Terahertz Near-field Nanoscopy Based on Self-mixing Interferometry with Quantum Cascade Resonators

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Terahertz Near-field Nanoscopy Based on Self-mixing Interferometry with Quantum Cascade Resonators

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Near-field imaging techniques at terahertz frequencies (0.5-10 THz), conventionally rely on bulky laser sources and detectors. Here, we devise a compact configuration for scattering near-field nanoscopy based on quantum cascade lasers (QCL) that can simultaneously act as powerful THz source and phase-sensitive detector, exploiting optical feedback interferometry [1], (see Fig 1a). Self-detection is based on the reinjection of the field scattered by the AFM tip into the laser cavity causing coherent interference. The near-field scattering is measured through the induced changes in the contact voltage of the QCL. By changing the path length with a movable mirror, self-mixing interference fringes are acquired and allow to retrieve both the amplitude and phase of the scattered field giving access to the complex-valued dielectric response of the sample [2]. Interestingly for imaging applications, this detection approach is fundamentally limited only by electron transport in the QCL allowing for fast image acquisition.

Here, we analyse amplitude and phase-sensitivity as a function of the driving current and feedback attenuation (Fig. 1b) using a single-mode Fabry Perot THz-QCL coupled to a s-SNOM, demonstrating fast (ps), sensitive (SNR>15) and high resolution (50 nm) nanoscopy of nanostructures and 2D nanomaterials.

Furthermore, we providing the first demonstration of self-mixing detection and s-SNOM with electrically-pumped, surface emitting random THz-QCL [3] exploiting a disordered arrangement of scatterers, lithographically patterned on the top laser surface, that act as light out-couplers [4], Fig.1c. The specific distribution of scatterers can cause either single-mode or multimode laser emission over a broad frequency bandwidth. These innovative sources offer easy surface-emission optical coupling, low-divergence (< 10°), large optical power output (>1 mW) in continuous-wave with low power consumption (< 3 W), electrical frequency tunability and/or multicolor emission, see Fig. 1d-e, and low spatial coherence which can be exploited for speckle free nanoimaging and quantum sensing across the far-infrared.

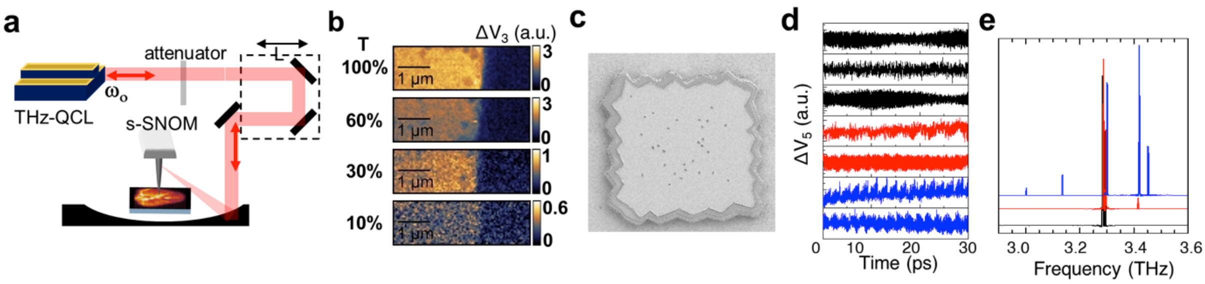

Fig. 1 THz near-field nanoscopy based on Self-mixing interferometry with THz-QCL to detect backscattered light from the AFM tip of a s-SNOM; b) Map of third order near-field signal ΔV_3 at the interface of an Au marker (higher signal regions) on Si substrate (lower signal region) as a function of the optical feedback attenuation controlled with an attenuator of transmission T; c) Scanning electron microscope image of a random QCL resonator having an area of 0.06 mm^2; d) Self-mixing fringes on near-field fifth order signal ΔV_5 acquired with random THz QCL in (c) at different driving current increasing from up to bottom, corresponding to tunable multimode spectra in (e) ;

References

[1] M. C. Giordano et al. "Phase-resolved terahertz self-detection near-field microscopy", Opt. Exp. 26, 18423-18435 (2018).
[2] E. A. A Pogna, M. Asgari, V. Zannier, L. Sorba, L. Viti, M. S Vitiello, "Unveiling the detection dynamics of semiconductor nanowire photodetectors by terahertz near-field nanoscopy" Light Sci. Appl. **9**, 1-12 (2020).
[3] K. S. Reichel, E. A. A. Pogna, S. Biasco, L. Viti, A. di Gaspare, H. E. Beere, D. A. Ritchie, M. S. Vitiello, "Self-mixing interferometry in a quantum cascade random laser at terahertz frequencies" Nanophotonics (2021) in press.
[4] S. Biasco, H. E. Beere, D. A. Ritchie, L. Li, A. G. Davies, E. H. Linfield, M.S. Vitiello, "Frequency-tunable continuous-wave random lasers at terahertz frequencies" Light Sci. Appl. **8**, 43 (2019).

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