

Self-Referenced THz Time-Domain Spectroscopy for Reflection Measurements

Kasturie Jatkar^{1,2}, Riccardo Piccoli³, Stefano Bonetti^{1,3}

¹Department of Physics, Stockholm University, 106 91 Stockholm, Sweden

²Now with the Department of Microtechnology and Nanoscience, Chalmers University of Technology, 412 96 Gothenburg, Sweden

³Department of Molecular Sciences and Nanosystems, Ca' Foscari University of Venice, 30172 Venice, Italy

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.

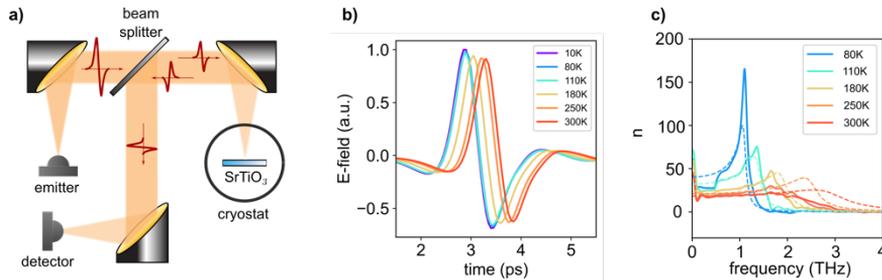


Fig.1 | a) THz-TDS setup in reflection geometry, **b)** THz time-domain traces of reflected pulses from SrTiO₃ across temperatures ranging from 10 K to 300 K, **c)** Real part of the complex refractive index after amplitude and phase correction. Dashed lines show the refractive index computed directly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

Contacts:

Riccardo Piccoli (riccardo.piccoli@unive.it)
Stefano Bonetti (stefano.bonetti@unive.it)

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