

Review

Applications of THz Technology in Materials Characterization, Sensing, Communication, and Biomedical Fields

Kunal Kumar and Abdullah Eroglu *

Department of Electrical Engineering, SUNY Polytechnic Institute, Utica, NY 13502, USA;
kumark2@sunypoly.edu

* Correspondence: eroglua@sunypoly.edu

Abstract

Terahertz (THz) technology has emerged as a versatile platform enabling advancements across materials characterization, sensing, wireless communication, and biomedical diagnostics. This review provides a unified perspective on these application domains by highlighting the central role of terahertz time-domain spectroscopy (THz-TDS) as a fundamental tool for probing material electrodynamics. THz-TDS enables simultaneous measurement of amplitude and phase of the electric field, allowing contact-free direct extraction of complex permittivity, conductivity and other dielectric properties. Building on this capability, the review connects material-level properties to device and system-level functionalities, including metamaterial-based sensors, graphene-enabled reconfigurable intelligent surfaces (RISs), and beam-steering architectures relevant to 6G and beyond communication systems. Furthermore, the potential of THz techniques in biomedical applications is discussed in detail, particularly for non-invasive tumor detection through dielectric contrast mapping and imaging-based reconstruction methods. By integrating developments across these domains, this review presents THz-TDS as a unifying framework that links materials physics to emerging technologies in sensing, communication, and healthcare, offering insights into future directions for THz research and applications. The principal contribution of this review is to present a cross-domain framework that relates THz field measurements and extracted material electrodynamics to sensing, reconfigurable wavefront control, communication technologies, and biomaterials characterization.

Keywords: THz-TDS; THz materials characterization; THz sensing; THz communication; metasurfaces; reconfigurable intelligent surfaces (RISs); THz biomedical imaging



Academic Editors: Yahya M. Meziani
and Kefeng Ji

Received: 16 April 2026

Revised: 25 July 2026

Accepted: 27 July 2026

Published: 4 August 2026

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1. Introduction to Terahertz Systems

Terahertz (THz) technology, spanning frequencies from approximately 0.1 to 10 THz, represents a unique region of the electromagnetic spectrum where electronic and photonic phenomena converge, enabling sensitive interaction with charge carriers, molecular dynamics, and material structures. Terahertz (THz) technology bridges the gap between electronics and photonics, offering unique capabilities for material probing and emerging device applications. A comprehensive review of terahertz (THz) technology with emphasis on its applications in materials characterization, sensing, communication, and biomedical diagnostics is presented in this review article. This review fortifies the perspective on terahertz time-domain spectroscopy (THz-TDS) as the fundamental unifying platform that enables these applications by linking material electrodynamics to device behavior and system-level functionality. Terahertz time-domain spectroscopy (THz-TDS) has emerged

as a powerful, contact-free technique for probing the electrical and optical properties of materials in the frequency range of approximately 0.1–10 THz [1]. It has become a widely used method due to its ability to directly measure both the amplitude and phase of the transmitted or reflected THz electric field [1,2]. Earlier, Neu and Schmuttenmaer provided a comprehensive overview of various THz generation and detection techniques developed over time involving different material systems and configurations such as optical rectification, spintronics, and PCA as a THz emitter along with their respective THz band coverage. THz-TDS enables extraction of the complex conductivity and dielectric response of materials without requiring electrical contacts, making it particularly suitable for fragile systems, nanostructured materials, and samples where conventional transport measurements are challenging [2]. Taken altogether, recent research on THz-TDS supports a clear and comprehensive perspective on its effectiveness in non-contact materials characterization and its contribution towards development of THz sensing and THz communication devices. Neu and Schmuttenmaer provided an overview of general transfer-functions, Fresnel reflections, and multilayer formalism that underpin quantitative THz-TDS analysis [1]. Peretti et al. show how this formalism can be elevated into a full inverse-problem and time-trace fitting framework for extracting physically meaningful parameters in complex or noisy systems [3]. Mickan et al. and related thin-film work demonstrate that sensitivity enhancement and iterative inversion are essential when phase accumulation is weak [4,5]. Drude and Drude–Smith modeling then connect the THz response to transport physics in semiconductors, thin films, nanomaterials, and disordered systems [6,7]. A typical THz-TDS system configuration is shown below in Figure 1, highlighting the generation, propagation, and detection of broadband THz pulses.

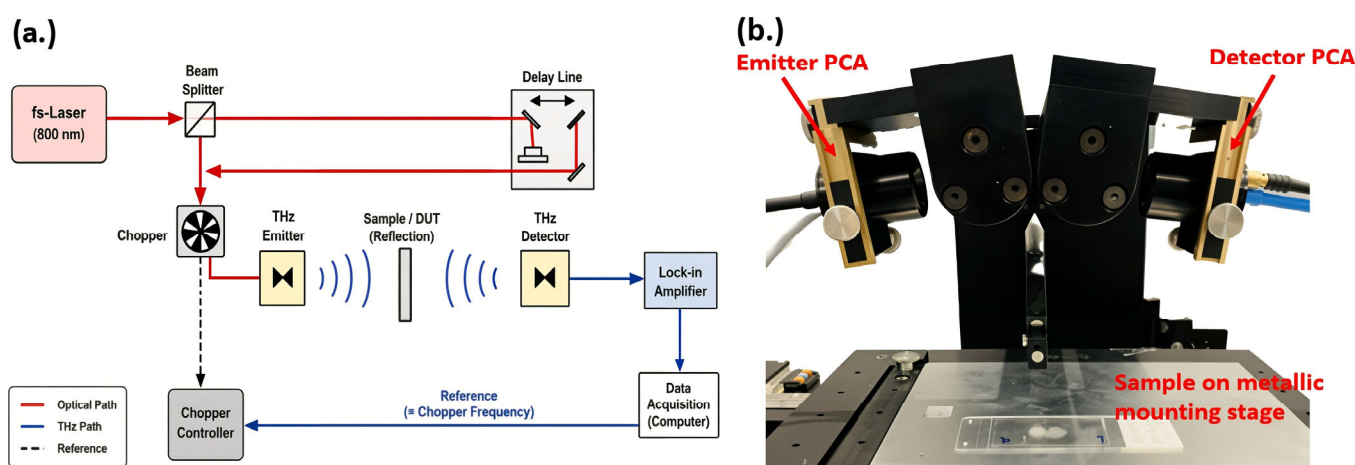


Figure 1. (a) Schematic representation of a typical terahertz time-domain spectroscopy (THz-TDS) system showing femtosecond laser excitation, photoconductive antenna generation/detection, and time-domain signal acquisition. (b) Conventional THz-TDS in reflection mode measurement setup.

Despite these advantages, conventional THz-TDS is fundamentally limited to probing equilibrium (ground-state) properties [8]. While it provides valuable information on intrinsic conductivity and carrier transport under steady-state conditions, it does not capture the ultrafast nonequilibrium processes that govern charge carrier dynamics. These processes—including carrier generation, scattering, trapping, and recombination—play a critical role in determining the performance of materials in optoelectronic and energy applications, and therefore require time-resolved measurement techniques [8,9]. To address this limitation, ultrafast pump–probe THz techniques have been developed [9]. In these approaches, an optical pump pulse excites the material and generates nonequilibrium charge carriers, while a delayed THz probe pulse measures the resulting transient change

in conductivity. This enables direct, contact-free observation of carrier dynamics with sub-picosecond temporal resolution [10].

In these measurements, an optical pump pulse excites the sample and generates a nonequilibrium carrier population, while a delayed broadband THz pulse probes the resulting change in its electromagnetic response. This configuration enables contact-free observation of carrier generation, scattering, trapping, relaxation, and recombination with sub-picosecond temporal resolution [9,10]. Optical Pump–Terahertz Probe (OPTP) spectroscopy and Time-Resolved Terahertz Spectroscopy (TRTS) are sometimes used interchangeably in the literature. In this review, OPTP refers to the measurement of pump-induced THz-field changes as a function of the optical pump–probe delay, whereas TRTS refers to the acquisition of the complete transient THz waveform at selected pump–probe delays [10,11]. The combined OPTP/TRTS configuration therefore contains two independently controlled delay coordinates. The optical pump–probe delay determines the time at which the photoexcited material is interrogated after excitation, while the THz sampling delay is used to reconstruct the THz electric-field waveform.

In a typical OPTP measurement, the THz sampling delay is fixed near the maximum of the THz pulse and the optical pump–probe delay is scanned. The difference between the pumped and unpumped THz signals then provides the temporal evolution of the photoinduced response, allowing carrier lifetimes and the time scales associated with trapping, relaxation, and recombination to be evaluated [9–11]. However, the OPTP amplitude can depend on both the carrier density and mobility; therefore, a reduction in the signal cannot always be attributed uniquely to carrier recombination alone.

TRTS provides the additional frequency-resolved information needed to interpret these dynamics. At selected pump–probe delays identified from the OPTP trace, the complete pumped and unpumped THz waveforms are recorded by scanning the THz sampling delay. Fourier transformation of their difference provides the complex pump-induced THz response, from which the transient complex photoconductivity can be extracted using an appropriate thin-film or multilayer transfer-function model [10–12]. The real and imaginary parts of the transient conductivity can subsequently be fitted using physical models such as the Drude or Drude–Smith formulations to retrieve carrier scattering time, mobility, localization, and backscattering characteristics [11,12].

OPTP therefore provides a relatively rapid measurement of the temporal evolution of photoconductivity, whereas TRTS provides a more complete spectral description of the photoexcited carrier response. Together, these techniques establish a unified framework for investigating both the temporal and frequency-dependent aspects of charge transport [9–12]. This capability is particularly valuable for nanostructured, amorphous, disordered, and polycrystalline thin-film materials, where conventional electrical measurements may be affected by contact resistance, sample morphology, or fabrication constraints. The two-delay TDS/OPTP/TRTS configuration, including the THz-generation and detection paths, optical pump beam, mechanical delay lines, and optical chopper used for differential detection, is illustrated in Figure 2.

Table 1 compares conventional THz-TDS, Optical Pump–Terahertz Probe (OPTP) spectroscopy, and Time-Resolved Terahertz Spectroscopy (TRTS) in terms of their measurement strategies, physical observables, advantages, limitations, and typical applications. Separating OPTP and TRTS clarifies that OPTP primarily provides rapid measurement of photoinduced carrier kinetics, whereas TRTS retrieves the frequency-dependent transient complex conductivity at selected pump–probe delays. Table 2 subsequently places THz-TDS in context with other established materials characterization techniques.

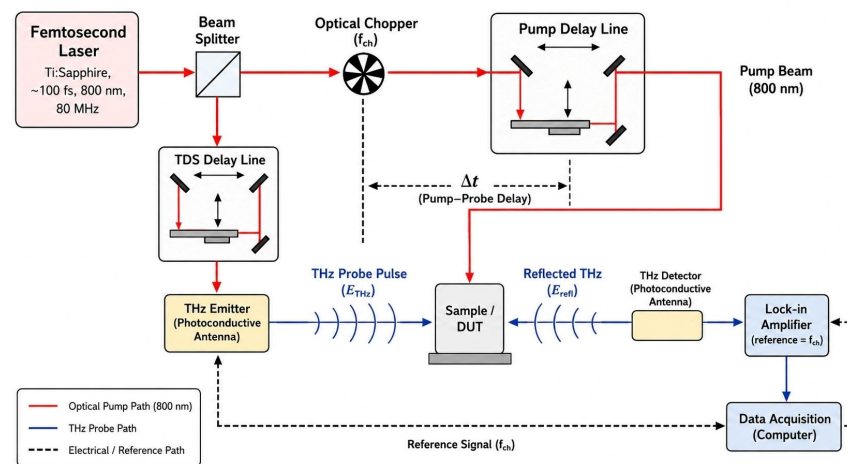


Figure 2. Schematic of a TDS/OPTP/TRTS spectrometer showing beam paths forming THz generation, and THz detection with the TDS delay line, a pump beam, which can be delayed with respect to the THz time axis, and an optical chopper, altogether enabling ultrafast OPTP and TRTS.

Table 1. Comparison of conventional THz-TDS, OPTP, and TRTS measurement methods and capabilities [1,9–12].

Feature	Conventional THz-TDS	OPTP	TRTS
Measurement type	Steady-state spectroscopy	Time-resolved pump-probe measurement	Frequency-resolved transient spectroscopy
Excitation	No optical excitation required	Optical pump followed by a THz probe	Optical pump followed by a broadband THz probe
Delay-scanning approach	THz sampling delay is scanned	Pump-probe delay is scanned	THz sampling at selected pump-probe delays
Measured quantity	THz electric field, $E(t)$	Pump-probe delay, $\Delta E(\tau)$	Transient field, $\Delta E(t_{\text{THz}}, \tau)$, and its frequency-domain response
Information obtained	Complex refractive index, permittivity, absorption, and conductivity	Temporal evolution of photoconductivity, carrier lifetime, trapping, relaxation, and recombination	Transient photoconductivity, scattering, mobility, localization, and backscattering
Advantages	Amplitude and phase retrieval	Rapid measurement of ultrafast carrier kinetics	Distinguishes the underlying physical mechanisms
Limitations	Does not resolve photoinduced nonequilibrium dynamics	Signal may contain contributions from carrier density and mobility	Longer acquisition time
Applications	Bulk material properties, optical constants, conductivity, dielectric response	Ultrafast carrier generation, recombination, trapping, relaxation dynamics	Transport analysis in semiconductors, nanomaterials, thin films, and disordered materials

Terahertz time-domain spectroscopy has matured into a broad and quantitatively rigorous platform for the characterization of materials, thin films, resonant structures, tunable metasurfaces, and communication devices. Its significance in this context arises from the fact that THz-TDS measures the electric field directly in the time domain rather than only the optical intensity. This distinction is not merely instrumental; it is what allows THz-TDS to recover the complex frequency-dependent response of matter and thereby extract refractive index, absorption coefficient, dielectric permittivity, and conductivity

without the need for Kramers–Kronig reconstruction [1]. Neu and Schmuttenmaer clearly emphasize THz-TDS as a broadband, phase-sensitive method capable of determining optical constants, conductivity, and transport-related parameters across a broad range of samples including semiconductors, 2D materials, superconductors, powders, multilayers, and metamaterial-based devices. They further note that THz-TDS is particularly valuable in materials science because mobile charge carriers strongly interact with THz radiation, allowing conductivity and electrodynamic behavior to be measured contact-free [1,2].

Table 2. Comparison of THz-TDS with commonly used characterization techniques.

Technique	Frequency Range	Information Obtained	Advantages	Limitations
THz-TDS	0.1–10 THz	Complex refractive index, permittivity, conductivity	Non-contact, phase & amplitude retrieval, subsurface sensitivity	Limited penetration in water-rich materials
Raman Spectroscopy	Optical	Molecular vibrations	High chemical specificity	Limited depth, fluorescence interference
Infrared Spectroscopy	Mid-IR	Molecular absorption modes	Mature technique	Strong scattering and absorption in some materials
Millimeter-Wave Spectroscopy	30–300 GHz	Bulk dielectric response	Greater penetration depth	Lower spectral resolution and weaker material contrast
Electrical Measurements	DC–GHz	Conductivity, mobility	Direct transport information	Requires contacts and sample preparation

The present article reviews developments in THz-TDS with emphasis on its spectral-analysis methods, theoretical and mathematical foundations, materials characterization capabilities, and applications in THz sensing, RIS-assisted communication technologies, and non-invasive biomedical analysis [13–20]. The distinctive contribution of this review is the development of a common THz-TDS-based framework connecting these application areas rather than treating them as independent topics. The review follows a common progression from the measurement of the THz electric field and extraction of complex electrodynamic parameters to their influence on carrier transport, resonant device behavior, sensing response, programmable wavefront control, and dielectric contrast in biological tissues. It also integrates conventional THz-TDS with OTP/TP/RTS methods, Fresnel-inversion techniques, transport models, and emerging physics-informed data-analysis approaches. This cross-domain perspective clarifies how material-level THz properties contribute to device-level behavior and system-level functionality across materials, sensing, communication, and biomedical applications.

2. THz Materials Characterizations

The THz-TDS and THz-TDS imaging-based spectroscopy methodology captures the time-domain electric field at a given spatial location, which is then followed by transformation into a frequency domain through Fourier analysis. The resulting frequency-domain signal, $E(\omega) = \mathcal{F}\{E(t)\}$, contains detailed information about attenuation, phase delay, and interference effects arising from interaction with the layered material system. This signal is not a direct imaging but rather a cumulative frequency-resolved electromagnetic response

received either in transmission mode or reflection mode that must be interpreted using a physical model to extract the dielectric properties. The central theoretical quantity in THz-TDS is the transfer function between sample and reference fields [1,2]. In the frequency domain, this is given as [2]:

$$T(\omega) = \frac{E_s(\omega)}{E_{ref}(\omega)}, \quad (1)$$

where, $E_s(\omega)$ and $E_{ref}(\omega)$ are the Fourier transforms of the measured sample and reference time-domain signals. The phase-sensitive nature of THz-TDS is critical here because the experiment yields the electric field itself, not merely intensity. Consequently, the Fourier transform of the time-domain waveform directly provides the complex spectral response [1]. Neu and Schmuttenmaer explicitly discuss this as one of the major advantages of THz-TDS over many conventional optical methods, especially when extracting complex refractive index and conductivity. In their formulation of time-domain spectroscopy, the directly measured THz field $E_{THz}(t)$ is recovered by convolving the short optical gate pulse with the longer THz pulse and scanning the delay between them, after which Fourier transformation gives the complex spectrum $E(\omega) = A(\omega)e^{i\phi(\omega)}$. This makes THz-TDS naturally suited for quantitative inverse analysis in materials characterization [3]. The transformation from time-domain to frequency-domain representation as given below in Figure 3 thereby enables extraction of complex optical parameters.

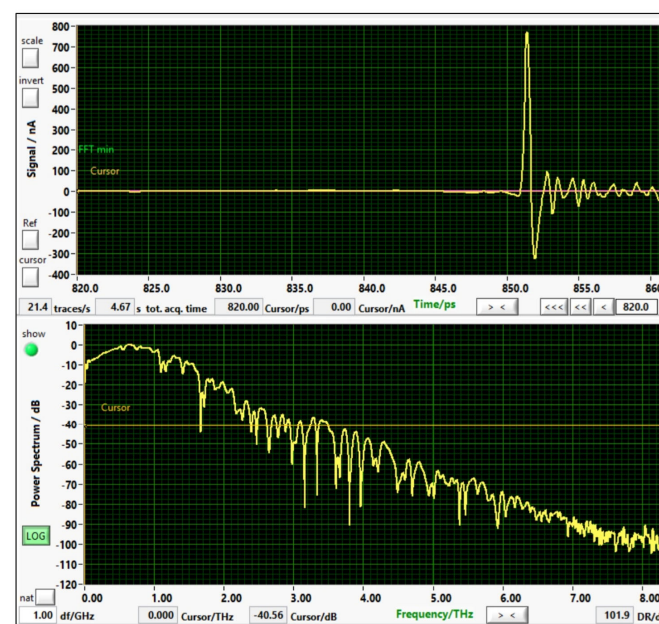


Figure 3. Time-domain THz electric field and corresponding frequency-domain spectrum obtained via Fourier transform, enabling extraction of amplitude and phase information in THz-TDS.

For a homogeneous material slab, the transfer function may be written as a product of the interface Fresnel terms, the propagation phase, and Fabry–Pérot contributions. Peretti et al. formulated the transmission as [3]:

$$\tilde{T}(\omega) = \tilde{s}(\omega) \exp \left[-j \frac{\omega d}{c} (\tilde{n}(\omega) - 1) \right] \tilde{FP}(\omega), \quad (2)$$

where the Fabry–Pérot contribution $FP(\omega)$ is given as:

$$\tilde{FP}(\omega) = \frac{1}{1 - [\tilde{r}_{2 \rightarrow 1}(\omega)]^2 \exp \left(-2j \frac{\omega d}{c} \tilde{n}(\omega) \right)}, \quad (3)$$

and d is the sample thickness, the tilde denotes a complex-valued electromagnetic quantity such as, $\tilde{n}(\omega)$ is the complex refractive index, $\tilde{s}(\omega)$ contains the interface transmission coefficients, and $\tilde{FP}(\omega)$ accounts for multiple internal reflections within the sample.

This expression is valuable because it makes THz-TDS an explicitly wave-propagation problem involving both bulk propagation and interface physics. It also clarifies why thickness, referencing, time-window length, and treatment of Fabry–Pérot echoes are all meaningful elements.

The transfer-function formalism becomes even more important for thin films and multilayer structures, because most practical material and device samples are not free-standing homogeneous slabs [1,3]. Neu and Schmuttenmaer provided a general multilayer treatment in which the material sample is modeled as a layer of refractive index n_2 and thickness d_2 deposited on a substrate of refractive index n_1 and thickness d_1 , with surrounding media n_0 and n_3 . In this formulation, the transmitted field with Fresnel transmission and reflection coefficients can be written as [1]:

$$t_{jk} = \frac{2n_j}{n_j + n_k}, \text{ and } r_{jk} = \frac{n_j - n_k}{n_j + n_k},$$

with the propagation factor given as $P_j = e^{-ik_0 d_j n_j}$, with the Fabry–Pérot term given as:

$$FP_{jkl} = \sum_{m=0}^M \left(r_{kl} P_k r_{jk} P_k \right)^m. \quad (4)$$

They further discuss that the number of reflected pulses captured experimentally determines the Fabry–Pérot contribution and the reliability of optical-constant extraction [3]. This makes clear that the THz-TDS model depends on the time-window length, the geometry of the sample, and the extent to which internal reflections are experimentally retained.

For highly conducting thin films on thick substrates, Neu and Schmuttenmaer discussed Tinkham approximation, which relates the complex transmittance to conductivity, where n_1 is the substrate refractive index, Z_0 is the vacuum impedance, and d is the film thickness as in [1,21],

$$T = \frac{1+n_1}{1+n_1+Z_0\sigma_2 d_2}. \quad (5)$$

This approximation essentially considers the assumption that the conducting sample layer is optically thin, so that both the phase delay and attenuation within the layer are small. Consequently, it works best for very thin, highly conductive films (e.g., superconductors, metals, doped semiconductors) where the film thickness is significantly smaller than the wavelength. This approximation does fail when internal reflections in the substrate are significant, or if the film is too thick, leading to incorrect calculations of the imaginary part of the conductivity. It is commonly used for studying photoexcited layers.

Significant developments in THz-TDS methodology have been made, which utilizes inverse modeling and time-trace fitting to stabilize extraction of material parameters. One can think of this major advancement in THz-TDS analysis as a shift towards inverse modeling and time-domain fitting [3,22]. Instead of extracting optical constants solely from frequency-domain ratios, the measured time-domain waveform is fitted using physically constrained models, thereby improving robustness in noisy systems, thin films, and resonant metamaterials, and allowing incorporation of physical dispersion models such as Drude, Drude–Smith, Drude–Lorentz, and coupled-mode formulations.

A Fourier-transform-enabled multilayer thin-film Fresnel-inversion model is employed to accurately retrieve material properties and allows for the accurate reconstruction of a parametric contrast spatial mapping. The multilayer thin-film Fresnel-inversion analysis framework utilizes a forward and inversion process [22,23]. Figure 4 below demonstrates

how multiple reflection pathways and the Fabry–Pérot contributions formulate in a multilayer THz material system to which a Fresnel-inversion modeling framework is used for dielectric parameter extraction [1]. Peretti et al. made a crucial distinction between the forward and inverse problems [3,22]. In the forward problem, the optical constants are assumed to be known and the expected THz waveform is computed. In the inverse problem, one starts from the measured sample and reference waveforms and retrieves the unknown refractive index or conductivity. As demonstrated by Peretti et al., this technique therefore uniquely positions the THz-TDS technique as a bridge between direct analytical inversion and inverse modeling with time-domain fitting.

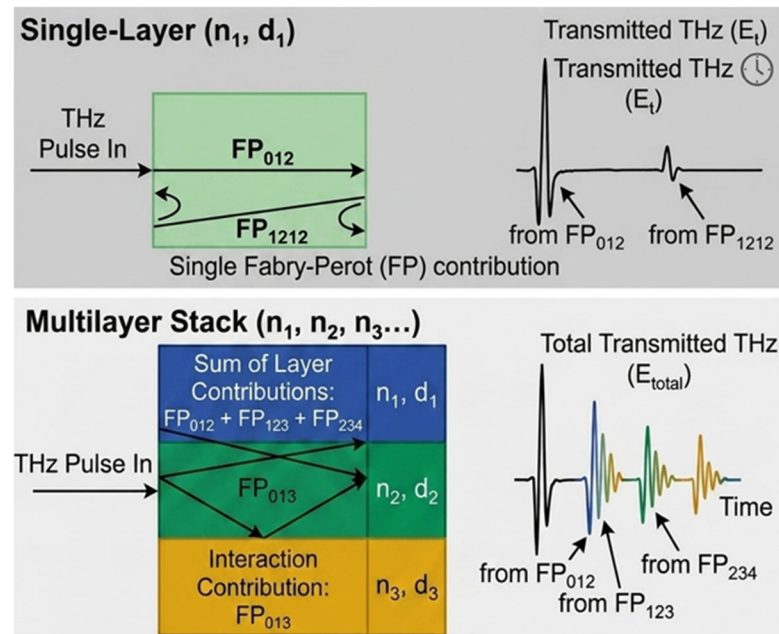


Figure 4. Schematic representation of THz transmission through a single layer and multilayer stratified material system showing multiple internal reflections and Fabry–Pérot contributions (FP012, FP123, FP234). The paths represent partially reflected waves contributing to the measured signal.

The forward process is based on Fresnel wave propagation in layered media. For an interface between two media with complex refractive indices $\tilde{n}_i(\omega)$ and $\tilde{n}_{i+1}(\omega)$, the reflection coefficient is:

$$\tilde{r}_{i,i+1}(\omega) = \frac{\tilde{n}_{i+1}(\omega) - \tilde{n}_i(\omega)}{\tilde{n}_{i+1}(\omega) + \tilde{n}_i(\omega)}, \quad (6)$$

And once the wave enters a layer of thickness d_i , it accumulates a propagation phase given as,

$$\phi_i(\omega) = \frac{\omega \tilde{n}_i(\omega) d_i}{c}. \quad (7)$$

Because $\tilde{n}_i(\omega)$ is a complex quantity, this phase factor captures not only delay but also attenuation. The total reflected or transmitted field is therefore a coherent sum of all partial waves produced by transmission and reflection at each interface. This is then handled through recursive Fresnel relations or transfer-matrix methods, exactly as in a multilayer materials analysis. The result is a modeled field $E_{\text{model}}(\omega)$ for assumed sets of layer refractive indices and thicknesses. An inversion process is then defined as the retrieval of the unknown dielectric parameters from the measured THz field. This process uses $\tilde{n}_i(\omega)$ and d_i , which make the modeled waveform reproduce the measured waveform. This is achieved through iterations. One begins with an initial estimate for the layer properties, computes $E_{\text{model}}(\omega)$, compares it with $E_{\text{measured}}(\omega)$, and updates the parameters until agreement is reached. The discrepancy between the experiment and model is evaluated over

a frequency interval and minimized using an error functional. The quantified parameters yield the best-fit refractive indices and thicknesses, from which complex permittivity $\varepsilon^*(\omega)$, refractive index $n(\omega)$, extinction ratio $\kappa(\omega)$ and absorption coefficient $\alpha(\omega)$ can be derived. This technique exploits the spatial variations in extracted electromagnetic parameters such as $\varepsilon'(\omega)$, $\varepsilon''(\omega)$, $n(\omega)$, and $\alpha(\omega)$. The complex permittivity of materials is not measured directly; rather, it is extracted from the measured electric-field response. The complex refractive index $\tilde{n}(\omega)$ is determined from the complex permittivity using the following relation:

$$\varepsilon^*(\omega) = [\tilde{n}(\omega)]^2, \quad (8)$$

which establishes a direct connection between the measured electromagnetic field and the intrinsic dielectric properties for both the complex materials and biomaterials. Neu and Schmuttenmaer highlight that the advantage of THz-TDS over other conventional techniques is that it simultaneously determines the real and imaginary parts of the refractive index. This fact becomes more important in biomaterials because contrasts are not captured adequately by single scalar observables compared to other methods that require Kramers–Kronig assumptions or intensity-only measurements [1].

These parameters are then reconstructed on a spatial map pixel by pixel and then inferred to localize anomalies and non-homogeneities such as tumor regions. Figure 5 below demonstrates how Fresnel-inversion analysis is implemented in combination with numerical analysis for finding the best fit by minimization of error, as given by equation 9 below, between the estimated (modeled) and the measured signal to extract the physical parameters of the material system under THz-TDS study [3,22,23]. Solving such physics-based optimization problems at each spatial point allows for the retrieval of the local dielectric properties and their reconstruction into a spatial map, forming the core of THz-TDS imaging methodology for complex materials and biomaterials, including tumor detection in bio-tissues.

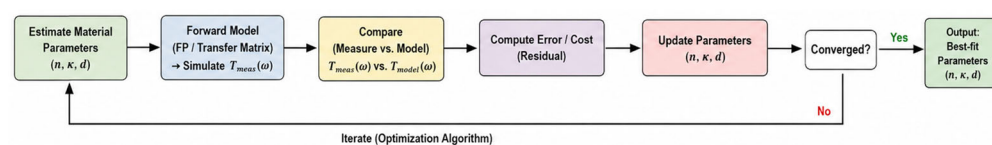


Figure 5. Description of Fresnel-inverse model framework for material parameter estimation for thin-film materials.

This Fresnel inversion methodology has been extensively developed and validated in the THz-TDS literature. Duvillaret et al. and other works have established foundational inversion techniques for extracting optical constants while accounting for multiple internal reflections [22]. These works collectively establish Fresnel-inversion-based modeling as the standard approach for quantitative THz characterization. Peretti et al.'s technique involved a time-trace analysis framework in which the measured THz waveform was fitted directly using a physically parameterized model for the material or metamaterial under analysis [3]. The idea is to simulate the full propagation problem in the time domain using these models and then retrieve the model parameters through Fresnel-inversion modeling and optimization. This analytical procedure turns an inverse problem into the minimization of an error function between measured and modeled spectra or waveforms. Building upon the Fresnel-inversion analytical methodology developed by Peretti et al. and Duvillaret et al., this physically constrained modeling approach dramatically reduces the number of free parameters and increases numerical analysis stability. Consequently, the extraction

problem can be formulated as an error function between the measured and modeled THz waveforms, which can be considered here as an optimization problem expressed as [3,22]:

$$\varepsilon = \sum_{\omega} |E_{\text{meas}}(\omega) - E_{\text{model}}(\omega)|^2. \quad (9)$$

Peretti et al. further demonstrated that time-domain fitting significantly improves robustness in cases involving thin films with weak phase response, noisy measurements, strong resonances in metamaterials, and also complex multilayer structures. They further showed that fitting directly in the time domain avoids numerical instabilities that often arise in purely frequency-domain inversion, especially when Fabry–Pérot oscillations or spectral artifacts are present. This establishes THz-TDS as a physics-based inverse modeling platform rather than a simple spectral analysis technique. THz-TDS uniquely enables extraction of carrier transport physics. This evolution toward a model-based inversion technique becomes especially important in the characterization of nanomaterials and conducting media, where the conductivity response carries direct information on charge carrier transport physics.

In bulk conductors, semiconductors, or relatively delocalized conductors, classical Drude model provides a direct route to extracting mobility-related quantities from THz-TDS conductivity spectra. The classical Drude model describes free-carrier dynamics as [6]:

$$\sigma(\omega) = \frac{ne^2\tau}{m^*(1-i\omega\tau)}, \quad (10)$$

where n is the carrier concentration, τ is the scattering time, and m^* is the effective mass of the charge (electrons). However, for nanostructured, disordered, or confined systems, the Drude model becomes insufficient due to carrier transport influenced by backscattering, grain boundaries, and localization effects. In such cases, the Drude–Smith model is appropriately employed, which captures a more realistic interpretation of THz-TDS conductivity spectra, given as [7]:

$$\sigma(\omega) = \frac{ne^2\tau}{m^*(1-i\omega\tau)} \left(1 + \frac{c_1}{1-i\omega\tau}\right), \quad (11)$$

where c_1 is the backscattering parameter. Negative values of c_1 indicate carrier localization and suppressed dc conductivity due to directional backscattering. In addition, dielectric and resonant responses arising from bound charges, phonon modes, or engineered resonant structures are commonly described using Drude–Lorentz-type dispersion models [24]. These models account for frequency-dependent polarization mechanisms and are especially relevant in the analysis of polar dielectrics, molecular systems, and metamaterial resonances. Together, this combination of Drude, Drude–Smith, and Drude–Lorentz formulations provides a comprehensive framework for interpreting THz-TDS measurements across a wide range of materials, linking experimentally measured electric-field responses to both transport phenomena and dielectric dispersion mechanisms.

Neu and Schmuttenmaer also explicitly identify classical Drude, Drude–Smith, and Drude–Lorentz models commonly used in THz-TDS parameter extraction, while the broader THz conductivity literature has firmly established these models as central to the interpretation of charge transport characteristics of nanostructured materials. THz conductivity measurements enable the probing of short-range transport physics, making them particularly powerful for nanomaterials, thin films, powders, and disordered systems where conventional electrical measurements are limited by contacts and morphology. Thus, THz-TDS does not only measure conductivity, but it enables direct extraction of material-specific transport physics in nanostructured systems. Because THz radiation probes short-range electrodynamics without the need for electrical contacts, it avoids many of the artifacts that affect dc conductivity measurements in powders, discontinuous films, and emerging

materials. This makes THz-TDS particularly valuable for semiconductors, nanomaterials, conductive thin films, and resonant metasurfaces, where morphology, contact resistance, and grain-boundary effects often obscure intrinsic transport when using conventional electrical techniques. Neu and Schmuttenmaer further go on to explicitly emphasize the advantage of contact-free conductivity measurements of metals, semiconductors, 2D materials, and superconductors as a major application of THz-TDS, while adding that the pump–probe THz literature further establishes THz-TDS as being sensitive to short-range charge carrier transport as well.

For thin-film material characterizations, a significant challenge is present due to weak phase accumulation relative to wavelength at THz frequencies [4]. When the film thickness is much smaller than the THz wavelength, the induced phase shift and amplitude change can be extremely small and therefore difficult to resolve against background noise. Mickan et al. addressed this limitation through developing a double-modulated differential THz-TDS (DTDS), which enhances sensitivity using modulation techniques and iterative extraction of thin-film optical constants, which enables detection of dielectric contrasts. Their work demonstrated improved dielectric extraction in micron-scale films, particularly for dielectric materials in MEMS devices and photonic integrated circuit applications. Further advancements by Pupeza, Wilk, and Koch introduced iterative inversion methods that incorporate Fabry–Pérot reflections and thickness-dependent propagation effects [5]. Their work provided significant developments to address high-accuracy optical-parameter extraction. THz-TDS is not only relevant to transmission-mode material analysis. Reflection-mode THz-TDS measurements are also essential for highly reflective and strongly conducting media. Matsuoka et al. demonstrated THz time-domain reflection spectroscopy on high-temperature T_c superconducting Cuprates, showing that reflection-mode THz-TDS can resolve sharp Josephson plasma edges, transition states, and reproduce previous far-infrared results while directly probing low-energy electrodynamics in highly reflective crystals [25]. Thus, reflection-mode THz-TDS has also been exploited to extract material physics, transport characteristics of electro-optic materials, and probe transition states in superconducting high-temperature Nickelates.

Overall, these contributions and developments establish thin-film material THz characterization not merely as a more delicate version of bulk analysis, but as a fundamentally sensitivity-limited inverse problem involving advancements through both experimental/instrumental innovations and algorithmic strategies exploiting inversion-method refinements [4,7–9,24]. Techniques such as differential THz-TDS (DTDS) enhance sensitivity by isolating small changes in transmitted signals, along with the inversion modeling approaches incorporating Fabry–Pérot effects and iterative fitting, which altogether significantly improve physical parameter extraction accuracy in thin and low-loss materials. These approaches reformulate THz-TDS as a rigorous inverse electromagnetic problem, enabling high-accuracy extraction even in thin-film materials and low-index materials [3,22].

3. THz Sensing Applications

Terahertz sensing is fundamentally governed by the strength of electromagnetic field confinement and the degree of interaction between the incident THz wave and the analyte material. While conventional THz-TDS provides broadband material-physics parametric extraction, the THz sensing performance can be significantly enhanced using engineered metamaterial structures that concentrate THz fields into subwavelength regions and amplify interaction with analyte materials through the localized resonances and strong field enhancement effects. The local field enhancement in metamaterials substantially increases THz-TDS sensitivity, enabling the measurement of very small concentrations and opening pathways to commercial sensing applications [2,26–28]. Metamaterial-based filters,

lenses, beam steerers, and perfect absorbers have all been characterized with THz-TDS, demonstrating that the technique is deeply integrated into resonant-structure engineering devices [26–28].

Resonant metasurface architecture development has been an active field of research recently to study their functionality and capabilities towards THz sensing applications. Chowdhury and Eroglu made significant contributions in performing groundwork research in developing metamaterials and resonant-engineered THz sensors [29,30]. The THz metamaterial sensor arrays were based on coplanar waveguide (CPW) transmission lines coupled with split-ring resonators (SRRs). Their formulation explicitly incorporates mutual inductance effects between resonators and transmission lines, enabling accurate equivalent circuit representation and network parameter extraction using ABCD matrix modeling. The proposed analytical approach demonstrated strong agreement with full-wave simulations and experimental measurements, establishing a reliable design methodology for THz sensor arrays. A critical advancement of this work is graphene-infused metamaterial THz sensors developed by Islam and Eroglu, which employs a multilayer stacked architecture consisting of a metallic ground plane (suppressing transmission), a dielectric spacer layer, a patterned resonator layer (SRR/patch), a graphene layer (tunable conductivity), and an analyte layer enabling tunable THz electromagnetic response. Essentially, in their work, a THz sensor is realized as a periodic array of these metamaterial unit cells, where each unit cell comprises such a metal–dielectric–metasurface–graphene multilayer stack architecture. The THz electromagnetic response is governed by both resonance behavior, graphene-tunable conductivity, and multilayer interference [31,32]. The multilayer architecture of the graphene-based metamaterial THz sensor is shown in Figure 6.

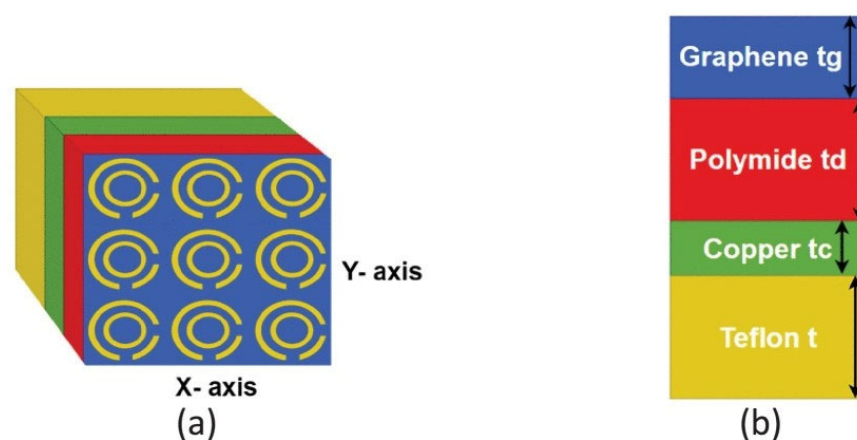


Figure 6. (a) Schematic of graphene-infused multilayer metamaterial THz sensor architecture; (b) its layered structure consisting of a metallic ground plane, dielectric spacer, resonator layer, graphene layer, and analyte layer [31].

The sensing mechanism arises from perturbation of the effective capacitance and local electromagnetic field distribution due to the presence of the layered architecture, exploiting the tunable graphene transport. The key result of this work was the demonstration of near-unity absorption ($\sim 99\%$), resonance centered at 4.48 THz, and strong sensitivity to thickness and refractive index, where the increase in thickness leads to an increase in capacitance and thus generates a redshift in resonance frequency. The sensor demonstrated high sensitivity (~ 23.75 GHz/RIU), along with strong figure-of-merit and quality factor, highlighting its effectiveness for refractive index-based material characterization.

The absorption relation and corresponding resonance shift is governed by the following equations:

$$A(\omega) = 1 - |R(\omega)|^2 - |T(\omega)|^2, \quad (12)$$

for ground-plane-based metamaterial sensors:

$$A(\omega) \approx 1 - |R(\omega)|^2. \quad (13)$$

A perfect absorption occurs when reflection is minimized via impedance matching, which is achieved through careful tuning of the metasurface geometry and graphene conductivity [26,28]. Their results demonstrated that increasing the analyte thickness (e.g., from 1 μm to 5 μm) results in a systematic redshift of the resonance frequency, which is attributed to an increase in effective dielectric loading and capacitance. Similarly, variations in the refractive index of the analyte lead to measurable shifts in resonance frequency and absorption amplitude.

Thus, the sensor mechanism can be understood as the analyte material perturbing the local electromagnetic energy storage, which changes resonance conditions and gives rise to measurable frequency and absorptivity shifts. This can be also interpreted using an equivalent LC resonance model, where the resonance frequency f_0 is given by:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}, \quad (14)$$

and

$$C \propto \epsilon_{\text{eff}},$$

such that the presence of the analyte modifies the capacitance C , thereby shifting the resonant frequency. The resonance-based sensing mechanism and absorption characteristics of the metamaterial sensor are illustrated in Figure 7. The strong localization of the electric field at the resonator enhances sensitivity to even small changes in dielectric environment, making such structures highly effective for material sensing [26,27]. The integration of high conductive graphene introduces an additional degree of freedom, enabling dynamic tuning, reconfigurability, and optimization of sensitivity [31,32].

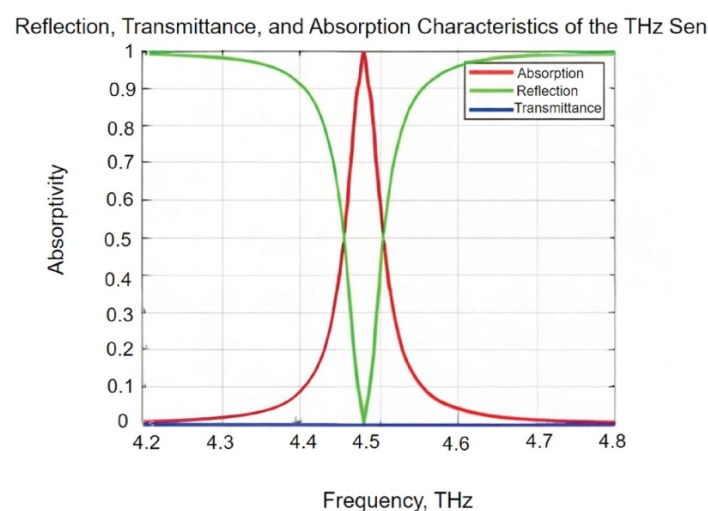


Figure 7. Absorption spectrum of the metamaterial THz sensor showing resonance behavior and sensitivity to analyte properties such as refractive index and thickness [31].

Additionally, Chowdhury and Eroglu demonstrated significant performance achieving high absorption and sensitivity via 3D electromagnetic simulations (HFSSs) incorporating an analytical equivalent RLC circuit framework involving mutual inductance effects among

resonators, substrate coupling, and metasurface arrays. This approach enabled tunable material-physics modeling and the physically interpretable design of resonant THz metamaterial sensors. Using transmission matrix (ABCD) formulation and network synthesis methods, they demonstrated accurate prediction of electromagnetic behavior across periodic structures. Experimental validation using large-scale arrays (e.g., 36×35 -unit cells) confirmed strong agreement between analytical, simulation, and measured results, reinforcing the robustness of their modeling framework [29,30].

These results are relevant to both sensing applications and reconfigurable THz devices, including RIS and beam-steering systems discussed later in this section. Broadly, these works significantly demonstrate how THz sensing can be engineered through an interplay of stratified electromagnetic design, resonant field confinement, and tunable graphene conductivity. This is also where the connection to reconfigurable intelligent surfaces begins to emerge. The graphene-mediated tunability that improves sensing performance can be used to tune reflection magnitude and phase in wavefront-control devices. This also serves to form a bridge between THz material characterization and THz resonant engineered devices, thus also leading towards THz communication systems functionality [31–33].

Additionally, Mukherjee et al. demonstrated refractive index sensing using THz metamaterial resonators with high quality factors, highlighting the importance of resonance sharpness in improving sensing resolution [33]. These works collectively reinforce that THz sensing performance is fundamentally governed by the quality factor of resonance, field confinement, and effective interaction volume between the electromagnetic field and analyte. The integration of tunable materials such as graphene further extends these capabilities by enabling dynamic control of resonance conditions, thereby bridging static sensing architectures with reconfigurable THz platforms [34]. Beyond the works discussed above, several studies have further established the role of metamaterials and metasurfaces in enhancing THz sensing performance. Chen et al. demonstrated resonant metamaterial structures exhibiting strong electric and magnetic field localization, enabling highly sensitive detection of dielectric perturbations in the THz regime [26]. Singh et al. reported ultrasensitive THz biosensors based on resonant metasurfaces, showing that even minute variations in analyte refractive index can produce measurable spectral shifts due to enhanced near-field confinement [27]. Withayachumnankul et al. further explored the use of THz metamaterials for sensing and spectroscopy, emphasizing their capability for label-free detection through resonance frequency shifts and absorption changes [28].

4. THz Communication Systems

In the context of reviewing recent developments towards THz RIS and beam-steering applications, most important is the work reported by Islam and Eroglu, which focuses on graphene-based RIS designs where the resonant structure arrays provide dynamic control of reflected THz fields [32]. The structure of the graphene-based RIS unit cell enabling dynamic electromagnetic control is shown below in Figure 8.

The proposed graphene-based RIS operates over a broadband range from 0.1 to 4 THz and exhibits near-total reflection approaching 96% across the band. Previous results by Eroglu et al. have demonstrated how resonant sensing arrays can be extended towards the development of RIS, incorporating THz metamaterial and structural tunability into dynamic reflection control and near-total reflection for THz-communication systems [27–32]. Graphene-tunable conductivity enables dynamic control of electromagnetic wavefronts through modulation in absorption and reflection as well as phase-gradients, thus enhancing the signal-to-noise ratios and establishing beam steering. This is a highly impactful contribution towards the demonstration of resonant metasurface-based RIS design capabilities and adaptive wave propagation control for THz wireless communication systems.

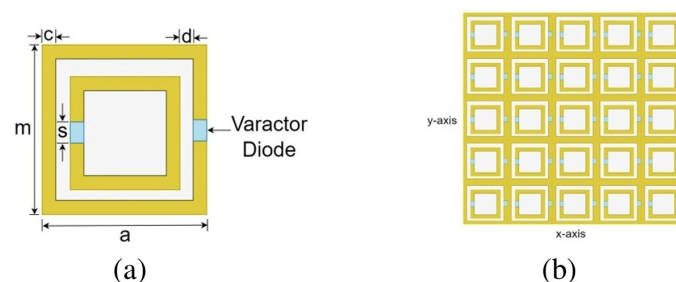


Figure 8. Schematic of graphene-based reconfigurable intelligent surface (RIS) unit cell with varactor diodes enabling tunable reflection of THz waves through controllable conductivity: (a) single element unit cell and (b) 5×5 array with final unit cell [32].

THz band is deemed attractive for wireless communications because it can support extremely high data-transmission speeds, reaching the terabit-per-second regime. It is important to mention here that THz metasurface RIS is, therefore, identified as a major enabling technology because of its ability to intelligently control wave propagation, enhance coverage, and improve the controllability of THz wireless channels [35–39]. However, there are severe limitations imposed by free-space path loss and molecular absorption, which restrict practical operation to short-range indoor environments unless the propagation environment is actively engineered. Recently, research in this field has gained momentum to overcome these limitations and a growing body of research has established RIS-enabled THz communication as a key direction for 6G systems. Wu and Zhang at an early stage introduced the concept of intelligent reflecting surfaces for wireless communication, demonstrating how programmable metasurfaces can enhance signal propagation through controllable phase shifts [38]. Di Renzo et al. further developed a comprehensive framework for RIS-assisted communication systems, highlighting improvements in energy efficiency, spectral efficiency, and coverage [36]. Basar et al. discussed the integration of RIS into next-generation wireless systems, emphasizing its role in overcoming path loss limitations at high frequencies [35]. Liu et al.'s work demonstrated a vanadium oxide THz chiral metamaterial employing temperature-induced phase transition tunability, offering temperature-controlled chirality and refractive index modulation [40]. In another related work, Liu et al. further demonstrated reconfigurable metasurfaces as switchable chiral mirrors and implemented polarization-dependent THz reflection characteristics [41]. These studies highlight the potential of temperature-controlled reconfigurable THz metamaterials for dynamic polarization control, adaptive wavefront control, and the development of reconfigurable intelligent surface (RIS)-assisted THz communication systems.

The basis of RIS operation lies in engineering the complex reflection coefficient of each unit cell such that a desired spatial phase profile is imposed across the surface, which is given as [38],

$$\Gamma(\omega) = |\Gamma(\omega)|e^{i\phi(\omega)}, \quad (15)$$

where

$$\phi(\omega) \in [0, 2\pi],$$

and the reflection coefficient in terms of surface impedance is given as:

$$\Gamma = \frac{Z_s - \eta_0}{Z_s + \eta_0}, \quad (16)$$

where Z_s is the surface impedance and η_0 is the intrinsic impedance of free space (377Ω). Beam steering and anomalous reflection are then achieved by a position-dependent phase gradient, which can be expressed through the phase-gradient version of Snell's law,

$$\sin \theta_r - \sin \theta_i = \frac{\lambda}{2\pi} \frac{d\phi(x)}{dx}. \quad (17)$$

Equivalently, the required local phase gradient is given for a desired beam-steering angle under appropriate simplifying assumptions as in [35–39]:

$$\frac{d\phi(x)}{dx} = \frac{2\pi}{\lambda} \sin \theta. \quad (18)$$

These equations are fundamental because they show that beam steering in a metasurface is produced by a deliberately engineered distribution of local reflection phases across sub-wavelength elements. In a graphene-based RIS, this phase response is controlled by conductivity, such that material transport properties and electromagnetic wavefront manipulation become coupled. THz-TDS serves as the tool to measure the underlying electrodynamic parameters of the metasurface that enables RIS and beam-steering applications. The relevance of these RIS structures is particularly important in the context of 6G and beyond communication systems [13,42,43]. Figure 9 below highlights a conceptual perspective of implementation of THz metasurfaces for RIS structures and beam steering through engineered phase gradients across the metasurface.

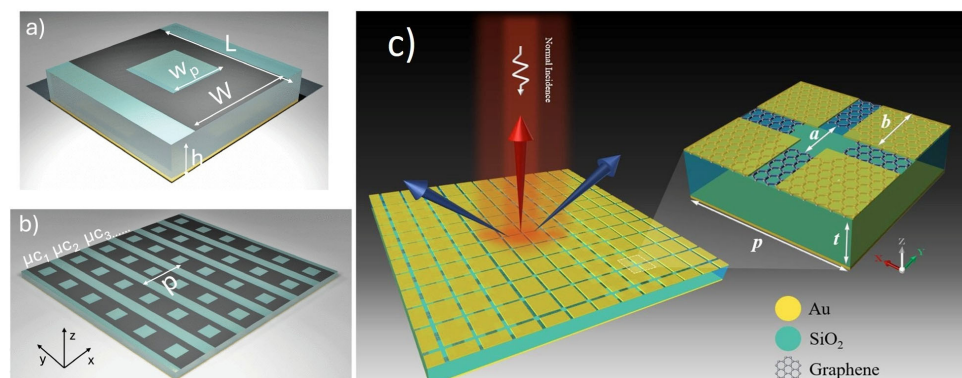


Figure 9. (a,b): Metasurface enabling directional control of reflected electromagnetic waves [43]; (c): schematic illustration of a graphene-based coding metasurface for THz beam steering. By electrically tuning the graphene conductivity, the metasurface enables programmable manipulation of reflected THz wavefronts, providing a practical route toward reconfigurable intelligent surface (RIS)-assisted THz communication systems [13].

It is important to understand and develop an overview from a communication systems perspective: the reason THz propagation is difficult is due to the rapid decrease in received power with shorter wavelengths, which can be expressed as per the below relationship providing receiver power scaling with respect to wavelength [37]:

$$P_r \propto \left(\frac{\lambda}{4\pi d} \right)^2. \quad (19)$$

As the wavelength λ decreases into the THz frequency regime, the available received power drops quickly for a given distance d , even before molecular absorption is considered. This is why high-gain directional transmission, beam steering, and programmable reflect arrays become so critical. Metasurface RIS architectures address this challenge by reshaping the environment rather than relying solely on transmitter-side beamforming. In this respect, RISs employ THz device physics where the resonant metamaterials and tunable

conductivities characterized by THz-TDS at the component level become the basis of signal-path control at the communication channel level.

In the THz domain specifically, recent studies have also shown that RIS-based beam steering can be achieved with highly directional transmission and adaptive channel control, which are essential for overcoming propagation losses and enabling reliable THz communication links. Collectively, these developments reinforce that RIS metasurfaces are not merely passive components but active elements in shaping electromagnetic environments, with THz-TDS serving as the foundational tool for characterizing and optimizing their material and device-level properties. An overall perspective that naturally builds upon this discussion is that THz-TDS extracts material electrodynamics, which further determines resonant metamaterial device behavior, and thus these resonant devices enable THz sensing and communication systems. In this sense, THz-TDS should not be understood as a standalone spectroscopy method but as a unifying platform that bridges electromagnetic theory, materials characterization, resonant device engineering, and system-level communication functionality. This is precisely why it plays such a central role in modern THz research as it not only measures the physics but also helps define the design rules for the sensing devices and communication system architectures built upon those physics.

5. THz Technology in Biomedical Fields

5.1. THz Systems for Biomaterials Characterizations and Biomedical Applications

Terahertz time-domain spectroscopy (THz-TDS) has emerged as a powerful technique for biomaterials characterization due to its strong sensitivity to hydration dynamics, molecular interactions, and structural organization, which are frequency-dependent characteristics in biological tissues [1,2,44]. Unlike conventional imaging modalities, this capability allows for the extraction of frequency-dependent dielectric properties, providing a quantitative framework for analyzing biomaterials. In this context, the complex permittivity of tissue serves as a fundamental descriptor of its electromagnetic response and plays a central role in distinguishing between healthy and pathological states, including tumor development [44–49]. The broader THz-TDS literature already recognizes biomaterials characterization as one of the important application domains of this technique, including proof-of-concept demonstrations in skin cancer detection and THz-metamaterial biosensing, further emphasizing that THz-TDS methodologies are attractive because they are non-invasive, non-ionizing, and highly sensitive to water-rich tissue contrast mechanisms.

The interaction of THz radiation with biological tissues is governed by polarization mechanisms associated with bound and free water charges and ionic contributions. As demonstrated by Pickwell and Wallace, these interactions collectively capture the influence of cellular and extra-cellular constituents in the biomaterials and are commonly described using the Debye relaxation model, which characterizes the frequency-dependent dielectric response of the polar media as well as directly correlates with the pathological changes such as tumor formation [1,44,47,48].

The Debye relaxation model gives the complex permittivity for the biomaterial expressed as:

$$\epsilon^*(\omega) = \epsilon'(\omega) - i\epsilon''(\omega), \quad (20)$$

$$\epsilon^*(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + i\omega\tau}, \quad (21)$$

where ϵ_s represents the low-frequency permittivity associated with fully relaxed dipolar polarization, ϵ_∞ represents the high-frequency permittivity corresponding to the instantaneous electronic response, and τ is the relaxation time. The real part $\epsilon'(\omega)$ corresponds to stored energy and polarization, while the imaginary part $\epsilon''(\omega)$ represents dielectric loss arising from absorption and molecular relaxation processes.

The Debye model is especially relevant for THz biomaterials characterization because tissue contrast in the THz band is strongly influenced by water-mediated dielectric dispersion. Neu and Schmuttenmaer explicitly identify Debye-type descriptions among the physically motivated models used in THz-TDS parameter extraction for lossy materials and liquids, reinforcing the relevance of this framework to biological systems [1].

For real biological tissues, however, a single Debye relaxation time is often insufficient. Their THz response typically contains contributions from multiple water populations and structural environments. Biological tissues typically exhibit multiple relaxation mechanisms due to their heterogeneous composition, including contributions from both bound and free water. To capture this complexity, the double-Debye relaxation model is often employed, where the complex permittivity is expressed as:

$$\epsilon^*(\omega) = \epsilon_\infty + \frac{\epsilon_1 - \epsilon_\infty}{1 + i\omega\tau_1} + \frac{\epsilon_s - \epsilon_1}{1 + i\omega\tau_2}. \quad (22)$$

This formulation enables more accurate modeling of dielectric dispersion across the THz frequency range and provides insight into the relative contributions of different hydration-dependent molecular environments and structural processes within the biological tissues, thus representing multiple characteristic relaxation pathways. The double-Debye relaxation model serves as a more reliable method for accurately describing how a healthy bio-tissue can be differentiated from a diseased tumor tissue based on hydration dynamics, polarized molecular environmental dynamics, and dispersive behavior with respect to their response across the THz frequencies. Tumor tissues frequently exhibit altered water fraction, denser vasculature, modified extracellular organization, and changes in cell packing, due to which their real and imaginary parts of the complex permittivity can both shift in a diagnostically meaningful way, thus forming the basis of THz contrast-mapping-based tumor detection. Besides the THz biomaterials characterization, this is one of the fundamental reasons THz-TDS is relevant to solving tumor-detection problems.

For tumor detection, the useful information is often not simply higher absorption or higher reflection, but rather a combination of changes in refractive index, absorption, loss tangent, and dielectric dispersion measured across the THz frequency band. This is exactly where THz-TDS becomes more powerful than a conventional single-frequency contrast technique. Subsequent studies as reported by Wallace et al. confirm that broadband THz imaging has the capability to yield frequency-resolved dielectric signature contrast originating due to hydration, relaxation, refractive index variations, absorption differences, and tissue composition heterogeneity in tumor-affected bio-tissues [14,45,46]. This is the fundamental basis for tumor discrimination including tumor localization and tumor detection in THz imaging and spectroscopy applications.

In practical applications involving THz imaging-based spectroscopy of bio-tissues, this extraction process requires a rigorous modeling framework due to the inherently heterogeneous and layered structure of the sample. Biological tissues are more accurately represented as stratified systems composed of multiple layers, such as skin, fat, connective tissue, and tumor regions, each characterized by distinct dielectric properties and thicknesses [14,44–46]. The measured THz signal represents a cumulative response arising from multiple internal reflections, attenuation, propagation delays, transmissions, interference effects, and phase shifts within the layered structure of the bio-tissue. THz fields propagate through air and interact with bio-tissue, followed by interactions within the substrate and, if considering a transparent substrate, it propagates through the substrate to the sample mounting material. Each layer is defined by a complex refractive index and thickness. At each interface between adjacent layers, partial reflection and transmission occur according to Fresnel relations, while propagation within each layer introduces a frequency-dependent

phase delay. Because multiple reflections occur within the layered structure, the measured THz signal is a coherent superposition of all such reflected or transmitted contributions. It is to be understood here that THz-TDS imaging in biomaterials is fundamentally a parametric contrast-mapping and spatial reconstruction technique and functionally differs from the conventional optical medical imaging diagnostics. THz-TDS imaging spectroscopy employing Fresnel-inversion modeling has been proven to yield highly-accurate tumor detection and localization in bio-tissues [14,50]. This framework provides a rigorous pathway to convert the measured THz electric-field data to intrinsic contrast in biomaterial properties. It ensures that the extracted parameters are consistent with electromagnetic wave propagation physics and are therefore physically meaningful. The resulting quantities, including refractive index, absorption coefficient, and both the real and imaginary parts of complex permittivity, provide direct insight into the composition and structure of bio-tissues. This framework becomes especially powerful for tumor detection because pathological tissues often differ from surrounding healthy tissue in precisely those properties to which THz radiation is sensitive. Tumor regions frequently exhibit increased water content, altered binding environments, changes in ionic distribution, increased cellular density, and modified extracellular architecture. These variations alter both the real and imaginary parts of the complex permittivity and therefore manifest as measurable dielectric anomalies in THz-TDS. Recent advances in THz imaging for cancer detection have been comprehensively reviewed where the contrast mechanism is attributed to variations in the complex dielectric properties of biological tissues [14]. In particular, tumor tissues exhibit higher water content compared to healthy tissues, resulting in increased refractive index and absorption coefficients in the THz frequency range. As illustrated in Figure 10, the frequency-dependent complex permittivity shows clear differentiation between tumor, fibrous, and adipose tissues, providing a strong physical basis for THz-based tissue discrimination. This dielectric contrast forms the foundation for extracting material parameters using THz-TDS and enables reliable identification of cancerous regions. Furthermore, the imaging capability of THz systems is demonstrated through experimental studies, as shown in Figure 11, where THz images reconstructed from time-domain and frequency-domain analysis exhibit distinct contrasts between malignant and normal tissues. These results highlight the potential of THz imaging as a non-invasive diagnostic modality for tumor localization and margin assessment. The broader THz tumor-imaging review literature emphasizes these mechanisms, viz., hydration-driven contrast, refractive-index variations, absorption differences, and tissue heterogeneity—central to cancer detection in the THz band, as reported by Neu and Schmittenmaer.

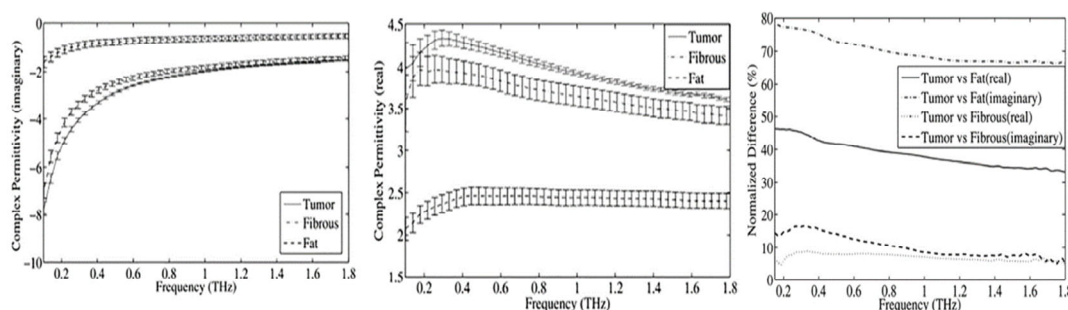


Figure 10. Frequency-dependent complex permittivity of biological tissues showing clear contrast between tumor, fibrous, and fat tissues. Dielectric differences form the basis for THz-based cancer detection through refractive index and absorption variations [14].

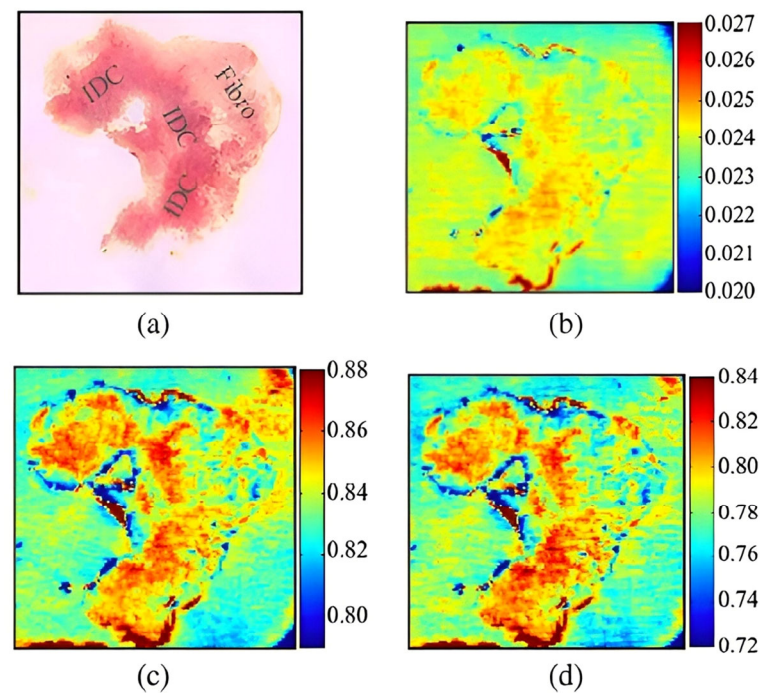


Figure 11. THz imaging of biological tissue demonstrating contrast between cancerous and normal regions. (a) Optical reference image; (b–d) THz images as a reconstructed spatial contrast mapping due to variations in dielectric properties of tissues [14].

Another important strength of multilayer Fresnel-inversion modeling to mention here is that it enables the separation of overlapping contributions from different tissue layers. Without such modeling, the measured THz signal would remain a composite response from the full structure, making it difficult to identify whether an anomaly originates at the surface, at an intermediate layer, or lies deeper in the sample. By explicitly accounting for layer-specific propagation and interface effects, the inversion procedure makes it possible to attribute extracted dielectric parameters to specific stratified regions containing the particular anomaly. This is especially important in tumor-detection problems where the pathological region may be embedded within otherwise normal tissues and where accurate localization rather than simple bulk discrimination is the real diagnostic objective.

Pickwell and Wallace demonstrated the application of inversion model methodologies and error minimization to biological tissues, emphasizing the importance of Fresnel-based modeling in biomedical THz imaging [45,46]. The application of this framework to tumor detection has been demonstrated in numerous studies. Wallace et al. showed that THz imaging can identify basal cell carcinoma through dielectric contrast correlated with histopathology. Ashworth et al., Bowman et al., and El-Shenawee et al. demonstrated that THz-TDS can distinguish between cancerous and healthy breast tissues based on differences in refractive index and absorption [47,49,50]. Grootendorst et al. remarkably demonstrated unique intraoperative feasibility of THz imaging for tissue margin assessment [51]. These studies confirm that tumor detection using THz-TDS relies fundamentally on accurate dielectric parameter extraction enabled by inversion modeling.

Although the above promising results have been reported for ex vivo tissue characterization and proof-of-concept imaging studies, significant translational challenges remain, including limited penetration depth in highly hydrated tissues, acquisition speed, system complexity, and the need for large-scale clinical validation prior to routine clinical deployment.

5.2. THz-Based Tumor Detection by Hybrid Physics-Based Inversion with Machine Learning Models

In recent years, machine learning (ML) and deep learning approaches have been increasingly explored for THz-based tumor detection, where classification models are trained directly on measured THz signals. These approaches aim to automate tissue classification and improve diagnostic accuracy by identifying patterns in frequency-domain responses or time-domain waveforms. While such methods have demonstrated promising results, they differ fundamentally from the physics-based Fresnel-inversion framework described in this work. For instance, Liu et al. demonstrated that support vector machine (SVM), k -nearest neighbors, and ensemble learning models can distinguish cancerous from non-cancerous breast tissues using THz spectral features [52]. They developed classification models to identify breast carcinoma using THz-TDS data. However, the resulting output of this methodology is limited to classification labels without direct access to physically meaningful parameters such as refractive index or complex permittivity. Wang et al. (2025) further showed that deep learning-assisted neural networks can achieve accurate cancer detection through automated feature extraction from THz signals [53]. Their results demonstrated a strong feature extraction capability and accurate identification of abnormal tissues, highlighting the potential of deep learning in THz biomedical applications. Despite these advances, the approach functions as a data-driven mapping between input signals and classification outputs, without explicitly incorporating electromagnetic wave propagation, multilayer interactions, or dielectric modeling of the tissue. Similarly, Vohra et al. applied hyperspectral THz imaging combined with spectral classification techniques such as spectral angular mapping (SAM), achieving classification accuracies in the order of 80–85% for breast tumor identification [54]. Their results demonstrating high accuracy indicate strong feasibility of statistical and machine learning techniques for THz-based tumor detection. However, their performance is closely tied to preprocessing steps, feature extraction methods, and the quality and diversity of training datasets, which can limit generalizability across different tissue types and measurement conditions.

While these ML-based approaches demonstrate strong classification capabilities, they fundamentally differ from the multilayer Fresnel-inversion framework in both methodology and interpretability. Machine learning models typically treat THz data as input features for pattern recognition, without explicitly modeling the underlying electromagnetic interactions between the THz wave and biological tissue. As a result, their outputs are often restricted to classification labels or probabilities, rather than physically meaningful quantities that describe the material itself. In contrast, the Fresnel inversion approach explicitly incorporates wave propagation, interface reflections, multilayer interference, and material dispersion, enabling direct extraction of intrinsic dielectric parameters such as refractive index and complex permittivity.

A key limitation of ML-based approaches is their dependence on large, well-labeled datasets and their sensitivity to variations in experimental conditions, including sample thickness, hydration state, and measurement geometry. Because these physical factors are not explicitly modeled, ML approaches may face challenges in generalization and reproducibility. Fresnel inversion inherently accounts for such variations through its physics-based modeling framework, making it more robust for quantitative characterization. Machine learning approaches offer advantages in handling complex datasets and can enhance detection sensitivity when combined with physically meaningful features.

We acknowledge the significant progress achieved by machine learning-based THz diagnostic methods; however, physics-based Fresnel inversion remains fundamentally superior in accuracy for quantitative THz biomaterials characterization, as it directly links measured electromagnetic responses to intrinsic material properties and enables

physically interpretable, parameter-driven analysis of tissue heterogeneity. Consequently, hybrid approaches that combine inversion-derived parameters with machine learning are emerging as a promising direction for further advancements.

The developments discussed in this section establish THz-TDS as a genuinely distinctive platform for biomaterials characterization and tumor detection because it connects a directly measured electromagnetic field to tissue electrodynamics through explicit physical modeling. The Debye and double-Debye frameworks provide the language for interpreting water-mediated dielectric relaxation. Complex permittivity extraction connects the measured THz field to intrinsic tissue parameters. Multilayer thin-film Fresnel inversion then provides the methodological bridge from measured waveforms to local dielectric properties in stratified, heterogeneous tissues. The collected THz E-field at each scan location becomes a spatial reconstruction procedure that maps intrinsic tissue parameters rather than only reflectivity. The biological contrast of tumors then emerges as a dielectric anomaly rooted in hydration, composition, and structure. Machine learning adds a valuable complementary layer for automated interpretation, but the physics-based inversion remains the foundational method for quantitative, mechanistically interpretable THz biomaterials analysis. In this sense, THz tumor detection is best understood not as a conventional diffraction-limited optical imaging modality, but as a field-resolved, model-based, dielectric-parameter-mapping technique for identifying pathological tissue heterogeneity.

6. Discussion and Future Outlook

THz-TDS serves as a unifying framework connecting materials characterization, sensing, communication technologies, and biomedical applications. These areas are fundamentally linked through the ability of THz-TDS to directly probe the interaction between terahertz electromagnetic fields and matter. Through the extraction of complex refractive index, dielectric permittivity, absorption coefficient, and conductivity, THz-TDS provides access to the intrinsic electrodynamic properties of material behavior which determines device performance. From a materials characterization perspective, THz-TDS enables investigation of charge carrier transport, dielectric response, and polarization dynamics through Fresnel formulations, inverse modeling, and transport models such as Drude and Drude–Smith. These extracted parameters form the basis for the design, implementation, and optimization of THz devices. This connection is significant in metamaterial-based sensing platforms, where resonance frequency, field confinement, and sensing performance depend on the dielectric properties measured using THz-TDS. With regard to reconfigurable intelligent surfaces (RISs) and beam-steering metasurfaces for future THz communication systems, the device architectures rely on resonant structures, field confinement, and tunable material platforms to control electromagnetic responses. Consequently, the material parameters extracted using THz-TDS directly influence device resonance behavior, phase control, absorption characteristics, and wavefront manipulation capabilities. THz-TDS therefore serves not merely as a material characterization tool but also as a foundation for the design and validation of advanced THz communication devices.

Similarly, for biomaterials characterization and tumor detection applications, the biological tissues exhibit distinct dielectric signatures arising from differences in water content, molecular composition, and tissue structure. Through Fresnel inversion and multilayer parameter extraction, THz-TDS enables spatial reconstruction of these intrinsic dielectric properties, allowing biomedical imaging to be interpreted as a dielectric parameter-mapping problem rather than solely an image-formation process. The contrast observed between healthy and diseased tissues ultimately originates from differences in electromagnetic properties, linking biomedical diagnostics to the same material characterization principles that govern sensing and communication devices. It is noteworthy

to mention here that THz technology for biomedical applications is still developing, and there are significant challenges that need to be addressed. This includes limitations in penetration depth for highly water-rich tissues, system complexity, and the need for faster data acquisition and processing. In parallel, there is an increasing interest in using machine learning for THz-based classification and diagnosis. While these approaches can be useful for handling large datasets and improving classification accuracy, they are less interpretable from a physical standpoint. In contrast, physics-based methods such as Fresnel inversion provide direct access to meaningful material parameters. A hybrid approach may be a useful direction going forward, where physically extracted parameters are used as inputs to data-driven models.

Despite significant progress in THz technology over the last two decades across materials characterization, sensing, communication systems, and biomedical applications, several challenges remain before many THz technologies achieve widespread deployment. Accurate parameter extraction for complex multilayer structures continues to require robust inversion methodologies and computationally intensive modeling approaches. In addition, the practical implementation of THz sensing and communication systems faces challenges related to device losses, fabrication complexity, tunability, integration with existing electronic and photonic platforms, and system-level scalability. Even for biomedical applications in particular, promising results have been reported for ex vivo tissue characterization and proof-of-concept tumor detection studies; however, significant translational challenges remain to be overcome as stated earlier.

Future developments in THz-TDS are now expected to be driven by advances in high-performance THz sources and detectors, tunable metasurfaces, reconfigurable intelligent surfaces, machine learning-assisted signal processing, and physics-informed inverse modeling approaches. Increasing efforts toward THz technology standardization, communication-system integration, and even large-scale clinical validation and adoption for biomedical applications are now also expected to accelerate translation from laboratory demonstrations to real-world applications. Recent developments further indicate a growing transition of THz technologies from fundamental research toward practical system-level implementation. Advances in metasurface engineering, THz source and detector technologies, communication architectures, and electromagnetic control platforms continue to expand the capabilities of THz systems while addressing challenges associated with scalability, integration, and deployment. These developments, together with ongoing efforts toward functional compatibility, benchmarking, and future communication-system integration, are expected to accelerate the translation of THz technologies into real-world sensing, communication, and imaging applications [55–57]. Looking forward, THz-TDS is likely to play an increasingly important role not only as a spectroscopy technique, but also as an enabling platform that bridges materials science, device engineering, communication technologies, and biomedical diagnostics across the broader THz ecosystem.

7. Conclusions

This review presents recent advancements in terahertz (THz) technology while emphasizing terahertz time-domain spectroscopy (THz-TDS) as a common electromagnetic framework that connects materials characterization, sensing, communication technologies, and biomedical applications. THz-TDS continues to demonstrate strong potential as a quantitative and versatile technique through its ability to directly extract material electrodynamic properties, including dielectric permittivity, refractive index, and conductivity. These capabilities provide the foundation for understanding and engineering resonant devices, metasurfaces, sensing architectures, reconfigurable intelligent surfaces (RISs), and biomedical imaging platforms.

Future progress is expected to arise from continued advances in modeling and inverse-parameter extraction techniques, improved integration with tunable materials and meta-surfaces, and ongoing efforts toward standardization and practical clinical validation. Collectively, these developments highlight the growing importance of THz technologies and their potential to bridge fundamental materials physics, device engineering, communication systems, and biomedical diagnostics toward emerging real-world applications.

Author Contributions: All authors contributed to this article equally. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We acknowledge the technical and administrative support through the department of Electrical Engineering, as well as through the various discussions and workshops held on this topic of interest at the College of Engineering of SUNY Polytechnic Institute.

Conflicts of Interest: The authors declare no conflicts of interest.

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