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.

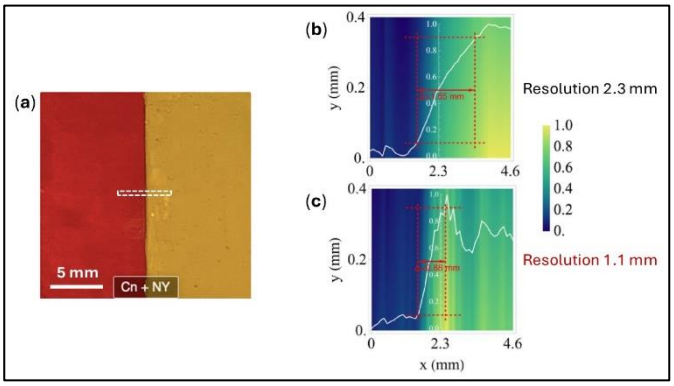

Fig.1 | (**a**) Mockup target of Cinnabar (Cn) and Naples Yellow (NY) paintings in contact on paper. (**b**) THz images at 0.3 THz of the dashed area in (**a**) without knife-edge. (**c**) Same area with knife-edge. Panels (**b**) and (**c**) show THz intensity profiles along x (white curves) and the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

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