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].

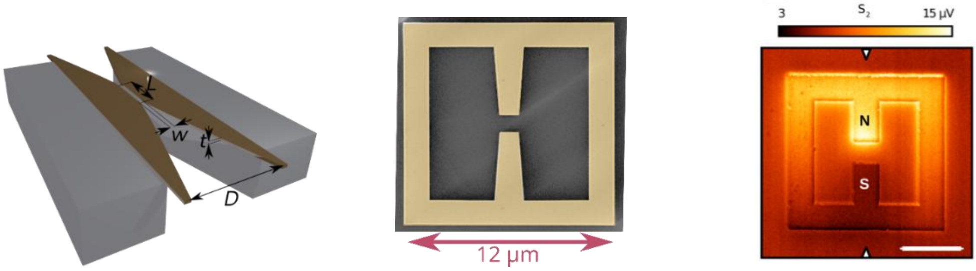

Fig.1 | THz field concentration strategies. **a**. Broadband butterfly device. (b) Single split-ring resonator for resonant sensing. (c) s-SNOM near-field map at 2.5 THz showing the asymmetric electric field distribution due to tip-resonator coupling.

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.

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