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 refraction 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 fitt 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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