{\Delta\epsilon_2}{1+(i\omega\tau_2)^{1-\alpha_2}}, \quad (1)$$

where ϵ_{∞} is the high-frequency permittivity, $\Delta\epsilon_{1(2)}$ is the dielectric strength, ω is the angular frequency, and $0 \leq \alpha_{1(2)} \leq 1$ is the Cole-Cole broadening parameter.

Fig. 1 shows $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ of the mixtures, both the experimental data and the output of the fitting model at a fixed frequency ($f = 0.6$ THz) as a function of molar concentration. A sudden drop in both $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ is observed by adding only a small amount of acetone ($X_M \approx 0.8\%$), showing that ATR-THz spectroscopy is capable to detect subtle disruptions of the hydrogen-bond network due to the presence of an aprotic molecule. As the concentration changes, the dynamics of the mixture varies and can be described differentiating three regions: (i) water-rich region (0-25% X_M), where the acetone is introduced into the existing water network in small amounts and its aprotic nature leads to a sudden disruption of the existing O-H bonds [4]; (ii) intermediate region (25-60% X_M), in which acetone and water molecules interact via O-H band formation. Each acetone molecule can accept up to two O-H bonds from water molecules via its carbonyl oxygens. A milder dielectric response reduction is observed in this region by increasing the acetone concentration; (iii) the acetone-rich region (60-100% X_M), where the water molecules become the guest and water clusters are not present anymore. Here new O-H bonds are not forming anymore due to the aprotic nature of acetone, and the added acetone molecules interact through dipole-dipole interaction only [8]. In this region, we do not observe a noticeable change in the dielectric response of the mixtures as the concentration varies.

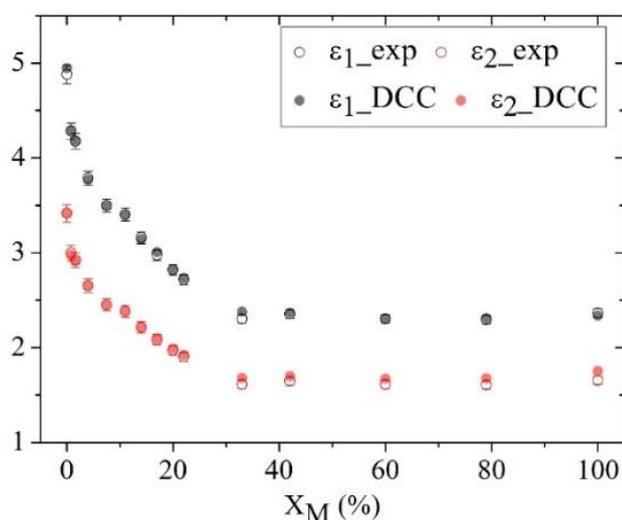


Figure 1. The comparison between the DCC model (full points) and the experimental data (open points) of the real (ε_1) and imaginary (ε_2) parts of the dielectric response of the water-acetone mixture as a function of concentration at 0.6 THz.

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Electromagnetic Modeling for Material and Metasurface Characterization through Terahertz Time-Domain Spectroscopy in Reflection Mode

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Abstract: The increasing demand for components for terahertz (THz) applications calls for accurate and effective methods for their electromagnetic modeling. In this contribution, we show our recent progress in the development of a general protocol for the characterization of materials and metasurfaces through THz time-domain spectroscopy in reflection mode. A vast measurements campaign is offered as a validation tool for the proposed method.

The characterization of the electromagnetic (EM) properties of materials is one of the fundamental applications of spectroscopic techniques, especially at terahertz (THz) frequencies where little information is available when compared to microwave or optical frequency ranges.

In the last few decades, THz spectroscopy benefited from the exceptional progress made in the realization of efficient THz sources and detectors, which allowed for the development of commercial setups based on either continuous-wave sources, i.e., frequency-domain spectrometers (FDS), or pulsed-wave sources, i.e., time-domain spectrometers (TDS).

When the frequency resolution is not a concern, TDS systems are typically preferred to FDS as they give access to the temporal and spectral response of the device under test (DUT) in a shorter measurement time. TDS techniques are typically divided into two categories, depending on whether the setup is mounted in transmission (THz-TDS-T) or reflection mode (THz-TDS-R). The former is usually preferred when transparent or weakly conductive and low-loss samples are investigated, whereas the latter is typically employed for characterizing highly absorbing or reflective samples.

Different THz-TDS-R methods have been proposed in the literature to characterize the EM properties of the DUT. In this contribution, we discuss the recent progress we made in the EM modeling of a conventional THz-TDS-R setup for the characterization of both materials and metasurfaces. As a significant difference with respect to previous approaches, we capture the entire free-space THz path with an EM model which rigorously accounts for all wave interactions between the THz waves and the complex media under analysis. In this approach, (among other features) we are also able to accurately characterize the Fabry–Perot-like resonances that manifest in the amplitude reflection spectrum and exploit them for an accurate characterization of the EM properties

of the DUT. This technique comes in stark contrast with previous approaches that typically avoid Fabry–Perot resonances, e.g., by time gating the reflected pulse to isolate the contribution of a given layer.

More specifically, we here show that the EM model can reproduce with remarkable accuracy the measured reflection spectrum in cases as diverse as: *i*) the study of the complex refractive index of dielectric materials [1] (including dielectric foams that require to account for the phase of the reflection spectrum [2]), *ii*) the sheet resistance of thin conducting films [3], *iii*) the sheet reactance of deeply subwavelength metasurfaces [4], and *iv*) the complex surface conductivity of Drude-like two-dimensional materials (such as graphene) [5].

In all these cases, we show that a theoretical reflection coefficient can easily be derived from the abovementioned EM model and used along with the measured reflection coefficient to define a Euclidian norm over the frequency range of interest where the physical parameters that describe the DUT are fitted to minimize a suitably defined objective function.

For each case study, we give proper emphasis to the physical mechanisms observed in the reflection spectrum, thoroughly discussing, e.g., the Salisbury screen condition in resistive films, the appearance of leaky, plasmonic, and dipole resonances in metasurfaces, and the red/blue-shift of resonances in purely inductive/capacitive metasurfaces. Future perspectives on this research are finally provided.

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More than meets the eye: depth-resolved THz chemical mapping of multilayered samples

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Abstract: A novel depth-resolved THz multispectral mapping method for uncovering hidden layers in artworks is presented. Exploiting spectral fingerprints related to chemical specificity of each pigment we successfully deciphered concealed text in multilayered mock-ups, resulting in better resolution compared to conventional temporal domain analysis.

Non-invasive imaging through thin stratified layers represents a significant analytical challenge in Cultural Heritage conservation as well as in many fields of material sciences. Well-established methodologies for this purpose, such as NIR, SORS or XRF analysis, usually face important limitations regarding this matter. They are typically hindered by scarce elemental contrast between different layers, fluorescence hindrance, or overlapping spectral signatures. At the same time, it is renowned that the terahertz spectral region offers a unique frontier for overcoming these hurdles: instrumentation operating in this range is considered almost unrivalled when it comes to depth-resolved non-invasive analysis of multilayered structures, thanks to its ability to penetrate non-conductive materials. Terahertz Time-Domain Spectroscopy (THz-TDS), in particular, has been conventionally exploited for stratigraphic reconstruction using time-of-flight analysis of the reflected echoes [1]. However, standard time-domain imaging often lacks chemical specificity, especially when refractive index contrasts are low. Our work, leveraging the interesting capability of THz radiation, presents a novel methodology based on THz reflection spectroscopy and evaluates data in the frequency domain. This is achieved thanks to a specifically designed algorithm that deciphers concealed images and separates pigment layers within stratified pictorial materials based on their specific vibrational modes.

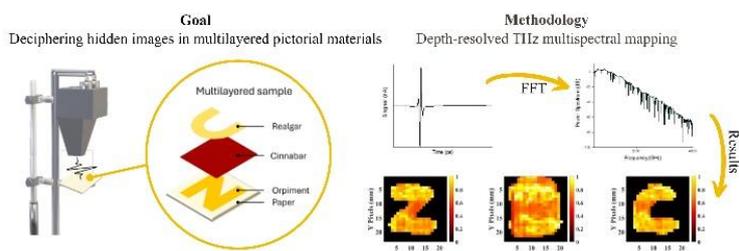


Fig.1 | Graphical representation of the study's objective (right) and schematic workflow of the presented approach (left)

Concerning experimental details, in this study we utilized a fiber-based femtosecond laser system operating in the 0.1–6 THz range. Measurements were conducted in reflection geometry, equipping the instrument with a supplementary reflection module (incident beam angle of approximately 8°) and using a mechanical X-Y raster scanner with a spatial

step of 1 mm, consistent with the beam spot size measured at the focal plane ($\sigma \approx 500 \mu\text{m}$). The subjects of this study were pictorial mock-ups prepared using historical red and yellow pigments such as cinnabar (HgS), orpiment (As_2S_3), and realgar (As_4S_4), bound with gum Arabic on paper to paint variously arranged letters. Lastly, one mock-up featured a peculiar multilayered structure designed to test depth-resolved imaging, where a hidden letter ("Z" in orpiment) was obscured by a cinnabar layer beneath a visible letter ("C" in realgar). Prior characterization of pure pigment pellets in transmission (0.5–3 THz) established a reference database, retrieving refractive indices and absorption spectra, including previously experimentally unreported peaks for realgar. The crucial objective was to move beyond standard time-domain echo detection to reach chemical specificity. Therefore, we developed a custom frequency-domain reconstruction algorithm that integrates spectral intensity (L_{signal}) within a narrow bandwidth ($\nu_0 \pm 0.02$ THz) around unique resonances. This strategy allowed for the selective identification of materials even when optically hidden: our frequency-domain analysis successfully revealed the concealed text "Z", a feature that was essentially indistinguishable using standard time-domain maximum/minimum amplitude mapping. The resulting high-contrast chemical maps demonstrated a pixel recognition discrepancy of approximately 13%. This deviation is primarily observed near structural boundaries (i.e., borders between the letter and the background), where the finite beam waist size limits spatial resolution. These artifacts, however, were refined through visual inspection of the spectral data. Finally, sparse deconvolution resolved temporally overlapping echoes. Combining this with measured refractive indices granted for a precise thickness quantification (down to $\sim 50 \mu\text{m}$), validated against cross-sectional optical microscopy: minor discrepancies can be attributed to the inherent variability of handmade specimens. From what is exposed above, this work sets THz multispectral imaging as a crucial tool for unravelling hidden layers in Cultural Heritage artefacts. By shifting the focus from time-domain to frequency-domain spectral fingerprints, we demonstrate the ability to chemically differentiate and spatially reconstruct hidden layers with high specificity, bridging the gap between fundamental spectroscopy and diagnostic applications [2].

Acknowledgments: we would like to express our sincere appreciation for all those who have contributed to our work: D. Francescone, A. Curcio, A. C. Felici, M. Bellaveglia, L. Piersanti and M. Migliorati. This work was carried out thanks to "PRIN 2022: TREX a prototype of a portable and remotely controlled platform based on THz technology to measure the one health vision: environment, food, plant health, security, human and animal health" funded by the European Union - Next Generation EU (CUP B53D23013610006 - Project Code 2022B3MLXB PNRR M4.C2.1.1) and Sapienza Large Projects Research Call 2023 titled "TforCH: R&D on the potentiality of THz radiation for Cultural Heritage".

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Self-Referenced THz Time-Domain Spectroscopy for Reflection Measurements

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Abstract: We demonstrate a reference-free THz time-domain reflection spectroscopy by extracting optical constants of SrTiO₃. Using its soft phonon as an internal reference, we reconstruct reflectivity and correct phase errors, enabling accurate determination of temperature-dependent refractive index across 10-300 K.

Terahertz time-domain spectroscopy (THz-TDS) in reflection geometry is essential for studying opaque or bulk materials that cannot be measured in transmission. However, accurate extraction of optical constants requires a reference measurement acquired under identical alignment conditions. In many experimental environments, obtaining a reliable reference measurement is not possible. A prominent example is a cryostat, where micron-level sample shifts caused by thermal contraction make it extremely difficult to reproduce the exact alignment required for reference and sample measurements. These slight displacements introduce phase errors in the reflected THz signal [1], preventing accurate determination of the complex refractive index.

To address this problem, we develop a reference-free THz-TDS method that reconstructs both amplitude and phase of the complex reflection coefficient without requiring a separate reference sample. As a demonstration, we investigate bulk SrTiO₃, a quantum paraelectric that hosts a strongly temperature-dependent soft transverse optical phonon (TO1) [2]. Because this phonon enhances reflectivity at low temperature, the 10 K measurement can act as an internal reference.

THz reflection spectra were acquired from 10–300 K using photoconductive antennas in a normal-incidence geometry (Fig. 1a). The measured THz pulses shift in time and decrease in amplitude with increasing temperature, as shown in Fig. 1b. We first normalize all spectra to the 10 K trace and model the resulting ratios using a Drude-Lorentz dielectric function [3], enabling reconstruction of the absolute reflectivity at each temperature. Although the amplitude of the reflectivity is robust to small misalignments, the spectral phase is strongly affected. We therefore apply a phase-correction method [4] based on enforcing Kramers-Kronig consistency in frequency regions preceding the phonon resonance.

After phase correction, the reconstructed amplitude and phase of the reflectivity yield the full complex refractive index of SrTiO₃ (Fig. 1c shows only the real part). The extracted phonon frequency, linewidth, and oscillator strength evolve with temperature in agreement with neutron scattering data [5], further confirming the validity of the approach.

This method enables accurate reflection-based THz spectroscopy in environments where referencing is impractical and provides a general framework for studying temperature-dependent excitations in a wide range of materials.

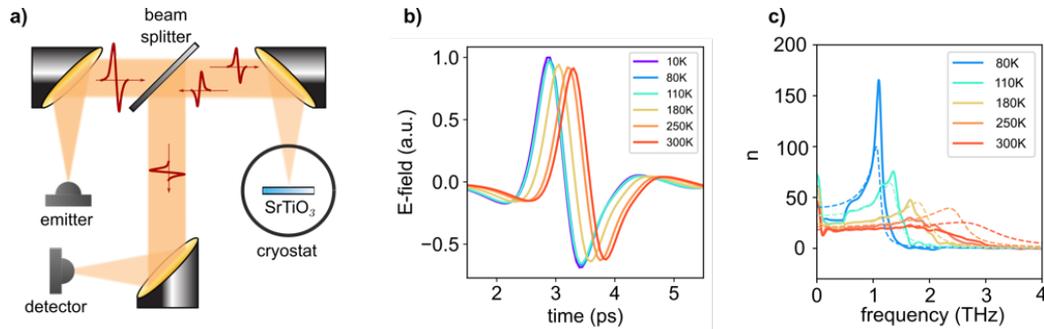


Fig.1 | **a)** THz-TDS setup in reflection geometry, **b)** THz time-domain traces of reflected pulses from SrTiO₃ across temperatures ranging from 10 K to 300 K, **c)** Real part of the complex refractive index after amplitude and phase correction. Dashed lines show the refractive index computed directly from the Drude-Lorentz fit parameters.

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Enhanced THz Permeability in Non-Magnetic Drude Conductors

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Abstract: The permittivity and the permeability of Al and Cu thin films have been measured through THz time domain spectroscopy. The unusually very high permeability values indicate the onset of strong coupling between electronic plasma and spins.

Non-magnetic metallic films are generally not expected to exhibit any magnetic response when probed with electromagnetic (EM) radiation. In fact, a large number of studies on EM simulations, particularly those involving metals, such as in the realization of metasurfaces [1], model them by setting $\tilde{\mu} = \mu_0$, where μ_0 represents the vacuum permeability. Veselago himself in his pioneering paper [2] on the negative refractive index (NRI) materials assumed that electronic plasma (Drude-like materials), being non-magnetic, could exhibit NRI phenomena only in the presence of ferromagnetic moments.

Time domain THz spectroscopy has been used to measure the permittivity ($\tilde{\epsilon}$) and permeability of aluminum and copper thin films. Results indicate that the electrical response is consistent with the Drude model characteristic of plasmonic media, whereas the permeability of the two materials exhibits slightly different behaviors. Specifically, the Al films are diamagnetic while the Cu films are paramagnetic.

Such results arise from a rigorous self-consistent retrieval process that exploits both transmission and reflection measurements [3]. This computational routine defines a narrow interval within which the true value of each electrodynamic parameter lies. The complex refractive index \tilde{n} and the optical impedance \tilde{z} are first retrieved through Fresnel's equations. Subsequently, the permittivity and the permeability are obtained through $\tilde{\epsilon} = \tilde{n}/\tilde{z}$ and $\tilde{\mu} = \tilde{n}\tilde{z}$, respectively. Fig.1 displays the four electrodynamic parameters of a 10nm-thick Al film.

It is important to emphasize that the spectroscopic $\tilde{\mu}$, shown in Fig.1(d) is inherently constrained to exhibit a positive real part whereas its imaginary part may be either positive or negative. This behavior arises from the adopted sign conventions of \tilde{n} ($n > 0, k > 0$) and from the requirement that ϵ_i remains positive. It can be demonstrated that a spectroscopic permeability characterized by $\mu_r > 0$ and $\mu_i < 0$ corresponds to a diamagnetic response, which is theoretically expected to assume the opposite behavior, namely $\mu_r < 0$ and $\mu_i > 0$. The observed phenomenology is consistent with the electronic plasma-spin theory [2] according to which the EM confinement in the metallic film induces the onset of spin waves that oscillate coherently with plasma waves.

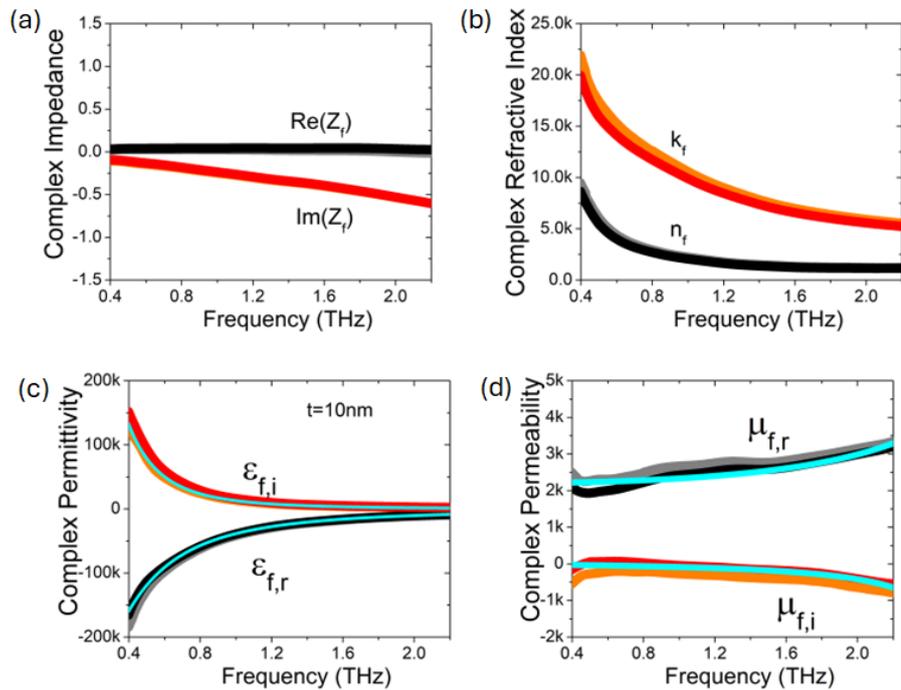


Fig.1: (a), (b), (c) and (d) show the optical impedance, the complex refractive index, the permittivity and the permeability of an aluminum thin film, respectively.

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On-chip coherent THz photonics with frequency combs

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Abstract: We discuss the on-chip generation of THz comb states in the 1-4 THz bandwidth and their on-chip manipulation. We demonstrate broadband (2.5-3.5 THz) frequency comb operation both in AM and FM regimes as well as integrated wavelength division multiplexing .

On-chip coherent THz signal generation and control [1] [2], is extremely appealing in a variety of different implementations from fundamental research to applications such telecommunication and spectroscopy. In the last 10 years, THz quantum cascade laser (QCL) frequency combs [3] have seen a tremendous development, with demonstration of dual-comb spectroscopy[4], dissipative Kerr solitons[5], passive and active mode locking [6], [7], [8]. We will discuss the generation of coherent THz signals in the bandwidth 1 to 5 THz and their on-chip manipulation. We leverage the frequency agility of the semiconductor intersubband gain medium combined with the ultrabroadband nature of double metal planarized waveguides to demonstrate broadband frequency combs operation both in AM and FM regimes. Particularly, we report on the generation of coherent pulse trains with arbitrary repetition rate from a monolithic on-chip device [9]. It is a novel regime of active mode-locking, which allows for an arbitrary amount of detuning between the modulation frequency f_{mod} and the natural repetition rate $f_{\text{rep},0}$.

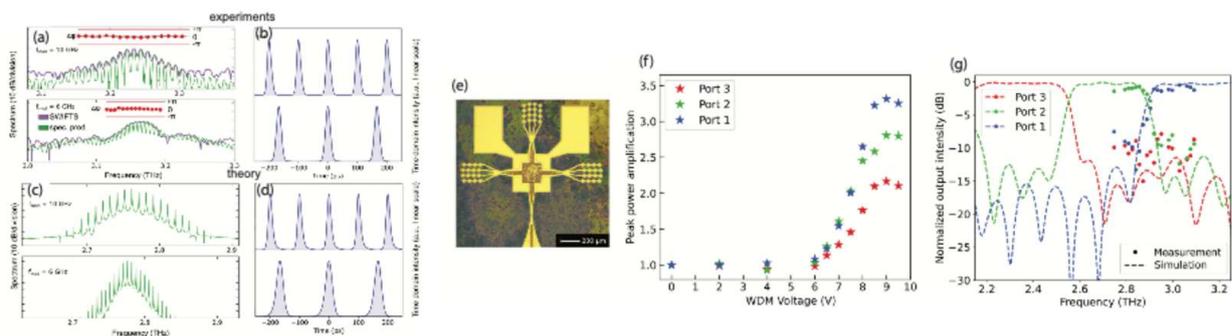


Fig.1. **a,b** Experimental SWIFTS results showing the tunable spectral mode spacing and repetition rate of the coherent pulse train. **c,d**: Numerical simulation for the same conditions in **a,b** have excellent agreement with experiments. **e**: Optical microscope image of the WDM. **f**: Measurement of the peak power amplification of the WDM output as a function of the bias voltage of the demultiplexer. **g**: Comparison of the WDM normalized output intensity with time domain 3D simulations.

We investigated a planarized THz QCL sample with a length of 6 mm ($f_{\text{rep},0} = 6.61$ GHz), active waveguide width of 40 μm , and top metal width of 300 μm , by performing a modulation frequency sweep study between 4-16 GHz. In this whole range we could observe pulse generation for arbitrarily injected RF frequencies. In Fig. 1(a,b), we show the experimental SWIFT spectroscopy results for modulation frequencies of 6 and 10 GHz, i.e., below and above the $f_{\text{rep},0}$. Both the spectral mode spacing and the repetition rate of the coherent pulse train match exactly the modulation frequency in each case. We also developed a numerical simulation model based on a semiclassical Maxwell-density matrix formalism, whose results reported in Fig. 1(c,d) show excellent agreement with experimental data.

We will discuss as well the performance of an active, on-chip, three channels wavelength division multiplexer (WDM)[10]. WDM's are essential components in signal processing, to fully exploit the highly coherent comb sources, allowing signal manipulation and routing directly on-chip. Previously, on-chip THz WDM's were demonstrated at maximum frequencies below 500 GHz. A unique property of our WDM, conceived using inverse design, is that it is an active device with gain, allowing for simultaneous spectral selection and amplification. In Fig.1e is visible a micrograph of the processed device. Figures 1e and 1f display the amplification and the spectral output intensity for each channel. Experimental data show a good agreement with simulation. The integrated laser operates as a frequency comb, yielding an on-chip integrated device that produces coherent THz radiation and routes it in the bandwidth 2.6-3.2 THz. Recent advances in high-temperature, Peltier-cooled quantum cascade lasers operating in a standard HHL mount will be also reported [11].

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Production and Modulation of Fully Circular Ultrabroadband THz Radiation Using Two-Color Plasma Generation

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Abstract: We demonstrate near-perfect circularly polarized terahertz radiation from a two-color plasma source by optimizing crystal geometry, phase, and chirp. The method enables robust broadband circularity, reveals intrinsic ellipticity chirp, and supports ultrafast, high-depth THz polarization modulation for advanced spectroscopy and communication.

Controlling the polarization state of broadband terahertz (THz) radiation is a central challenge in advancing THz spectroscopy, imaging, and next-generation wireless communication [1-3]. Two-color laser-induced plasma, driven by a fundamental wave (FW) and its second harmonic (SHW), is among the most powerful and broadband THz sources. Yet, achieving strong or fully circular polarization in this scheme has remained elusive: traditional single-arm configurations offer high stability but limited ellipticity, while two-arm systems enable tuning but suffer from phase and alignment instability. As a result, reported THz ellipticities rarely exceeded 0.75.

In this work [4], we combine numerical modeling with systematic experimental optimization to demonstrate, for the first time, **near-perfect circularly polarized THz radiation from a single-arm two-color plasma source**, achieving a record ellipticity of **0.99**, as shown in Fig. 1. We perform a full parametric investigation of the BBO crystal’s rotation and tilt angles, the FW–SHW phase delay, and the laser chirp, identifying the operating conditions that maximize ellipticity while retaining high stability and reproducibility.

A key result is the discovery and characterization of an **intrinsic frequency-dependent ellipticity (“ellipticity chirp”)** in the generated THz field. Because higher-frequency components carry greater ellipticity than the DC contribution, circular polarization is only attainable when the THz spectrum extends sufficiently into the high-frequency regime (8–30+ THz). Experiments using silicon and Teflon filters confirm this monotonic dependence: removing high-frequency components dramatically reduces ellipticity, while maintaining full bandwidth preserves the circular state. These measurements agree quantitatively with simulations based on the local current model.

We further show that the circular polarization is **highly robust to laser chirp**, provided the SHW phase is adjusted accordingly. Even under large positive chirp, ellipticity remains

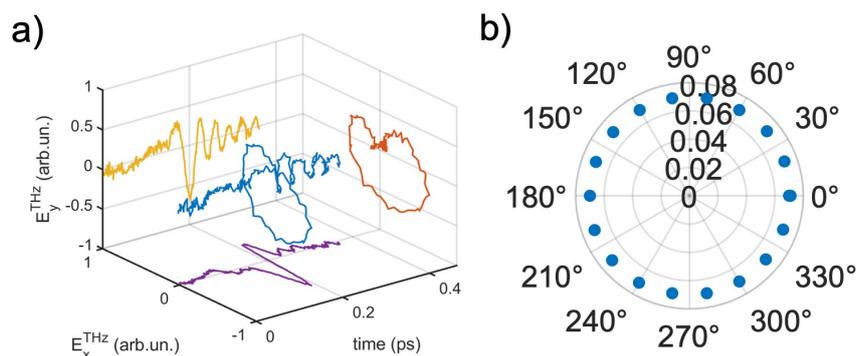


Figure 1. (a) THz electric field obtained via electro-optic sampling using a GaP detection crystal. The red curve represents the projection of the electric field trajectory on the xy plane. (b) Experimental polarimetric diagram measured using a Golay Cell.

above 0.95, enabling independent spectral shaping of the pump pulse—critical for targeting specific molecular, excitonic, or topological resonances—without sacrificing the THz polarization state.

Although operating at maximum ellipticity reduces THz energy by roughly 50%, the resulting pulses retain sufficient strength for nonlinear and time-resolved studies ($\sim 0.1 \mu\text{J}$ and $\sim 100 \text{ kV/cm}$).

Finally, we exploit the extreme sensitivity of THz polarization to BBO orientation to demonstrate that we may achieve **98% ellipticity modulation depth**, representing the most complete THz polarization control demonstrated to date. Based on this result, we propose two schemes for **high-speed THz polarization modulation**.

Together, these results establish the first clear route to generating and dynamically controlling fully circular, ultrabroadband THz fields from two-color plasma. This work provides both fundamental insight into polarization formation and practical tools for high-speed THz polarimetry, spectroscopy, imaging, and communication technologies.

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Acknowledgement: The research leading to these results has received funding from the European Union under Grant Agreement No. 10104665—‘MIMOSA’.

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THz Generation via LSPhP-Enhanced Optical Rectification in LiNbO₃ Metasurfaces

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Abstract: We demonstrate THz generation in LiNbO₃ rod metasurfaces mediated by localized surface phonon polaritons (LSPhPs). Our theoretical model predicts tunable LSPhP-enhanced emission. Preliminary characterization of fabricated structures confirms enhancement of generated THz spectrum based on the rod geometry.

Generation of THz radiation from dielectric metasurfaces has recently emerged as a promising pathway toward compact, efficient, and versatile THz sources [1–5]. While most demonstrations primarily rely on local enhancement of the optical pump field and on the dispersive $\chi^{(2)}$ response, engineering the electromagnetic properties at THz frequencies provides level of control that can substantially improve optical-to-THz conversion efficiency. Localized surface phonon polaritons (LSPhPs) supported by polar dielectrics offer strong field confinement, making them excellent candidates for enhancing and tailoring optical-to-THz generation.

In this work, we introduce a phonon-polariton–assisted THz source based on LiNbO₃ rod metasurface designed to excite LSPhP resonances efficiently coupled to second-order optical rectification. The structure consists of a periodic array of LiNbO₃ rods on a fused-quartz substrate, with geometry shown in Fig. 1a. The periodicity perpendicular to the rod axis is fixed, while the periodicity along the rod axis is varied with the rod length, L , to maintain a constant fill factor. The THz electromagnetic response is analyzed using finite-element-method simulations implemented in COMSOL Multiphysics. As shown in Fig. 1b, the metasurface absorbance exhibits a pronounced peak that is due to the LSPhP resonance, which red-shifts as the rod length increases.

The THz spectra generated by optical rectification of an ultrafast pump pulse calculated with full-wave electromagnetic simulations is shown in Fig. 1c. To provide additional physical insight and facilitate the design process, we also developed a simplified semi-analytical model capturing the essential LSPhP-driven emission mechanism. The model incorporates the dispersive $\chi^{(2)}$ response of LiNbO₃ near its transverse-optical phonon and accurately reproduces the trends obtained from full-wave calculations. Both approaches consistently show that the rod length controls the LSPhP resonance, leading to a systematic red-shift in the generated THz spectrum.

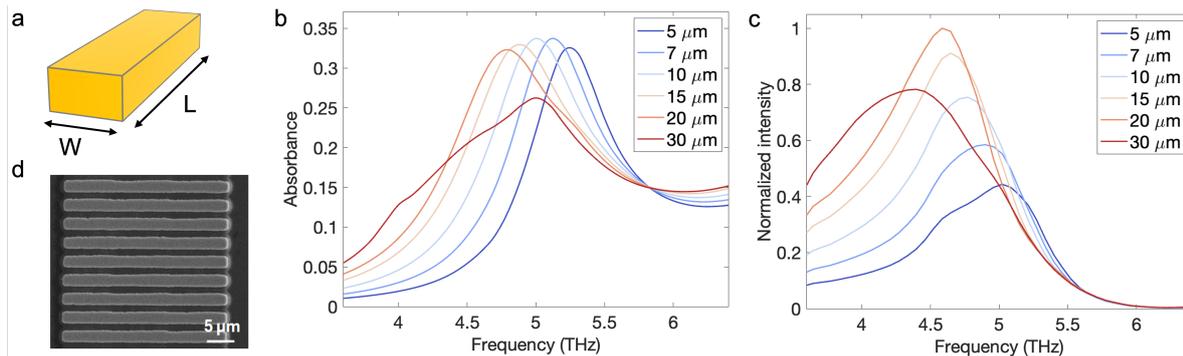


Fig.1 | **a** Schematic of the LiNbO_3 rod geometry, defined by width W and length L . **b** Numerically calculated THz absorbance spectra for different rod lengths L with the incident electric field polarized along the rod axis. **c** Numerically computed THz spectra generated via optical rectification as a function of L . **d** SEM image of a section of a fabricated LiNbO_3 rod metasurface.

Finally, LiNbO_3 metasurfaces were fabricated on 500-nm-thick LiNbO_3 films on fused quartz (NanoLN). An SEM image of one fabricated array is shown in Fig. 1d. The THz emission produced through optical rectification was characterized via THz time-domain spectroscopy. Preliminary measurements reveal a clear enhancement in both peak THz electric field and integrated THz power compared to unpatterned LiNbO_3 films, confirming the expected LSPHP-mediated enhancement. These results highlight LSPHP-engineered metasurfaces as a promising novel platform for compact, tunable, and high-efficiency nonlinear THz generation schemes.

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Acknowledgement

The work was supported by European Union – Next Generation EU PRIN 2022 project NOLIMITHz (2022BC5BW5)

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Generation of Few-Cycle THz Pulses in DSTMS Driven by an 8.3-MHz Amplified Mamyshev Oscillator

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Abstract: We demonstrate few-cycle THz pulse generation at 8.3-MHz repetition rate via optical rectification in a 190- μm DSTMS crystal driven by a 31-fs, 1.1-W amplified Mamyshev oscillator, delivering 40 μW average THz power and > 4 THz bandwidth.

Ultrafast ytterbium-doped fiber lasers based on Mamyshev oscillators (MOs) offer broad spectra, high pulse energies and excellent compressibility to few-tens-of-femtosecond durations, making them attractive drivers for nonlinear optics and laser-driven terahertz (THz) generation via optical rectification (OR) in χ^2 crystals [1]. Here we investigate THz generation at multi-MHz repetition rate using a compact Yb-fiber system built around an amplified MO operating at 8.3 MHz and delivering 31-fs pulses at 1.1 W average power near 1 μm [2], which pump a 190- μm -thick DSTMS organic crystal.

Thanks to its large effective nonlinear coefficient and favorable phase-matching, DSTMS enables stable, broadband few-cycle THz emission [3]. By measuring the average THz power as a function of the incident infrared pump power, as shown in Fig. 1(a), we observe the purely quadratic dependence expected for an OR process, and we reach a maximum average THz power of 40 μW at 1.02 W pump power. Possible limitations due to heat accumulation and nonlinear absorption in the organic crystal at MHz repetition rate are evaluated by varying the duty cycle of a high-speed chopper between 10% and 50% at fixed pulse energy, and by comparing these measurements with continuous operation. The results are displayed in Fig. 1(b): the normalized THz power scales linearly with duty cycle and shows no evidence of saturation up to 100% duty, indicating that thermal effects, cascaded OR and multiphoton absorption remain marginal in our regime.

The electro-optic sampling shown in Fig. 2(a) confirms the few-cycle character of the emitted THz pulses and reveals a power spectral density extending from quasi-DC frequencies below 0.25 THz to beyond 4 THz, with clear water-vapor absorption lines and only moderate attenuation of the highest-frequency components due to the detection crystal, well visible in Fig. 2(b). When the DSTMS crystal is replaced by a 500- μm -thick GaP emitter under identical pumping conditions, the detected THz power drops by more than an order of magnitude while maintaining a comparable usable bandwidth, in agreement with the higher effective nonlinearity of DSTMS. A complementary Schottky-diode measurement of the power spectrum around the laser repetition rate shows a

narrow, high-contrast line at 8.3 MHz without additional excess noise introduced by the OR process.

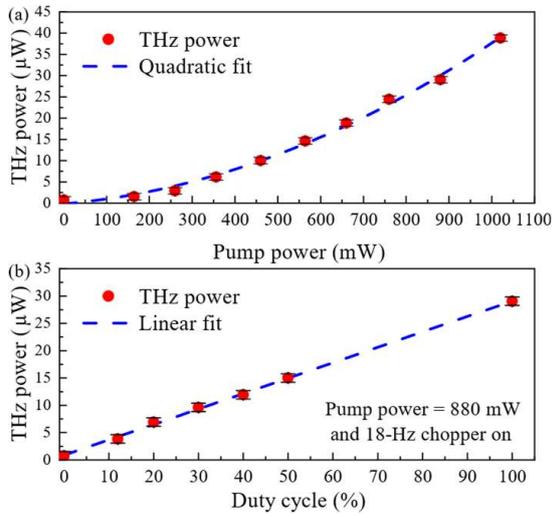


Fig.1 | THz average power measured with the pyroelectric power meter as a function of the infrared pump power **(a)** and of the chopper's duty cycle **(b)**.

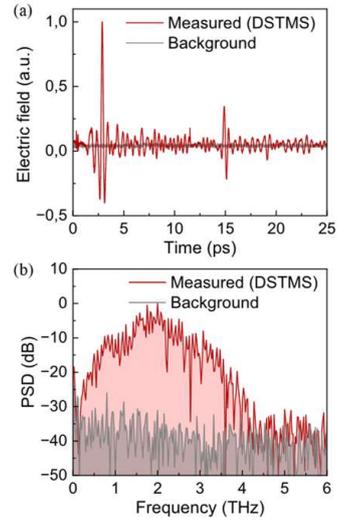


Fig.2 | Electro optical sampling of THz pulses **(a)** and spectrum **(b)**.

Overall, these results demonstrate that amplified Mamyshev oscillators can efficiently drive thin organic crystals at multi-MHz repetition rates to produce broadband, few-cycle THz pulses, opening promising prospects for compact THz time-domain spectrometers and advanced spectroscopy schemes based on this laser technology. Future work will focus on exploring other organic emitters with different phase-matching characteristics, such as BNA, in order to tailor the THz spectrum and potentially further increase the conversion efficiency.

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THz Field Induced Second Harmonic Generation in Epsilon Near Zero Indium Tin Oxide Thin Films

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Abstract: Epsilon-near-zero (ENZ) materials boost strong nonlinear optical effects. In this study THz pulses break the symmetry enabling THz-field-induced second-harmonic generation in ENZ thin films. A four-wave-mixing model matches experiments, revealing strongly coupled linear–nonlinear dynamics in the NIR–THz regime.

Epsilon-near-zero (ENZ) materials have recently emerged as promising platforms for enhanced and tunable light–matter interaction. In the field of nonlinear optics such materials demonstrated their capability to boost nonlinear optical processes even at relatively low optical fluences, thanks to the substantial field enhancements realized [1]. Indium tin oxide (ITO), featuring ENZ properties in the telecom wavelength range, is one of the most broadly explored conducting oxides thanks to the easy fabrication. Yet, being centrosymmetric, ITO thin films are commonly applied for the enhancement of odd nonlinear processes, such as third harmonic generation [2]. In this work, we employ a ITO thin film to study THz-field-induced second harmonic generation (SHG), highlighting a THz-controlled χ^2 response in a nominally centrosymmetric ENZ material. This phenomenon provides a new route for integrating ultrafast, field-programmable nonlinear functions into THz-driven photonic systems.

Using high-field, single-cycle THz pulses synchronized with a near-infrared pump (here named probe), we demonstrate that an intense THz bias is capable of dynamically breaking the inversion symmetry in ITO via strong perturbation of conduction-band electrons (see Figure 1a). The induced asymmetry enables SHG that is absent under equilibrium conditions. As expected, the generated SHG signal scales quadratically with the THz field amplitude (i.e. linearly with the THz field intensity) and is maximized when the NIR probe is tuned near/above the ENZ wavelength (i.e. > 1250 nm), where the internal field enhancement boosts the effective nonlinear susceptibility [3] (see Figure 1b). Time-resolved measurements show sub-picosecond gating of the nonlinear response, directly following the THz waveform and enabling precise temporal control of the frequency-conversion process. A nonlinear Drude-type model incorporating field-dependent carrier dynamics reproduces the observed behavior and confirms that the dominant mechanism originates from strong-field electronic distortion rather than structural effects.

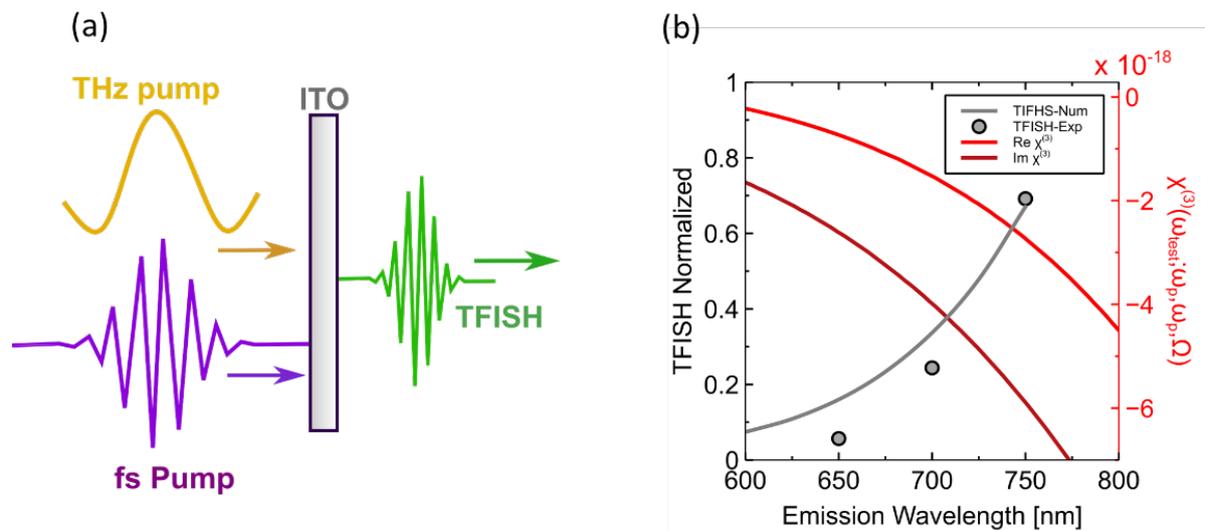


Figure 1 (a) Schematic diagram of the TFISH four wave mixing process in centrosymmetric ITO. The spatial and temporal overlap of a NIR fs pulse and THz pulse results in the emission of a TFISH pulse at double the frequency of the fs pump pulse. (b) The calculated and measured TFISH signal as a function of emission wavelength which scales directly with the third order nonlinear susceptibility of the ITO thin film.

These results establish ITO at its ENZ condition as a versatile platform for THz-programmable nonlinear optics and demonstrate a practical pathway for achieving dynamic χ^2 functionalities in compact thin-film devices. The approach opens new opportunities for THz detection, ultrafast signal modulation, and active integration of ENZ materials into emerging THz photonic architectures.

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Terahertz driven nanosecond dynamics of oxygen defect state in anatase TiO_{2-x}

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Abstract: Oxygen deficient TiO_2 has tunable photocatalytic activity thanks to a large defect state absorption band below the ultraviolet gap. Terahertz short pulses explore the electrodynamics around the oxygen vacancies, where deeply localized charges are converted into long-lived metastable states with potential applications in electro-optic switching devices.

Ultrafast nonlinear terahertz (THz) spectroscopy is applied at the TeraFERMI beamline of the Italian FERMI Free Electron Laser (FEL), where intense (multi MV/cm peak field), broadband (up to 5 THz) and ultrashort (< ps) terahertz (THz) pulses are generated by Coherent Transition Radiation from the relativistic electron bunches of the FEL [1].

The beamline allows addressing the THz nonlinear properties of materials, ranging from quantum materials to bio-chemical samples, by measuring the single(two) color THz pump-THz(infrared) probe response.

Here, we aim at showing an example on titanium dioxide, a largely available and naturally occurring functional oxide, and a benchmark among photocatalytic materials.

Oxygen vacancies in titanium dioxide have a strong impact on its photoactivity, by introducing band-gap states and consequently extending the photoresponse from the UV to the visible light region [2].

We achieved control on the oxygen defect state in TiO_{2-x} , by modulating the infrared response associated to photoexcitation of oxygen vacancies by employing the intense terahertz short pulses delivered by TeraFERMI.

The signatures of the presence of the electronic states associated to oxygen in TiO_{2-x} have been first identified by means of a multi-technique approach, including XRD characterization and steady-state optical spectroscopy from the infrared to the ultraviolet. The time-resolved THz pump/infrared probe measurements allow to explore the polaron-like electron dynamics around these oxygen vacancies, by unveiling the conversion of deeply localized defect states into long-lived metastable states, with a lifetime in the nanosecond range [3].

This approach is completely new, being based on a pump-probe experiment where a sub-gap terahertz pump beam is used for the first time.

Our new finding impacts the exploitation of oxygen deficient titanium dioxide, a functional material largely usable for solar energy conversion, as well as in novel opto-electronic applications.

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SiGe on Si material platform for THz applications

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Abstract: The advantages and challenges of the non-polar SiGe material system as a promising candidate for the development of a THz platform compatible with CMOS technology, as well as the progress achieved so far, will be discussed.

Intersubband (ISB) transitions in semiconductor quantum wells (QWs) enable a broad range of advanced THz electronic and photonic technologies, including high-performance detectors, modulators, and quantum cascade (QC) lasers—key elements for fully integrated photonic platforms.

SiGe presents a unique mix of advantages and challenges compared with III–V semiconductors for THz applications. It is fully CMOS-compatible, allowing monolithic integration with silicon electronics. Its non-polar lattice eliminates the Reststrahlen band, enabling THz emission and absorption in spectral regions inaccessible to III–V materials.

However, the full exploitation of SiGe is still limited by the difficulty of growing high-quality SiGe/Ge heterostructures on Si, due to the mismatch in lattice parameters and thermal expansion coefficients. The resulting epitaxial and thermal strain strongly affects material quality and electronic properties, thereby impacting device design [1,2].

This work reports advances in the growth of rectangular and parabolic QWs in n-type, high-Ge-content SiGe/Ge heterostructures using ultra-high-vacuum chemical vapor deposition (UHV-CVD). We demonstrate precise control over composition, band profile, strain compensation, interface sharpness, and doping—requirements that enable accurate engineering of electronic states in the QWs. The structures were grown on reverse-graded SiGe virtual substrates, with strain-compensation conditions optimized to prevent plastic relaxation of the active region. Composition and conduction-band profiles were tailored by continuously tuning the silane/germane ratio during growth. Structural characterization was carried out using STEM, SIMS, and XRD, while optical properties were evaluated via FTIR spectroscopy.

Rectangular QC structures with Ge wells and SiGe barriers as thin as 2 nm were successfully realized, exhibiting sharp interfaces, controlled dopant profiles at nm level. Recent demonstrations of THz electroluminescence (EL) in Ge/SiGe QWs highlight the potential of this material system for QC lasers [3]. Furthermore, the precise nanometer-scale control achieved during the growth process, together with the resulting high

crystalline quality of the deposited QC structures, paves the way for the next future development of THz QC photodetectors.

Parabolic SiGe QWs with varying widths and doping levels were also grown. Their dichroic transmission spectra show an almost temperature-independent absorption signature, a distinctive fingerprint of parabolic QWs. Moreover, SiGe parabolic QWs embedded in a MIM-cavity architecture reached the ultra-strong coupling regime with the observation of upper and lower intersubband polaritons up to room temperature [4].

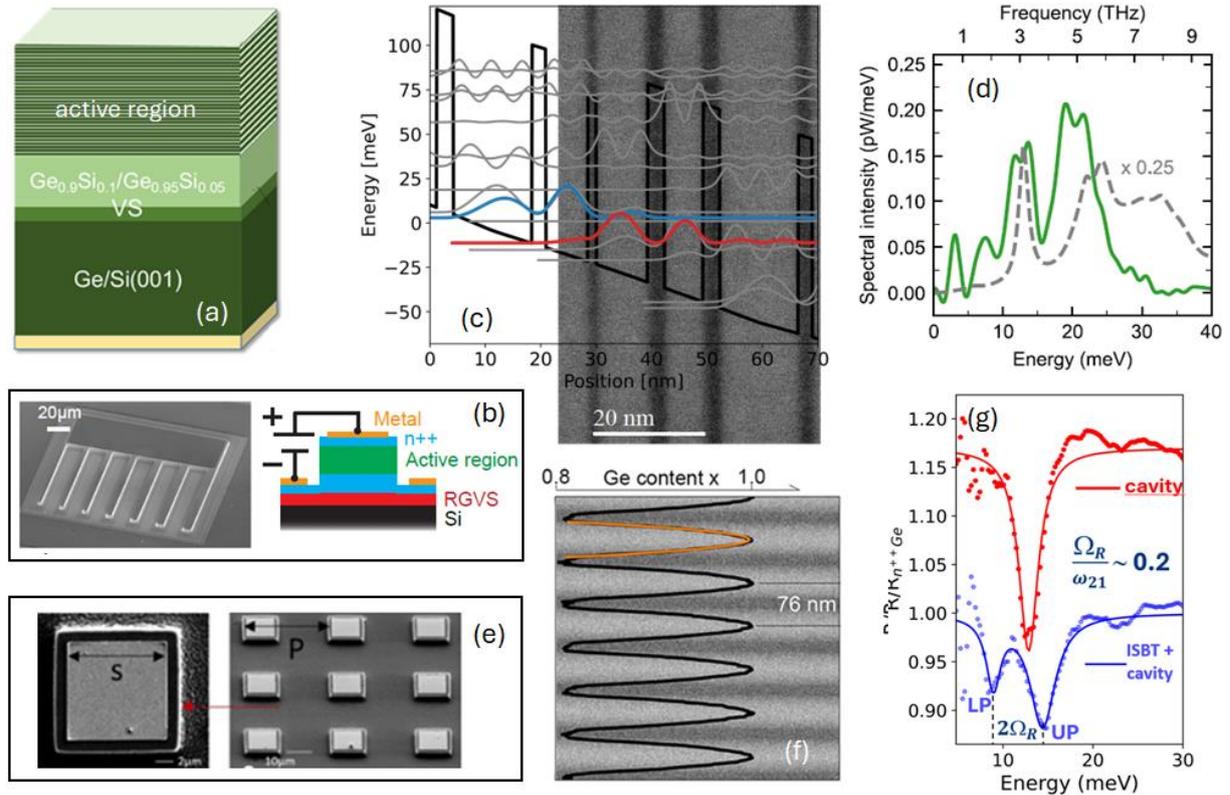


Fig.1 (a) schematics of the deposited samples; (b) SEM image and schematic diagram of the gratings used for EL measurements; (c) Calculated conduction band profile and electronic states (squared modulus) of the QC laser structure superimposed to the STEM image of the sample (d) EL spectrum (green curve) compared to the NEGF simulation (grey dashed curve). (e): SEM images of the arrays of MIM square patch cavities fabricated on PQW sample whose SIMS-calibrated STEM composition profile is shown in (f); (g) Reflection spectra of the bare cavity and of the cavity embedding doped PQWs showing the formation of upper and lower ISB polaritons.

In conclusion, this work demonstrates the capability to realize high-quality SiGe/Ge heterostructures with engineered band profiles using UHV-CVD, marking a significant step toward the integration of SiGe-based quantum photonic devices.

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Dielectric Relaxation Dynamics in Silver Nanoparticle-Doped Chitosan Films

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Abstract: This study explores Ag-NPs-doped chitosan's electro-optical properties using THz spectroscopy. Drude-Smith, Havriliak-Negami, and Cole-Cole analyses revealed increased conductivity and enhanced, broadened relaxation dynamics. These findings demonstrate that Ag-NPs incorporation fundamentally alters chitosan's dielectric mechanisms, suggesting potential for advanced terahertz applications.

Nanoparticle-embedded polymers have emerged as promising candidates, offering a versatile platform to engineer dielectric properties and manipulate THz wave interactions. Chitosan (CT) has garnered significant attention due to its exceptional properties. This study employs terahertz Time Domain Spectroscopy (THz-TDS) to investigate the enhanced relaxation dynamics in silver-doped chitosan nanocomposites, aiming to better understand the influence of the electronic properties and charge transport mechanisms[1].

Ag nanoparticles were synthesized using pulsed laser ablation directly in the chitosan liquid matrix to prepare free standing films. Terahertz Time Domain Spectroscopy served as the primary experimental technique, enabling us to determine the complex dielectric function of our samples over a broad frequency range.

After extracting the dielectric function of the CT and the CT-Ag composite, we used the Drude-Smith (DS) equation to describe the frequency-dependent conductivity of the samples, providing insights into the dynamics of free and bound charge carriers. Moreover, we employed the Havriliak-Negami (HN) equation to model the complex dielectric function, accounting for the distribution of relaxation times(Fig 1,a). From the outcome of the initial analysis, we further investigated the complex impedance and dielectric modulus analysis to gain deeper insights into the electrical relaxation processes taking place in the composites. Finally, to complete and visualize the dielectric response, we utilized Cole-Cole plots, providing a clear graphical representation of the dielectric data and facilitating the analysis of relaxation processes and impedance characteristics(Fig 1,b).

The Drude-Smith model revealed a significant increase in high-frequency conductivity for the composite compared to pure chitosan, attributed to silver nanoparticles and structural defects, while confirming localized charge carriers for both films, which

remained insulating. Havriliak-Negami analysis demonstrated enhanced relaxation dynamics in the composite, evidenced by a decreased relaxation time and a broadened distribution of relaxation times despite both materials exhibiting near-Debye behavior. Furthermore, Cole-Cole plots visually corroborated these findings, transitioning from a Debye-like semicircle in pure chitosan to a distinct quarter-circle with a linear region for the composite, indicating broader relaxation time distributions, interfacial polarization effects, and potential DC conductivity. Complementary complex impedance and modulus analyses further underscored significant departures from ideal Debye behavior in the composite, supporting the role of heterogeneity, interfacial effects, and altered local electric field distributions[2]. These results collectively provide strong evidence that silver nanoparticle incorporation fundamentally alters the dielectric properties and relaxation mechanisms of chitosan, showcasing their potential for advanced terahertz applications.

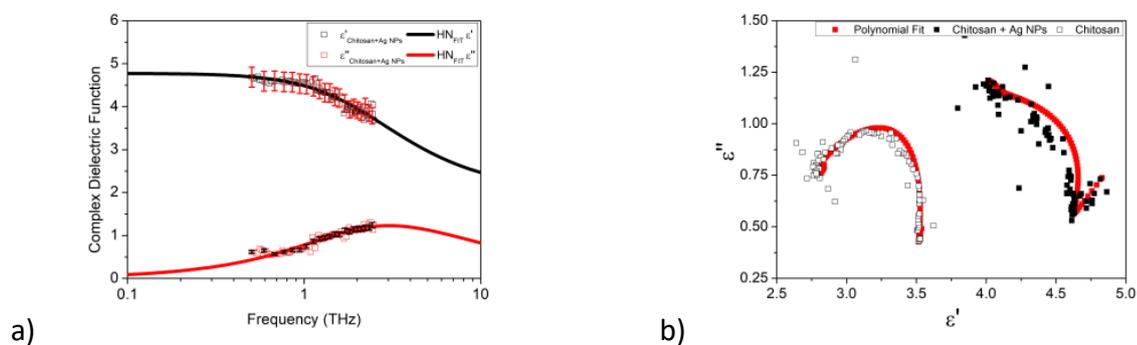


Fig.1 | a, Havriliak-Negami model fits to the complex dielectric function of the silver nanoparticle-doped chitosan composite film. b, Cole-Cole plot for the pure chitosan film and the silver nanoparticle-doped chitosan composite film.

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Doping density and carrier-phonon coupling in tin based perovskites

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Abstract: We use time resolved THz spectroscopy to measure the doping density in tin-based perovskites, where tin oxidation results in a significant background hole population and analyze its effect on carrier phonon coupling and polaron formation.

Tin-based halide perovskites (THPs) have emerged as promising candidates for both photovoltaics and near - IR light emitting applications thanks to their high carrier mobilities low band gap, ideal for pairing with Silicon in tandem solar cells [1]. A key characteristic of THPs is the remarkable stability of acceptor defects such as Sn vacancies and I interstitials, resulting in a large population of self – doping holes that can negatively impact device performance if not adequately managed. As such, it is of critical importance to devise strategies to both quantify and control the dopant hole densities in THPs by compensating the oxidation state of Sn during material fabrication using additives such as SnF₂ [2].

In this context, terahertz (THz) spectroscopy represents a powerful tool to characterize the carrier populations and dynamics in THPs [3]. THz radiation is sensitive to mobile charge carriers [4], as well as their coupling with lattice phonons [5]: this can shed light on charge transport properties in THPs, as low frequency phonons in the THz range have been shown to limit their thermal and electrical conductivity. However, as the doping density affects both transparency to THz radiation and carrier phonon coupling, THz absorption spectroscopies can be used as a sensitive, contactless probe to characterize the self – doping density even in samples where it has been brought down to levels comparable to background carrier densities suitable for device applications (e.g. 10¹⁵ - 10¹⁶ cm⁻³), and that could be challenging to characterize by traditional Hall effect measurements. Furthermore, time resolved THz spectroscopy after optical excitation of the material allows to follow the dynamics of photogenerated carriers with fs temporal resolution enabling the retrieval of radiative and nonradiative carrier recombination rates and identifying the additives effect on defect-assisted carrier recombination.

In this work, we study FACsSnI₃ thin films with both high and low doping concentrations with time resolved THz spectroscopy, and develop a robust technique to study doping

hole density by fitting the THz conductivity with a Drude – Smith model. By supporting our results with DFT calculations, we also investigate the effect of doping concentration and defect states on optical phonon frequencies and their coupling to charge carriers.

Acknowledgements: *The authors would like to acknowledge funding from the ERC grant SOPHY (G.A. 771528), the MSCA – ITN Smart –X (GA 860553), the integrated infrastructure initiative I-PHOQS and the PRIN project HAPPY.*

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Λ -photonic for Terahertz Light -Matter interactions enhancement: from broadband concentration to near-field imaging

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Abstract: We address THz spectroscopy of sub-wavelength samples using field concentration. Broadband and resonant architectures achieve sensing of 10 nL and 1 nL volumes. s-SNOM imaging identifies tip-resonator coupling, establishing a framework THz spectroscopy of sub wavelength samples.

Terahertz (THz) spectroscopy systems are now established commercial products, and the technique has expanded across various scientific fields. Among these, THz spectroscopy has long been considered to have significant potential for biological applications [1]. Indeed, THz vibrational spectroscopy probes delocalized modes at the nanoscale [2]; it follows that the THz spectrum can serve as a fingerprint of the nanostructure of such samples. In biology, proteins are fundamental molecules that drives the functions of living organisms. These functions are determined by their folding, and this folding occurs at the nanoscale. This provides the primary motivation for developing THz spectroscopy for protein analysis, despite challenges ranging from water management to the physical interpretation of measurements [1,3].

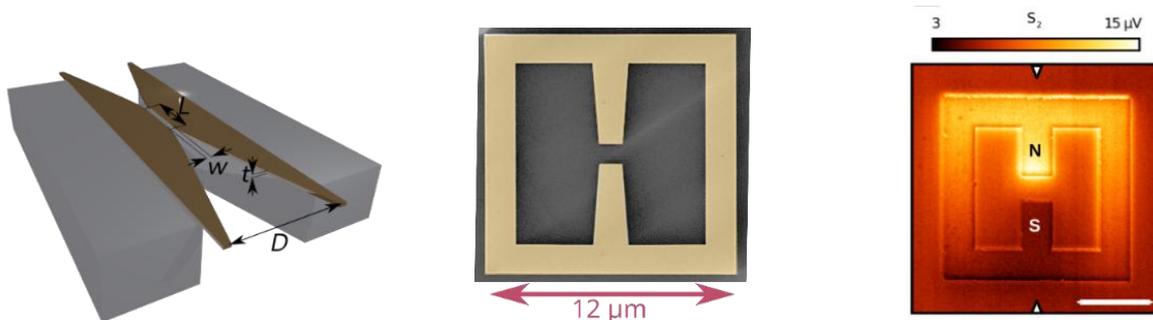


Fig.1 | THz field concentration strategies. **a.** Broadband butterfly device. **(b)** Single splitting resonator for resonant sensing. **(c)** s-SNOM near-field map at 2.5 THz showing the asymmetric electric field distribution due to tip-resonator coupling.

Protein microcrystals are a standard form for structural studies. These crystals consist of approximately 80% water bound to proteins and range in size from tens to hundreds of micrometers, making them sub-wavelength objects in the THz regime. Consequently, it is impossible to focus a standard beam entirely onto the sample, necessitating near-field approaches. In this presentation, I will discuss the analysis of sub-wavelength samples in the THz range and the resulting necessity for field concentration. I will cover broadband configurations, narrowband resonators, and scattering-type scanning near-field optical microscopy (s-SNOM).

To this end, we developed a device combining a thick slot waveguide with two antennas for the injection and extraction of the Time-Domain Spectroscopy (TDS) beam. The metallic slot waveguide supports a TEM mode, characterized by an absence of frequency cutoff and low losses and dispersion. The exponentially tapered Vivaldi antennas maintain a planar geometry while enabling broadband far-field to near-field conversion. This architecture, shown in fig a, enabled broadband spectroscopy of 10 nL samples of lactose and glutamic acid up to 3 THz [4].

To analyze even smaller volumes, further field concentration is required. We utilized split-ring resonators (SRR) with gaps as narrow as 30 nm. By combining these with a specialized data processing approach [6], we achieved the measurement of faint signals (<1‰). This allowed the characterization of single SRRs over more than a decade, from 200 GHz up to 3 THz. By covering a 1.2 THz SRR with glutamic acid, we successfully retrieved the frequency and width of the vibrational resonance in this range [6].

Finally, we analyzed these SRRs using a THz s-SNOM setup equipped with a 2.5 THz gas laser [7]. We imaged the electric field within the gap and demonstrated that metallic devices, acting as scattering element led to a complex response. This is due to the interactions between the s-SNOM tip and the resonator, both of which act as antennas, resulting in asymmetries in the retrieved near-field images.

In summary, we proposed two approaches for THz field concentration: a broadband structure for 10 nL samples and a resonant structure for volumes as small as 1 nL. We further examined the resonant devices, highlighting an antenna-coupling effect between the tip and the resonator. Future work will focus on using these devices to couple SRR resonances with material vibrations to achieve strong coupling, while using s-SNOM to scrutinize hybrid modes in exotic materials.

Acknowledgment:

This work was financially supported by the ERC CoG TUSCany ERC-2022-COG GRANT AGREEMENT 101089040.

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Crack Detection in Pompeii wall paintings using Terahertz Imaging

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Abstract: Sub-THz imaging enables nondestructive analysis of frescoes, revealing internal structures without damaging sensitive artworks. Using a 300 GHz FMCW radar on a robotic arm, we acquired 3D scans of crack on a wall in Pompeii.

Cultural heritage conservation has greatly benefited from nondestructive testing techniques. In this context, imaging with sub-THz radiation due to a penetration of some mm, offers a promising candidate for the determination of the internal structure of ancient artworks that may be very sensitive to light, thermal and/or mechanical stimuli [1]. Among many proposed applications of THz imaging on cultural heritage, we are focusing on the ancient wall paintings (frescoes) and in particular on the delicate and sensitive frescoes found in the city of Pompeii (Italy).

A commercial THz scanner, an FMCW radar operating at 300 GHz (Terascan 300, Lytid SAS, France) mounted on a six-axis robotic arm, was used to acquire three-dimensional images over areas up to 50 mm×50 mm (figure 1). Measurements were performed in a room within the Villa of Diomedes in Pompeii.



Fig.1 | Experimental setup

As an example of structural discontinuity, we show a crack on the wall surface using the parameter map extracted from the fitting procedure (Figure 2). The plotted parameter is sensitive to the height variations, allowing us to investigate not only the surface morphology but also the internal evolution of the fracture.

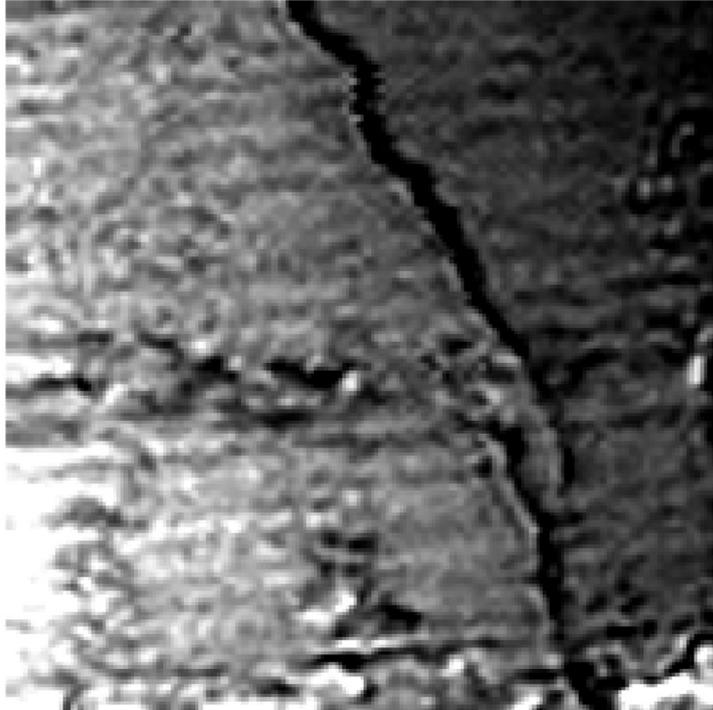


Fig.2 | THz picture of a crack

We thank IIT-CCHT and Pompei Archeological Park for support.

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Probing Ozone Exposure Effects on Different plant species with THz Imaging

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Abstract: This study evaluates Terahertz (THz) imaging for early detection of ozone (O₃)-induced plant damage. Exposure to increasing O₃ concentrations reveals that THz imaging is efficient in detecting subtle ozone-induced physiological changes, providing a promising tool for monitoring plant health and climate-related stress adaptability.

Ozone (O₃) pollution poses a significant threat to plant health, affecting physiological processes and water dynamics. One of the primary physiological effects of O₃ exposure is stomatal sluggishness, which alters water regulation and carbon assimilation, ultimately influencing plant water use efficiency (Paoletti, 2005). Non-destructive techniques such as THz spectroscopy and imaging have emerged as powerful tools for assessing plant stress, offering high sensitivity to water content changes (Rawson and Sunil, 2022).

Here, we investigated ozone (O₃)-induced plant damage using THz continuous-wave imaging through two distinct experimental studies.

The first study (Pagano et al., 2024) focused on two European hornbeam species, *Carpinus betulus* L. (CB) and *Ostrya carpinifolia* Scop. (OC), with the aim of assessing whether THz imaging could identify leaf damage induced by ozone exposure. Experiments were conducted in the field at the O₃ Free-Air Controlled Exposure (FACE) facility in Sesto Fiorentino, Italy, where plants were exposed to three ozone levels: ambient air (AA), 1.5 ×AA, and 2.0 ×AA.

In this experiment, ozone damage was detected by identifying localized spots in THz leaf images appearing as transparent regions. These areas exhibited intensity values comparable to the background, indicating that the leaf tissue was effectively transparent to THz radiation in those points. Such features were interpreted as damaged zones associated with ozone stress. The analysis revealed a higher occurrence and extent of these damaged areas in OC compared to CB, indicating a greater sensitivity of OC to ozone exposure.

The second experiment was performed on *Zelkova serrata*. with the objective of determining whether ozone-induced damage could be detected earlier in the THz range

than in the visible region. THz measurements were carried out before ozone exposure and after one, two, and three months of treatment under the same ozone conditions (AA, 1.5 ×AA, and 2.0 ×AA). The results showed a progressive increase in THz-detected damage over time for all exposure levels. Importantly, clear differences were already observable after two months of exposure, when visual symptoms were still weak or barely detectable, as also shown in figure 1.

Overall, these results demonstrate that THz imaging is an effective tool for the early identification of ozone-induced leaf damage, allowing discrimination between species sensitivity and revealing stress effects before they become evident in the visible domain.

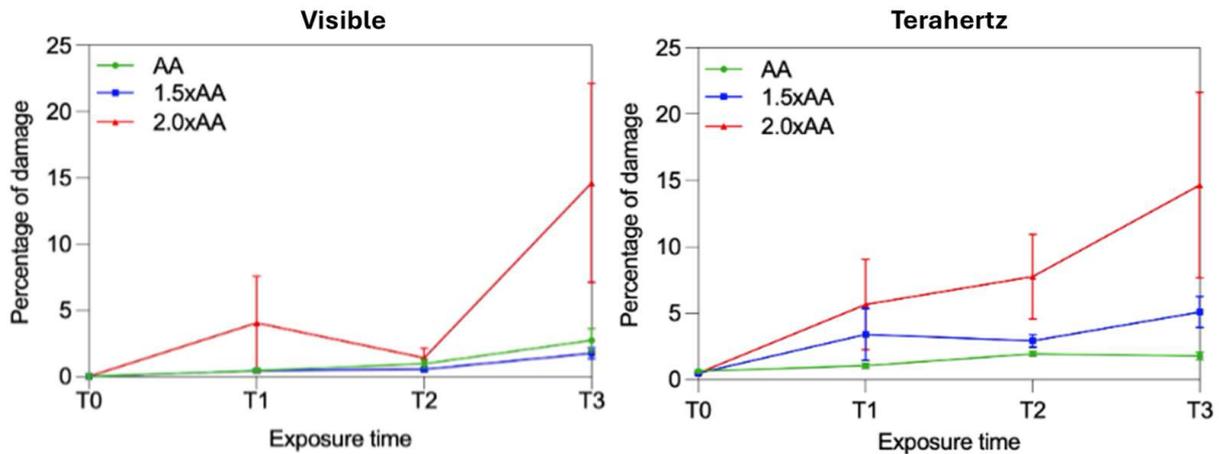


Fig.1 | Percentages of ozone damage as a function of the Ozone exposure time.

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Terahertz Spectroscopic Imaging and Unsupervised Analysis for Multidomain Non-Destructive Diagnostics

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Abstract: THz spectroscopic imaging combined with unsupervised learning was applied to food safety, environmental monitoring, protein identification and artistic stratigraphy, with planned extensions to pharmaceutical aging. The results demonstrate a unified, non-destructive framework capable of extracting structural, chemical and subsurface information with high sensitivity.

THz time-domain spectroscopy enables non-destructive access to structural and chemical features through its sensitivity to refractive index, absorption and layer interfaces. Its versatility spans heritage science, food inspection, environmental analysis and pharmaceuticals, with growing emphasis on coupling THz imaging with unsupervised machine learning to enhance the interpretation of complex datasets.

A multimodal THz framework combining spectroscopy, imaging and unsupervised learning was demonstrated across different application domains.

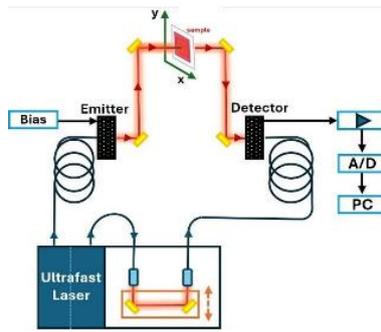


Fig.1 Experimental set up

- Fungal Infections in Chestnuts — Unsupervised machine learning applied to THz absorption features enabled the clustering of infected and healthy regions.
- Microplastics in Soil — Microplastics showed distinct THz spectral fingerprints, allowing correlation-based mapping of polymer distributions.
- Protein Identification — Ferritin, BSA, GFP and silica–protein composites exhibited characteristic signatures in the 0.2–0.5 THz band, separable via PCA and K-means.
- Underdrawings Detection — Graphite underdrawings beneath acrylic layers were revealed using complementary spectroscopic contrast and Pearson correlation.
- Pharmaceutical Aging — Planned analyses will monitor absorption-coefficient evolution to track binder degradation over time.

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Recent Advances in Terahertz Spectroscopy and Imaging for Materials and Cultural Heritage Studies

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Abstract: We present recent advances in THz spectroscopy and imaging for material characterization and cultural heritage. THz-TDS and imaging probed saccharides, ancient paper, 3D-printed photonic structures, and Fano-to-BIC transitions, enabling sub-diffraction, non-invasive analysis of structural and vibrational properties.

In this contribution, we present recent results from the THz research group at the CNR Institute for Complex Systems, Rome. Our work employs THz time-domain spectroscopy (THz-TDS) and imaging techniques [1], across several research areas, using numerical and analytical simulations.

The low-energy vibrational properties of organic materials were investigated for both fundamental studies and cultural heritage applications. A comprehensive THz study of saccharides (glucose, galactose, lactose, cellobiose, cellulose) clarified the interplay of intra- and intermolecular interactions governing their low-energy dynamics [2,3]. THz-TDS measurements of absorption coefficients and refractive indices, after pellet characterization and removal of Fabry–Perot oscillations [4], were compared with density functional theory simulations. Low-energy vibrations were dominated by intermolecular librations and intramolecular motions, with differences among saccharides arising from molecular structure, H-bond networks, and water content.

Studies on ancient paper correlated THz spectral features with hydration levels and degradation state, independently assessed with complementary techniques [5,6]. A mathematical procedure was developed to retrieve optical constants from thin sheets (~100 μm) affected by Fabry–Perot interferences [4]. Time-domain THz imaging probed the stratigraphy of ancient phonograph discs [7].

Using ultrashort-pulse THz sources, we also studied dynamic scattering in 3D-printed photonic structures [8]. Stacked dielectric rods were characterized by THz-TDS and compared with analytical Maxwell solutions. Below 0.3 THz, Mie and Bragg features matched theory; above, printing-induced disorder affected band gaps. Temporal broadening of pulses quantified disorder via a dynamic diffusion model.

Furthermore, the transition from Fano resonances to bound states in the continuum (BIC) was studied in 1D photonic crystal slabs [9]. THz-TDS measurements of 3D-printed structures validated simulations, showing collapse of Fano resonances into high-Q quasi-BICs near normal incidence.

Finally, a super-resolution THz-TDS imaging method was developed for non-invasive cultural heritage diagnostics [10]. Using a knife-edge scan to filter evanescent waves, it achieves sub-diffraction spatial resolution (Fig. 1) and was validated on mock-ups and a medieval parchment fragment.

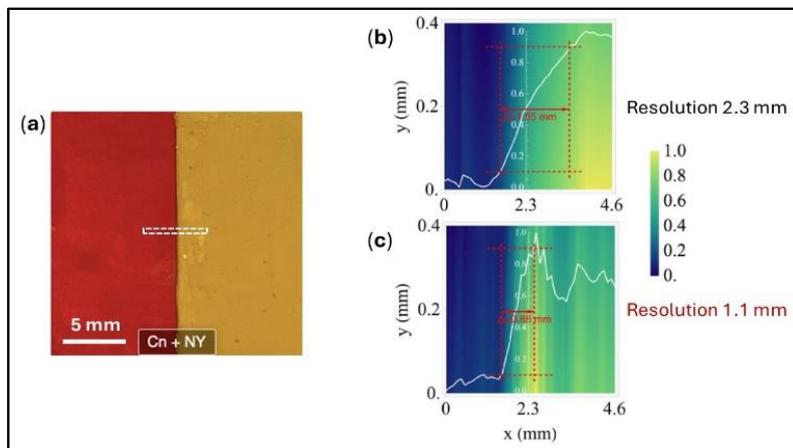


Fig.1 | (a) Mockup target of Cinnabar (Cn) and Naples Yellow (NY) paintings in contact on paper. (b) THz images at 0.3 THz of the dashed area in (a) without knife-edge. (c) Same area with knife-edge. Panels (b) and (c) show THz intensity profiles along x (white curves) and the calculated slope, corresponding to Abbe diffraction limits of 2.3 mm and 1.1 mm, respectively.

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Demonstration of a Transportable QCL-Based Free-Space link for Reliable THz Communications

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Abstract: THz frequencies would enable Tbps links and robust free-space optical communication (FSOC) in harsh environments. We demonstrate the first cryogen-free THz FSOC link, based on a QCL and a graphene-based field effect transistor as the room-temperature detector.

The growing need for multi-hundred-Gbps to Tbps data rates and low latency (less than 10 ms) is driving communication systems toward the terahertz (THz) band. THz waves, less sensitive to Rayleigh scattering than infrared (IR) and visible waves, are well suited for harsh environments and industrial applications. Despite of this favorable feature, the absorption of water vapor in the atmosphere limits terrestrial THz wireless communication (TWC) distances. However, this could even represent an advantage in terms of security for intersatellite links (ISLs) [1]. Free space optical communication FSOC links in the 2–5 THz range have been enabled by high-power QCLs, but both transmitters and receivers still require strong cryogenic cooling [2].

We present a THz-FSOC link based on a 2.83 THz QCL hosted in a compact closed-cycle cryostat. The receiver is a solid-state graphene-based field effect transistor (GFET) operating at room temperature. This marks the first experimental realization of a cryogen-free QCL-based TWC link, offering a portable solution for practical applications. Our TWC link is divided into a transmitter block (TX), an optical free-space channel, and a receiver block (RX), as depicted in Fig. 1.

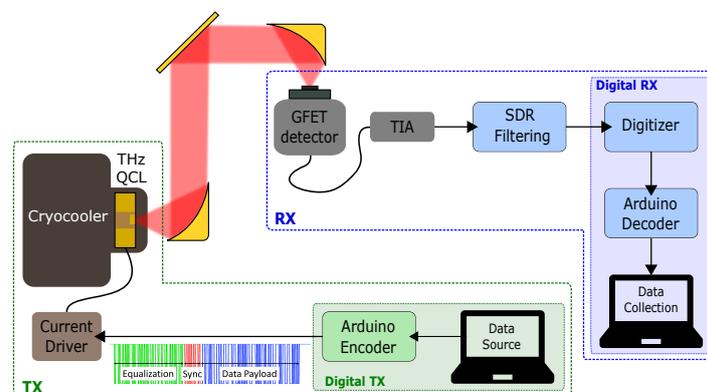


Fig.1 | Schematic of experimental set-up: The lower panel shows TX block diagram, with an ArduinoDUE board depicted to encode the signal. TX block generates a stream of packets,

which are sent through the optical free-space channel that includes a QCL hosted in a Stirling cryocooler, and a room-temperature GFET detector. The upper panel shows the RX block diagram with digital decoding. The output of the GFET detector after passing through a variable-gain TIA, is digitized through a single-threshold Schmitt comparator, and decoded through a second Arduino DUE board, also performing a byte-wise comparison for PER calculation.

A digital board generates a stream of packets at various bit rates, with the digital information encoded by modulating the Terahertz Quantum Cascade Laser (QCL) intensity, using an On-Off Keying (OOK) scheme with Manchester encoding. The 2.83 THz QCL of approximately 1 mW maximum power, is hosted in a compact K353 Stirling cryocooler by Ricor, stabilized at 38.4 K while the QCL is driven by a current of 570 mA. The modulated THz beam is received by the RX stage, where it is converted into an electric signal by the GFET [3]. A variable-gain transimpedance amplifier (TIA) boosts the signal. A software-defined radio (SDR) digital filter removes excess noise before the digitizer/decoder stage on a second RX digital board [4]. This unit determines the received packets, comparing each with a reference message pre-stored on the board, and calculates the Packet Error Rate (PER). The system bandwidth is limited by the current driver at 1.4 MHz, thus we set the gain of the Femto DHPKA-100 TIA considering a trade-off between RX sensitivity and ultimate bandwidth, allowing error-free communication at 1 Mbps. By choosing higher amplification at the cost of lower bandwidth, we test the TWC for 115 kbps, demonstrating error-free communication up to approximately 3 m of distance. To assess the potential of this TWC system, we conducted simulations of the PER versus distance, assuming a QCL emitting a frequency window with reduced water absorption. Our simulations show that longer distances can be achieved with our communication link. This novel cryogen-free TWC system represents a major advancement, being the first with no need of strong liquid-helium cooling at both TX and RX stages. This achievement opens the door to portable, field-ready, and satellite-compatible THz links above 2 THz.

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Tailoring sub-THz Beams by Liquid Crystal Assisted Reconfigurable Intelligent Surfaces

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Abstract: Reconfigurable Intelligent Surfaces (RIS) are on the verge of revolutionizing wireless communications, due to their ability to manipulate the propagation environment and enhance the network coverage. Here, we present the design, the fabrication and preliminary experimental test of a liquid crystal (LC) assisted reflective RIS operating in the mm-wave/THz band.

A typical RIS architecture mainly consists of a planar surface and an external controller. The surface is covered by a periodic array of reflecting or transmitting elements (single cells or macrocells), each of which can independently impose, using the controller, the required phase shift on the incoming electromagnetic signal [1]. In the mm-wave/THz spectral range PIN diodes and varactors, which are currently employed for the electronic control of metasurfaces in the microwave region, can hardly be as tuning elements because of their inherent large size and low operational frequency [2]. Liquid crystals (LC), instead, address these limitations offering a low-loss and continuously tunable alternative that remains effective at very high frequencies. LC anisotropy permits electrically controlled phase modulation with minimal perturbation of the metasurface resonance. LC-based tuning, however, is inherently slower (on a time scale of milliseconds) than semiconductor technologies and requires precise LC alignment and electrode design. Nevertheless, LCs currently remain a compelling and practical choice for THz programmable metasurfaces due to their broadband tunability and compatibility with large-area fabrication, which can be leveraged by utilizing display technology.

The proposed RIS is composed of several layers, including an array of conducting "meta-atoms" on quartz, the intercalated LC, and a reflecting ground plane on quartz again. The meta-atom pattern is based on a complementary split ring resonator (CSRR) made of a 300 nm thick aluminum thin film, so that the overall array provides high reflectance and the single unit cell achieves the desired metasurface response. The LC has high birefringence ($\Delta n \approx 0.38$) and low loss (absorption coefficient $< 10 \text{ cm}^{-1}$ for both ordinary and extraordinary polarization) at the considered frequency range [3], and it fills the gap (25 μm thick) in between the upper and lower quartz substrates. The design enables a phase difference close to π in correspondence with the working frequency nominally set at around 300 GHz, due to the LC molecules re-orientation. The designed RIS device is realized using UV lithography and LC filling/assembling techniques. To avoid accelerated aging and potential device damage caused by charge accumulation in the liquid crystal layer under DC bias conditions, a square wave operating at 20 V and 1 kHz is generated.

Defining the state having a different phase response as state 0 and state 1, a 1-bit programmable RIS is obtained. We present the amplitude and phase response of the device as a function of frequency at 0 and 1 state respectively, under a linearly polarized incident wave. RIS characterization is carried out using a THz time-domain spectrometer (TDS) equipped with photoconductive antennas for emission and detection and an optical setup with polymeric (TPX) lenses. Measurements are conducted in reflection mode with a variable detection angle θ or with a normal configuration ($\theta = 0$). The design and fabrication of the metasurface consisting of the CSRR array, the TDS characterization setup, and the first experimental results are briefly summarized in Fig. 1.

A complete RIS prototype, comprising 16 independently controlled channels, is currently under characterization enabling multi-channel beam steering and advanced dynamic reconfiguration. To verify the two-dimensional beam scanning capability, we will measure the far-field normalized scattering patterns in both x - z and y - z planes (z being the beam direction) for different coding sequences.

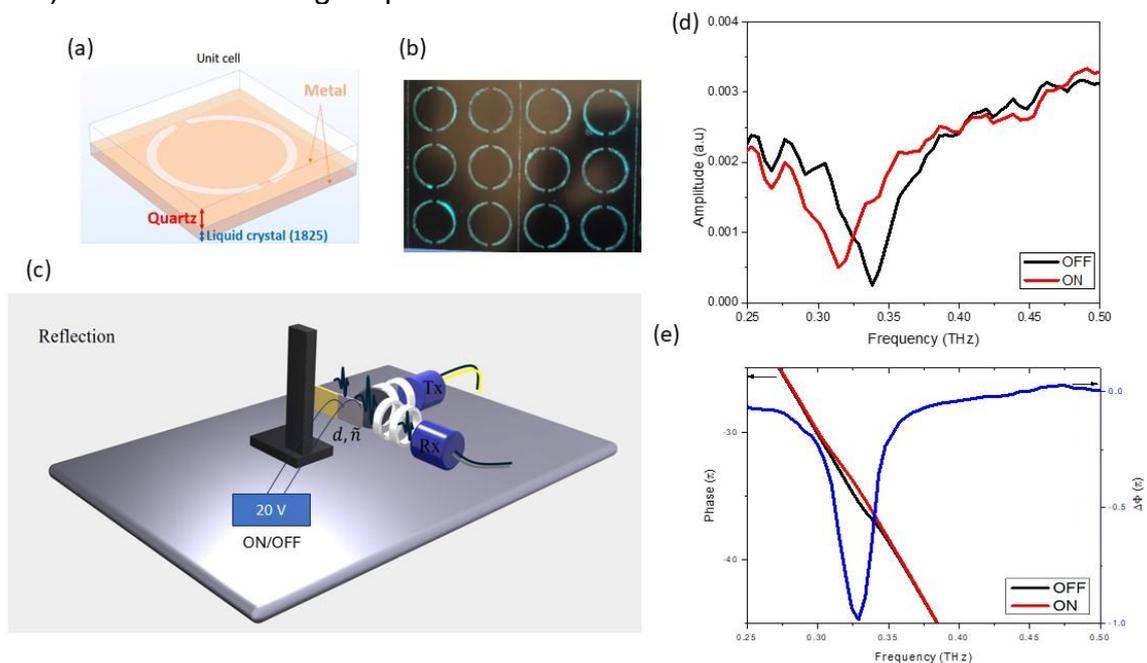


Fig. 1 | (a) design of the “meta-atom”; (b) picture of the upper layer showing a detail of the CSRR array; (c) pictorial scheme of the TDS setup; (d), (e) measured response (amplitude and phase respectively) vs frequency at $\theta = 0$ for a single coding sequence (000... or 111...).

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Photonics at Space–Time Interfaces for Advanced THz-Wave Manipulations

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Abstract: We present a theoretical study of electromagnetic wave scattering at a space–time interface, a subwavelength slab with Lorentz-type dispersion whose plasma frequency experiences an abrupt temporal change. Our analysis uncovers several unconventional photonic effects induced by this spatiotemporal discontinuity, highlighting new opportunities for compact and ultrafast THz photonic devices.

We investigate wave scattering at a space-time interface. i.e., a thin dielectric slab characterized by Lorentz-type dispersion, whose plasma frequency undergoes an abrupt temporal change. Remarkably, the temporal discontinuity in plasma frequency triggers unusual phenomena. We have developed a semi-analytical theory demonstrating that a space–time interface enables linear frequency generation at all wave modes supported by the medium [1]. The temporal discontinuity can excite waves at the system's intrinsic resonance frequencies ω_0 , and at the epsilon-near-zero (ENZ) crossing points, corresponding to Ferrell–Berreman modes. Furthermore, unlike conventional approaches that rely on spatial structuring (such as gratings or prisms), our method shows that incident propagating waves can directly excite evanescent modes triggered by a sudden temporal boundary. In Fig. 1, we report the incident, reflected and transmitted wave-packet spectra, normalized with respect to the peak value of the incident one, in the Transverse-Electric (TE) case with an angle of incidence $\theta_{in} \approx 24^\circ$ and center frequency $\omega_{in} = 2.5 \omega_0$. The arrival of the wave-packet is synchronized with the occurrence of the plasma frequency switching. The peaks associated with the excited modes $\pm\omega_0$ lay inside the area highlighted with red shading, which represents the evanescent spectral range. Conversely, in absence of the time-switch, such modes would not be excited. We also investigate spin-dependent effects occurring at a space–time interface [2]. A purely temporal interface induces phase-conjugated backward waves and leads to anomalous spin conversion. When both spatial and temporal boundaries are present, the scattered field results from their combined action, forming a superposition of the incident wave's polarization and its phase-conjugated counterpart. Remarkably, this mechanism enables polarization conversion without the need for bi-anisotropy, chirality, or nonlinear effects. It is now worth mentioning that all our results are supported and validated by full-wave simulations. Finally, we discuss potential implementations in realistic

material systems, emphasizing that the investigated parameters are compatible with standard semiconductor platforms operating at terahertz frequencies [3-5].

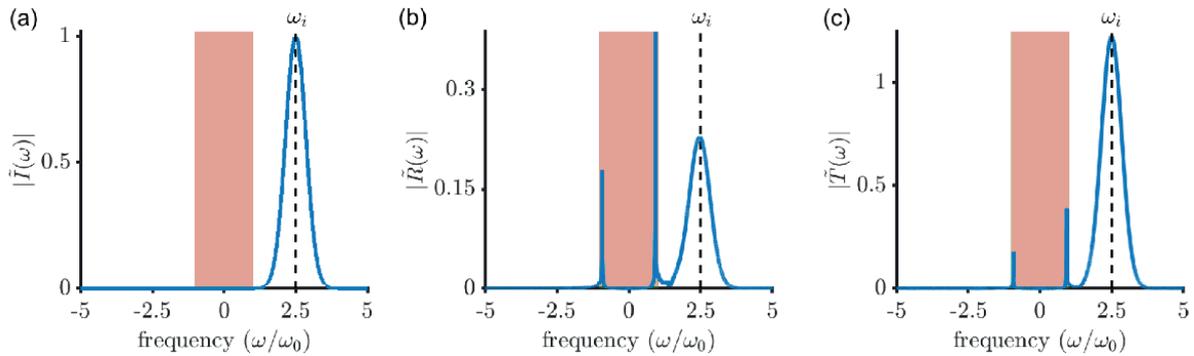


Fig.1 | Normalized spectra of the incident **(a)**, reflected **(b)**, and transmitted **(c)** wave packets; the dashed vertical lines represent the carrier frequency of the incident field. All spectra are normalized with respect to the peak value of the incident one. The area highlighted with red shading represents the evanescent spectral range.

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Modeling of electromagnetic wave propagation in semimetals

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Abstract: We describe a Finite Element Method formulation for the analysis of arbitrary layers of semimetal deposited on a substrate. The magneto-electric coupling has been introduced by axion electromagnetics. Numerical results indicate in some cases non reciprocal propagation in the form of anisotropic plasmons.

Weyl and Dirac semimetals may be considered a new frontier of non-trivial topological materials [1]. Their unconventional electromagnetic properties may open the way to applications in mm-wave, sub-THz and optics, such as new types of isolators and circulators, but also in thermal engineering (non-reciprocal thermal emission) [1-3].

The purpose of this paper is to set up a numerical modeling of electromagnetic propagation in semimetals. In some cases, the problem has been studied quite extensively in the past (e.g. graphene, a 2D Dirac semimetal), but in other cases there is basically no data available in the literature, whose focus is on the band structure and the corresponding physical properties.

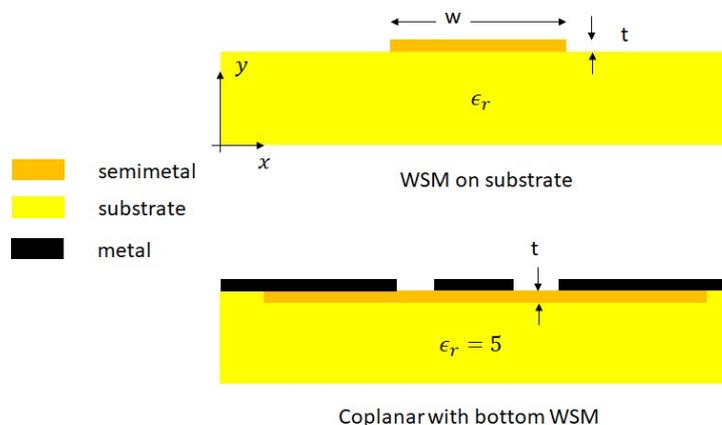


Fig.1 | The cross-sections of the structures analyzed.

However, an accurate modeling of wave propagation can be important in practical applications, especially in the sub-THz and THz frequency range. It should be noted that the specific form of magneto-electric coupling does not allow the use of commercial software and even by introducing some simplifications, the numerical performance of currently available commercial software was observed to lack of robustness.

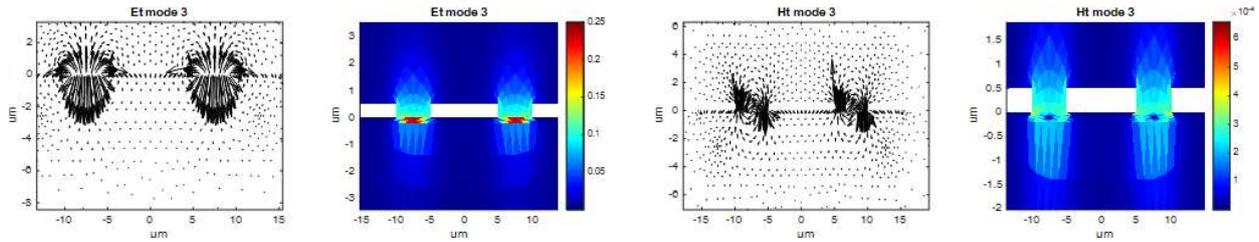


Fig. 2. A mode propagating in the semimetal

For these reasons we have developed a custom numerical modeling of propagation in general semimetals based on the Finite Element Method (FEM). We discuss in this work the application to Weyl semimetals. The equation of propagation is derived in the frame of Maxwell's equations, obtained from a modified Lagrangian that includes the axion term [4]. The final result, after some manipulations, can be written as:

$$\begin{aligned}\nabla \times \mathbf{E} &= -j\omega\mathbf{B} \\ \nabla \times \mathbf{B} &= j\omega\mu_0\mathbf{E} - \frac{j\mu_0 e^2 \omega_e}{2\pi^2 \omega \hbar} \nabla \times \mathbf{E} + \frac{\mu_0 e^2}{2\pi^2 \hbar} \mathbf{k} \times \mathbf{E}\end{aligned}$$

The second term in the right-hand member of the second equation represents the chiral magnetic effect, whereas the last term represents the contribution of anomalous Hall current.

The discretization of the corresponding weak form is straightforward and it leads to a sparse non-symmetrical matrix equation that is solved by standard routines. The structures analyzed are shown in Fig. 1. An example of anisotropic plasmons is shown in Fig. 2. A more detailed discussion on the various modes is presented at the meeting.

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Nonlinear phonon-polaritonic flat-optics for temporal edge detection in the THz

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Abstract: Edge detection is a crucial application of nanophotonic platforms for signal processing. Temporal edge detection with a nonlinear phonon-polaritonic sheet is theoretically demonstrated, detecting optical events through rectification to the THz. The performance is optimized by resorting to a metasurface- $\chi^{(2)}$.

Recently, emerging nanophotonic metadevices of sub-wavelength thickness have been proposed as an alternative to bulky diffraction-limited optical systems for image processing, providing high sensitivity, broadband response and compactness for functionalities such as spatial boundary detection, which is a key issue for applications in microscopy, computer vision or automation [1]. In time domain, edge detection allows for the recognition of events occurring in an optical signal over time, a task for which metamaterial-based technology could entail an ulterior innovative approach by engineering the spectral response of the system at will. In this work, a theoretical concept for temporal edge detection in a flat nonlinear slab with second-order nonlinearity $\chi^{(2)}$ is presented; the events to be detected are contained in one or two time-dependent near-infrared (NIR) images impinging on the nonlinear layer where, via the $\chi^{(2)}$ -mediated difference-frequency generation (DFG) process in the vicinity of phonon resonances, the time domain derivative of the optical envelope is imprinted on the temporal profile of the nonlinearly generated terahertz (THz) signal. The results are supported by full-wave numerical simulations and an AlGaAs metasurface is proposed to enhance the nonlinear THz event detection signal with respect to that of the unpatterned thin film.

As a reference scenario, a spatially uniform non-centrosymmetric dielectric sheet concentrated at $z = 0$ is considered in the limit of vanishing thickness (Fig. 1a). Assuming that the latter contains a single non-vanishing $\chi^{(2)}$ tensor component, $\chi_{yxx}^{(2)}$, with a linear dispersion in the THz frequency range, the second-order nonlinear THz polarization density induced in the sheet through the interpulse DFG between two x -polarized NIR pumps corresponds to a THz carrier modulated by the first-order temporal derivative of the product of the two input optical envelopes. Fig. 1b shows the analytic solution to this reference scenario for the case in which both input optical signals have the same Gaussian temporal profile. The assumed dispersion of the ideal $\chi_{yxx}^{(2)}$, which linearly

crosses its zero value at 4 THz, enables low-frequency filtering around such a THz carrier frequency, retaining only high-frequency components in which the event occurrence is encoded. As such, the induced THz polarization density, and thus, the radiated field peak at the instants when the optical envelopes' product undergoes the most rapid variation.

To showcase a more realistic scenario, an AlGaAs thin film is considered and the temporal edge detection experiment is numerically evaluated via finite-element method (FEM) simulations. Remarkably, the coupling of THz light to infrared-active transverse-optical phonons yields a highly dispersive bulk $\chi^{(2)}$ of polar semiconductors in the THz region, whose real part shows a quasi-linear dispersion at certain frequencies and thus makes these materials promising candidates for optical event detection. The simulation results are reported in Fig. 1c for a 400 nm thick [001]-cut AlGaAs slab (black curve) and an AlGaAs nanopillar metasurface of the same thickness (pink curve), both standing upon a [0001]-Al₂O₃ substrate. The input optical information signal is a rectangular pulse whose rising and falling edges are precisely highlighted by the nonlinearly reflected THz electric field, which shows a 2-fold enhancement in the case of the metasurface.

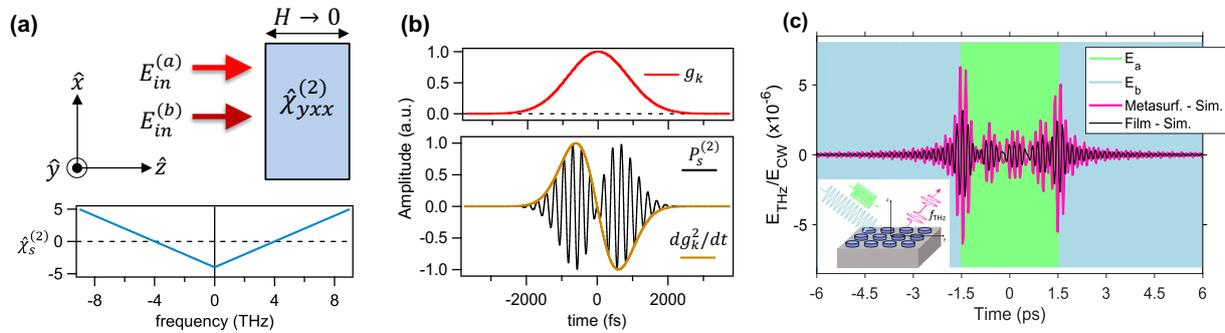


Fig.1 | **a** Top: vanishing-thickness slab together with the wavevectors for the incident fields and the laboratory frame. Bottom: dispersion of the ideal sheet nonlinear susceptibility in the THz region. **b** Top: temporal envelope of the two input Gaussian optical pulses in the ideal reference scenario. Bottom: normalized THz polarization density resulting from DFG (the yellow curve represents its THz envelope). **c** Full-wave simulation results for edge detection in a 400 nm thick AlGaAs film and nanopillar metasurface (pillar radius of 160 nm and period of the square lattice of 400 nm), upon sapphire. The green and blue backgrounds represent the two TM-polarized optical input signals, i.e. a rectangular pulse and a continuous-wave pump, respectively (not on scale). The two optical carriers are separated by 5.6 THz, frequency around which the real part of AlGaAs' DFG- $\chi^{(2)}$ shows a linear dispersion around a zero-crossing point. Adapted from [2].

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Temperature-dependent birefringence behavior of NdGaO₃ probed by terahertz spectroscopy

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Abstract: Time domain THz spectroscopy has been applied to measure the complex refractive index of Neodymium Gallate (NGO) samples. Temperature-dependent refractive index and birefringence properties of samples have been measured in the interval ranging between room temperature and 70K.

Neodymium Gallate (NGO) is a valuable crystal mostly employed for the epitaxial growth of thin films of current interest like Neodymium Nickelate NdNiO₃ [1], presenting a metal to insulator transition at liquid nitrogen temperatures, or GaN [2], since it provides a hetero-interface keeping film roughness as low as 0.5 nm. Similarly, NGO can be also used to deposit high-temperature superconductors [3], since it offers structural matching, low thermal expansion mismatch and low dielectric loss, or to fabricate Y: ZrO₂ thin films with an accurate control of the crystallographic orientation, strain and domain structure [4]. For all these reasons, it might be a useful practice to characterize this material in the THz region, to verify its feasibility for the development of novel devices operating at ultra-high frequencies.

By employing THz time domain spectroscopy, we measured the electromagnetic response of a NGO (110) slab in the frequency range (0.3 – 2.3) THz. By studying the variation of the complex transmission $\tilde{T}(\omega)$ for different temperatures and crystal orientations, we have observed that the sample shows birefringence and dichroic characteristics. In Fig.1 some data showing the temperature dependance of the NGO refractive index (real part) and its birefringence are reported.

Cooling – Down Approach

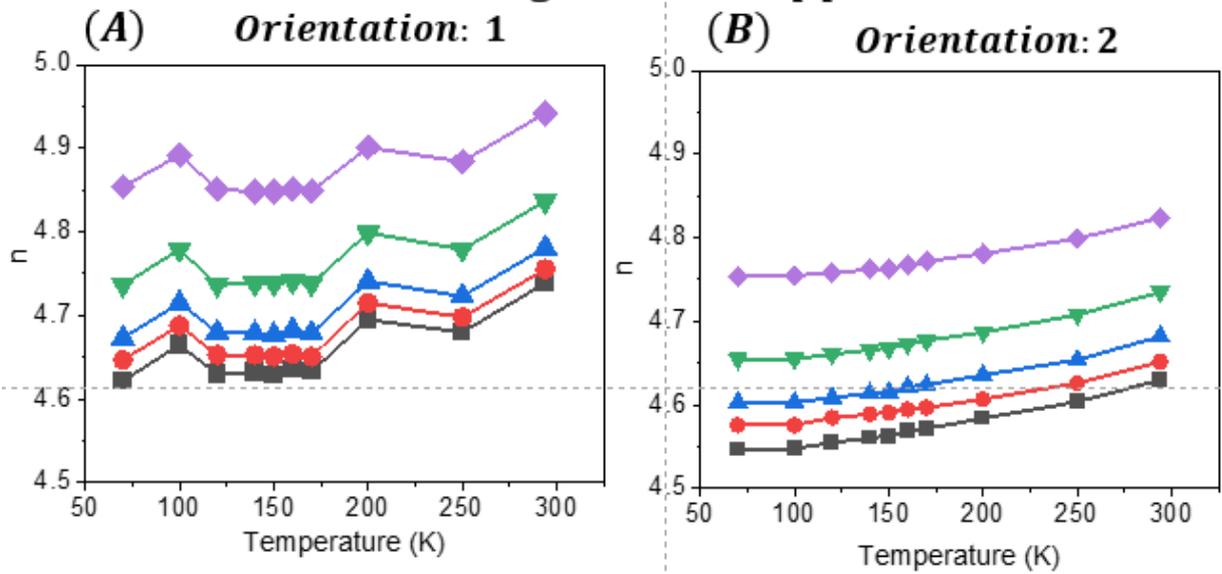


Fig.1: Temperature dependence of the NGO refractive index at a frequency range (0.3 – 2.3) THz for the two perpendicular orientations of the crystal.

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Unveiling the Semiconducting Properties in Four Different Metal Triphenylenehexathiol-based Metal-Organic Frameworks

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Abstract: Optical Pump-THz Probe analysis of charge transport reveals semiconducting behavior in THT-based 2D MOFs, showing increased photoconductivity after excitation and dispersive spectra well-described by the Drude-Smith model.

Metal-organic frameworks (MOFs) constitute a class of hybrid coordination polymers consisting of metal ions connected by organic ligands. The intrinsic porosity of these structures, that gives an extraordinary surface area per unit volume, has resulted in a natural appeal to use MOF in gas sieving and storage. Thanks to the recent discovery of the unique combination of the high porosity and electrical conductivity in materials that were seen essentially as insulators, we have begun to explore yet other broad areas of potential applications of MOFs as active elements in optoelectronics and chemiresistive sensing, but also in electrocatalysis and energy storage [1].

In particular, 2D layered MOFs and especially graphene analogues MOFs have been reported to have high conductivity [2,3]. Among those example, we shall mention MOFs based on triphenylene linkers. In this work we interrogate a broad family of triphenylenehexathiol (THT) MOF, prepared with four different transition metal cations (Fe, Co, Ni and Cu), to analyze their electro-optical properties in the attempt to establish a more clear relation between the metal centers and the charge transport.

Optical Pump-THz Probe (OPTP) represents a powerful technique to study the complex-valued photoconductivity of these materials in a fully non-contact fashion (Fig. 1a). All of the samples present a semiconducting response, predicted by DFT analysis and hereby demonstrated by the increase of conductivity upon light excitation (Fig. 1b). Photoconductivity spectra obtained from OPTP, revealed also a characteristic dispersion that can be adjusted with the Drude-Smith model (Fig. 1c).

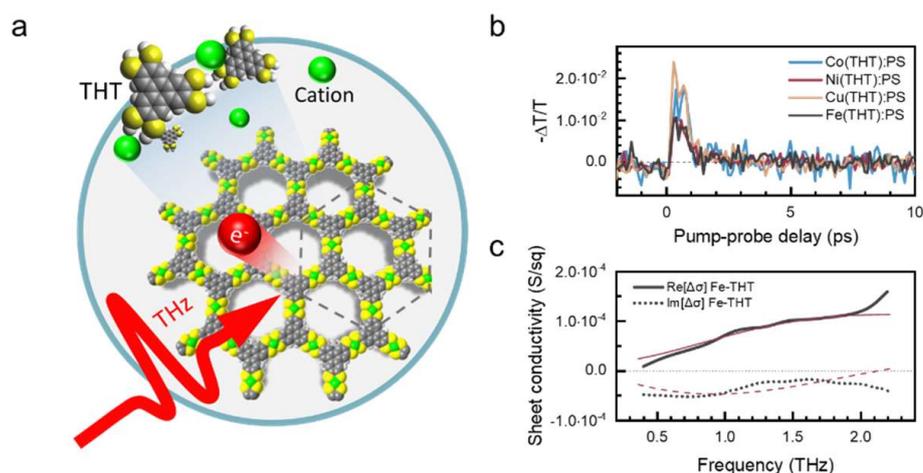


Fig.1 | a) Graphical representation of metal triphenylenehexathiol (M-THT) MOFs irradiated by THz light. b) Differential transmission in (M-THT) MOFs measured via OPTP. c) Frequency resolved photoconductivity in Fe_2THT_3 MOF (black) and fit according to the Drude-Smith model (burgundy).

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Transient Terahertz Polaron Conductivity of Magnetite

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Abstract: After a brief discussion of the polaron concept, the static and transient terahertz conductivity across the Verwey insulator-to-metal transition of magnetite, the textbook example of polaron physics, is presented.

Although the concept of polaron was introduced by Salomon Pekar in 1946 to describe a composite quantum object consisting of a charge carrier dressed by a cloud of virtual phonons (lattice polaron), its meaning was quickly expanded to include other couplings, such as spin waves (magnetic polaron), eventually leading to the introduction of more complex states where electric charges form bipolaron or multipolaron quasi-particles. Polarons significantly influence the equilibrium electrical conductivity and optical properties of materials, being fundamental to reduced charge mobility and to induce metal-to-insulator transition (MIT) phenomena. In this talk, after a brief overview of our research on polaronic physics [1,2,3], we will discuss both equilibrium and transient (time-dependent and non-linear) terahertz properties of lattice polarons. In particular, we will present examples of polaronic behavior in magnetite (Fe_3O_4) [4], utilizing advanced static and pump-probe Terahertz optical techniques.

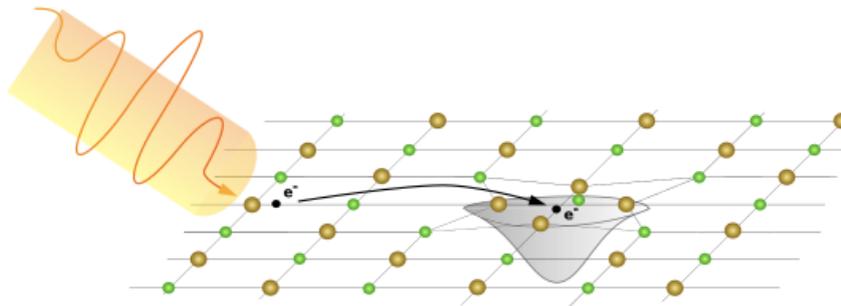


Fig.1 | A metastable polaronic charge survives over hundreds of nanosecond time scale in magnetite after a femtosecond photodoping.

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Advancing atmospheric pollution monitoring with airborne THz spectrometer

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Abstract: This study presents a UAS-mounted THz-CW system for spatially resolved in situ spectroscopy for air-quality monitoring. Ground tests verified detection of multiple volatile organic compounds, and flight experiments demonstrated remote gas sampling. The system enables precise, real-time pollutant monitoring across diverse environments, supporting improved environmental and public health assessment.

Accurate, real-time detection of atmospheric pollutants is essential for advancing environmental monitoring and safeguarding public health. Terahertz (THz) spectroscopy offers strong chemical specificity for gas-phase detection, but its integration into airborne systems has remained limited [1]. To address this challenge, we developed an airborne terahertz continuous-wave (THz-CW) spectrometer integrated with an unmanned aerial system (UAS), reported in Fig. 1.



Fig.1 | a) The assembled UAS-THz-CW system in ground station; b) and c) in flight during in-field trials for stability test; d) UAS-THz-CW system in flight during remote sampling with the 5-meter aspiration tube for the collection of the targeted analyte.

This system's performance was rigorously assessed through a two-phase validation process, beginning with controlled laboratory and ground-based experiments [2]. With the stationary drone, reagent-grade pollutants were individually introduced into a sampling cell, and absorption spectra were recorded. These spectra consistently showed excellent agreement with laboratory data and published literature, confirming the system's ability to identify target VOCs under controlled conditions. Building upon this foundational validation, a series of in-flight measurements was subsequently conducted adopting an aspiration-based sampling method: an onboard aspiration pump and electronically controlled valves were activated to draw atmospheric analytes directly into the gas chamber. This configuration enabled the remote detection and quantification of individual gaseous species as well as multi-component mixtures. The resulting in-flight spectra displayed clear, characteristic THz absorption features consistent with reference databases, demonstrating reliable chemical identification even in dynamic airborne

environments. The system also successfully resolved and quantified individual constituents within multi-component mixtures through a multiple absorber fitting approach (Fig. 2), highlighting its potential for real-time analysis of complex atmospheric samples. This proof-of-concept study shows that an airborne THz spectrometer mounted on a drone can successfully perform remote atmospheric sensing [3]. By combining THz continuous-wave spectroscopy with unmanned aircraft and aspiration-based sampling, the system enables efficient, spatially resolved detection and measurement of gaseous pollutants in areas that traditional instruments cannot easily access.

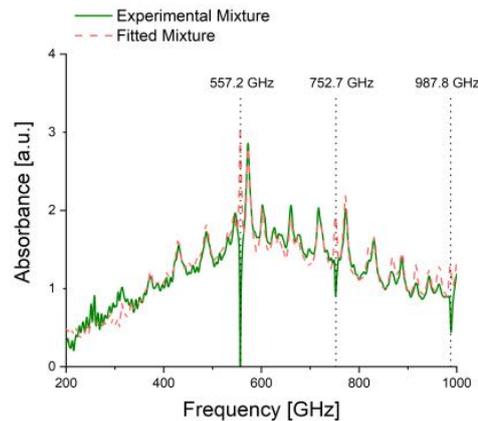


Fig.2 | Comparison between the experimental five components mixture aspirated inside the sampling cell and the spectrum obtained from the retrieved coefficients in the range 0.2-1 THz.

Acknowledgments

The authors acknowledge the contributions of all collaborators to this work: A. Curcio, C. Merola, D. Francescone, M. Magi, M. Coppola, L. Giuliano, M. Migliorati, M. Reverberi, L. Mattiello. This work was carried out thanks to "PRIN 2022: TREX a prototype of a portable and remotely controlled platform based on THz technology to measure the one health vision: environment, food, plant health, security, human and animal health" funded by the European Union - Next Generation EU (CUP B53D23013610006 - Project Code 2022B3MLXB PNRR M4.C2.1.1) and was supported by Sapienza Large Projects Research Call 2021 titled "R-SET: Remote sensing for the environment by THz radiation" Large Research Projects of Sapienza, University of Rome.

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Lattice dynamics and carrier transport in HgPSe₃ by THz time domain spectroscopy

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Abstract: In this work we exploited THz time resolved spectroscopy to investigate the interaction between low energy lattice dynamics and charge carrier transport in a bulk layered semiconductor: HgPSe₃.

In recent years, significant interest has emerged regarding a new class of layered van der Waals materials: the metal phosphorus trichalcogenides (MPX₃). This attention stems from the momentum generated by graphene and transition metal dichalcogenides (TMDs), as MPX₃ materials offer a way to overcome some limitations of TMDs [1].

Among this family, mercury phosphorus triselenide (HgPSe₃) stands out for its photoconductive performance, driven by a direct bandgap near 2.0 eV at room temperature positioning HgPSe₃ as a strong candidate for fast, broadband photodetectors [2]. Despite this potential, there is not yet a fundamental understanding of the material's ultrafast properties, particularly regarding the interaction between charge carriers and the low energy collective lattice dynamics, such as the shear and breathing modes of the layered structure.

In this work, we employ ultrafast Terahertz Time-Domain Spectroscopy (THz TDS) to investigate the microscopic scattering mechanisms governing charge transport and recombination in bulk HgPSe₃. With both static transmission and optical pump-THz probe experiments, we disentangle the interplay between low-energy vibrational modes and carrier conductivity.

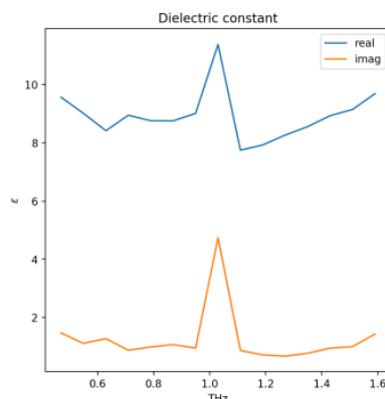


Fig.1 | Static dielectric constant of HgPSe₃

Static measurements in the 0.5–1.5 THz spectral window reveal distinct resonances identified as interlayer breathing and shear modes, Figure 1. Subsequently, time-resolved

measurements probe the transient photoconductivity following ultrafast excitation. The spectral response reveals a complex conduction mechanism, characterized both by a Drude-like free carrier transport and strong localization effects driven by the coupling to the vibrational modes previously identified, Figure 2.

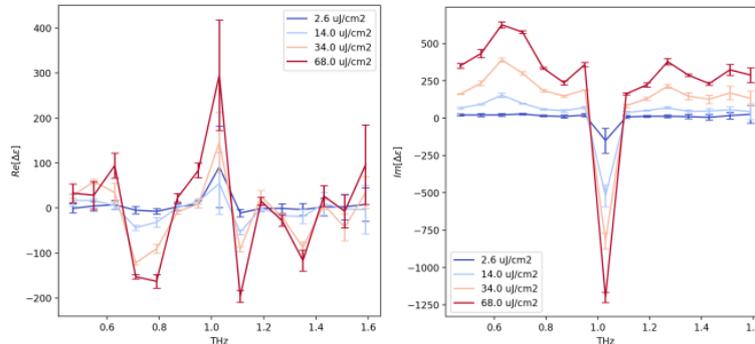


Fig.2 | Real and imaginary part of the transient dielectric constant at different fluences

This work's aim is to set a starting point over the study of such low energy vibrational modes and their interaction with the transport dynamics of layered semiconductors with the aim of improving their optoelectronic performance.

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