

RESEARCH ARTICLE

Terahertz Optical and Dielectric Properties of Sapphire Investigated by Time–Domain Spectroscopy

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ABSTRACT: The optical and dielectric behavior of sapphire at terahertz frequencies was investigated experimentally across the 0.25 to 4 THz range using a terahertz time-domain spectroscopy system. Key parameters including the complex refractive index, absorption coefficient, and complex dielectric constant were extracted from the measured THz waveforms through numerical analysis with Teralyzer software. The refractive index obtained from spectral analysis was 3.10 ± 0.001 , which agrees well with the value of approximately 3.11 calculated independently from the temporal data. The extinction coefficient remained nearly constant, varying only from 0.03 at 0.25 THz to 0.04 at 4 THz, suggesting excellent optical transmission characteristics. No distinct absorption peaks appeared within the measured frequency window, though the absorption coefficient increased gradually from about 5.5 cm^{-1} to 19 cm^{-1} . The real part of the dielectric constant stayed stable between 9.8 and 10 throughout the entire range. These results confirm that sapphire functions as a dispersion-free, broadband THz substrate suitable for bandwidths extending to approximately 4.3 THz.

Keywords: Sapphire, Terahertz Time-Domain Spectroscopy, Complex Refractive Index, Extinction Coefficient, Dielectric Constant, Absorption Coefficient

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1. INTRODUCTION

Sapphire, the single-crystal form of aluminium oxide (Al_2O_3), has become a material of considerable interest for terahertz (THz) photonic systems, particularly as a substrate for thin-film measurements and device fabrication. Its appeal rests on a combination of properties that few other materials can match: exceptional chemical purity, a wide optical transparency window, high mechanical hardness, and remarkable thermal stability [7]. These attributes make sapphire especially attractive for THz applications where reliable performance over broad spectral ranges is essential. As THz technology continues to push toward higher

frequencies and wider bandwidths, the demand for substrate materials that can sustain extensive spectral coverage without introducing measurement artefacts has grown accordingly [2]. The choice of substrate is not merely a practical concern; it directly influences the fidelity of spectroscopic data and the performance of THz devices.

Among the available techniques for characterizing materials in the sub-terahertz to multi-terahertz regime, THz time-domain spectroscopy (THz-TDS) stands out as one of the most powerful and versatile [1]. The method works by probing a sample with an ultrashort THz pulse and recording the transmitted electric field in the time domain. Fourier transformation of these waveforms then yields the amplitude and phase information needed to extract the material's complex refractive index. The appeal of THz-TDS lies in its ability to obtain both amplitude and phase simultaneously, without relying on indirect mathematical transformations such as the Kramers-Kronig relations [3]. The complex

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transmission function of the material is computed, and the resulting equations for phase and amplitude are solved numerically to give the optical constants. The complex dielectric constant follows directly from these parameters, providing a complete picture of the material's electromagnetic response [4].

The theoretical framework for extracting optical parameters from THz-TDS data has been developed extensively over the past three decades. The foundational work of Duvillaret and colleagues established reliable methods for determining material parameters from time-domain measurements, and their approach remains widely used today [5]. The refractive index can be estimated initially from the temporal delay introduced by the sample relative to a reference, using the relationship between sample thickness and the speed of light in vacuum. More rigorous spectral analysis then refines these estimates by solving the full system of nonlinear equations that govern transmission through the sample. The real part of the dielectric constant characterizes the material's capacity to store electromagnetic energy, while the imaginary part quantifies dielectric loss. Together, these parameters provide a comprehensive description of how a material interacts with THz radiation.

Despite sapphire's well-established material virtues and its widespread use as a THz substrate, a thorough experimental characterization of its optical and dielectric response across a broad THz frequency range has remained necessary. Much of the existing literature has focused on narrow frequency windows or specific applications, leaving gaps in the understanding of how sapphire behaves across the full spectral range relevant to modern THz measurements [6]. In particular, a systematic determination of the complex refractive index, absorption coefficient, and dielectric constants using consistent experimental conditions and a single, well-characterized sample would provide a valuable reference for the THz community. Such data are essential not only for validating theoretical models but also for guiding the design of THz optical components and thin-film experiments where sapphire serves as the substrate. The novelty of the present work lies in its comprehensive approach: by combining temporal and spectral analysis methods and employing TeraLyzer software for parameter extraction, we provide a self-consistent set of optical and dielectric parameters for sapphire across the 0.25 to 4 THz range, with careful attention to experimental reproducibility and data consistency. This level of detail has not been previously reported in a single study covering this bandwidth.

In this paper, we report a detailed experimental investigation of the THz optical and dielectric properties of sapphire using a custom-built THz-TDS system. The complex refractive index, absorption coefficient, and complex dielectric constant are extracted from the measured waveforms across the 0.25 to 4 THz frequency range. The results are analyzed in terms of their frequency dependence, and the implications for sapphire's use as a broadband THz substrate are discussed. The findings confirm that sapphire exhibits remarkably stable optical properties over this spectral window, reinforcing its suitability for high-fidelity

THz thin-film and device characterization.

2. EXPERIMENTAL DETAILS

2.1. Sample Description

The sapphire sample used in this investigation was a single crystal of aluminium oxide (Al_2O_3) with initial dimensions of $1 \text{ cm} \times 1.5 \text{ cm} \times 0.04 \text{ cm}$. For the THz optical measurements, the sample was carefully cut and prepared into a 0.4 mm thick piece. The choice of sapphire for this study was motivated by its high chemical purity, which is a critical requirement for obtaining accurate and reproducible THz optical data [7]. The sample was inspected to ensure uniform thickness and optical quality prior to measurement, as any variation in these parameters would directly affect the reliability of the extracted optical constants.

2.2. Theoretical Framework for Optical Parameter Extraction

The extraction of optical parameters from THz time-domain data follows a well-established procedure that combines time-domain analysis with spectral methods. An initial estimate of the refractive index n can be obtained from the temporal delay Δt introduced by the sample relative to the reference waveform. This relationship is expressed as [3]:

$$L(n - 1) = c\Delta t \quad (1)$$

Where L represents the sample thickness and c denotes the speed of light in vacuum. This simple relation provides a quick consistency check on the refractive index before more sophisticated analysis is performed.

A more rigorous determination of the frequency-dependent refractive index $n(\omega)$ and extinction coefficient $k(\omega)$ is achieved through spectral analysis. The complex transmission function of the sample is constructed from the Fourier-transformed THz waveforms, and this function is then decomposed into its phase and amplitude components. The resulting system of nonlinear equations is solved numerically using TeraLyzer software, which implements the standard parameter extraction algorithms for THz-TDS data [4]. The real and imaginary parts of the complex dielectric constant are subsequently calculated from the extracted n and k values according to the relations:

$$n = (\epsilon_r + k^2)^{\frac{1}{2}} \quad (2)$$

$$n = \frac{\epsilon_i}{2k} \quad (3)$$

In these expressions, ϵ_r represents the real part of the dielectric constant, which characterises the material's ability to store electromagnetic energy, while ϵ_i represents the imaginary part, which quantifies the dielectric loss associated

with energy dissipation in the material.

2.3. THz Time-Domain Spectroscopy Setup

The THz waveforms were acquired using a custom-built THz-TDS apparatus configured for transmission geometry [8]. Measurements were performed for two configurations: an air-holder serving as the reference and the sapphire sample serving as the specimen. The experimental arrangement allowed for stable and reproducible positioning of both the reference and sample, ensuring that any observed differences in the THz waveforms could be attributed solely to the presence of the sapphire.

The frequency-domain spectra corresponding to each time-domain waveform were obtained through Fast Fourier Transform processing. This approach enabled spectral characterization spanning the frequency range of approximately 0.25 to 4 THz. All experimental measurements were conducted at room temperature, maintained at approximately 20 °C throughout the duration of the experiments. Teralyzer software was employed for all data processing and optical parameter extraction, providing a consistent and reliable framework for analyzing the recorded waveforms.

3. RESULTS AND DISCUSSION

3.1. Time-Domain Waveform Analysis

The THz time-domain waveforms acquired for the air-holder reference and the sapphire sample exhibit two distinct and readily quantifiable differences that provide the foundation for all subsequent parameter extraction. The first observation concerns the temporal shift introduced by the sapphire sample. A measurable time delay of approximately 2.82 ps was recorded relative to the reference waveform, which directly reflects the higher refractive index of sapphire compared to air. This delay arises because the THz pulse

travels more slowly through the sapphire than through the same path length in air, and the magnitude of the delay is proportional to both the sample thickness and the difference in refractive index between the sample and the surrounding medium.

The second notable difference appears in the peak amplitude of the THz electric field. For the air reference, the peak amplitude reached approximately 4.25 nAmp, whereas the sapphire sample transmitted a peak amplitude of only about 2.65 nAmp. This corresponds to an attenuation of roughly 37.6 percent. The reduction in transmitted amplitude can be attributed primarily to absorption losses within the 0.4 mm thickness of the sapphire, along with minor contributions from Fresnel reflections at the sample surfaces. These two features, the temporal shift and the amplitude reduction, form the basis for determining the optical constants of sapphire across the THz frequency range.

Spectral analysis of the time-domain waveforms was performed using Fast Fourier Transform processing. The resulting frequency-domain spectra reveal that the THz signal transmitted through sapphire maintains its integrity up to approximately 4.3 THz. Beyond this frequency, the signal-to-noise ratio deteriorates due to the combined effects of reduced source power and increased absorption in the sapphire. This observation establishes the reliable measurement bandwidth for the present study and confirms that sapphire can serve as a substrate material for THz applications requiring spectral coverage extending well into the multi-terahertz regime.

3.2. Complex Refractive Index

The refractive index of sapphire was first estimated from the temporal delay using the relationship between the sample thickness, the speed of light, and the measured time shift. Substituting the experimental values of $\Delta t \approx 2.82$ ps and $L = 0.4$ mm into equation (1) yielded an initial estimate of $n \approx 3.11$. This value served as an independent consistency check against the results obtained from the full spectral analysis.

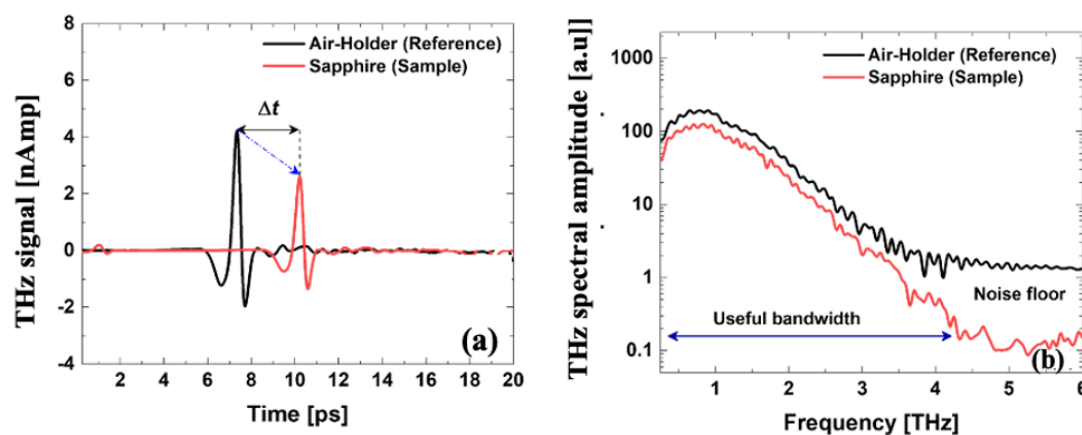


Fig. 1. THz temporal waveforms recorded for the air-holder reference (black solid line) and sapphire substrate (red solid line) (a). The corresponding frequency-domain spectra derived via Fast Fourier Transform are shown in (b).

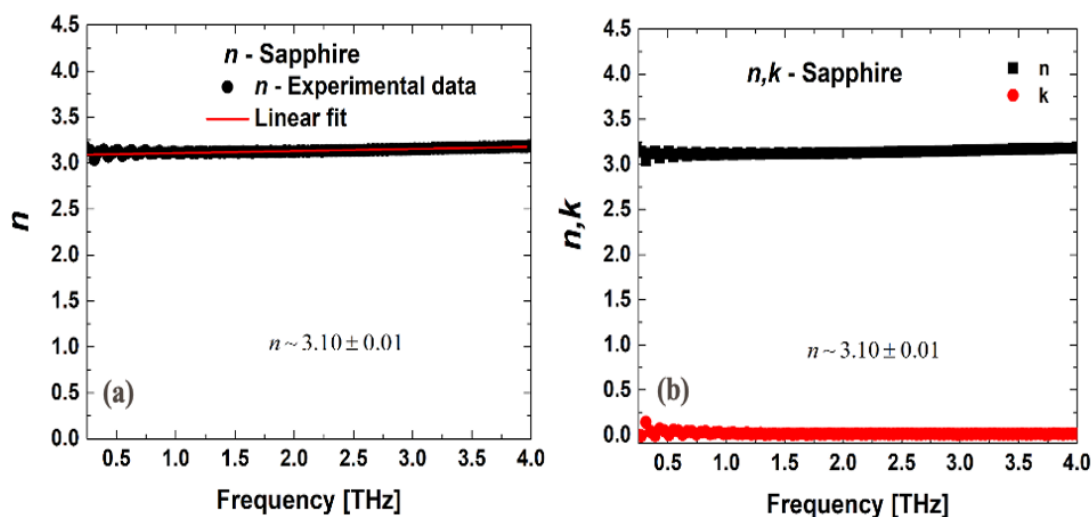


Fig. 2. (a) Spectrum of the extracted average refractive index n for a 0.4 mm thick sapphire sample across 0.25–4 THz, obtained using Teralyzer software; the red line represents a linear fit to the data. (b) Spectral components of the complex refractive index $\tilde{n}$: real part n (black squares) and imaginary part k (red circles).

The spectral extraction using Teralyzer software over the 0.25 to 4 THz range produced a refined refractive index of $n = 3.10 \pm 0.001$. The close agreement between the time-domain estimate and the spectrally resolved value confirms the internal consistency of the two independent approaches and validates the reliability of the extracted optical constants [5]. Throughout the entire measured frequency range, the refractive index remained essentially flat, showing no measurable dispersion. This dispersion-free behavior is particularly desirable for substrate materials used in precision THz thin-film measurements, as it ensures that the substrate does not introduce frequency-dependent phase distortions that could complicate the interpretation of spectroscopic data.

The extinction coefficient k , which quantifies the imaginary part of the complex refractive index, was extracted simultaneously with n . The values of k were found to be approximately 0.03 at 0.25 THz, with a marginal increase to about 0.04 at 4 THz. The near-constancy of k across this wide spectral range indicates that THz absorption in sapphire varies negligibly with frequency. This behavior reinforces the characterization of sapphire as a low-loss optical medium in the THz region and supports its use in applications where minimal signal attenuation is required.

3.3. Absorption Coefficient

The absorption coefficient α provides a direct measure of how strongly the sapphire absorbs THz radiation at each frequency. Over the 0.25 to 4 THz range, the extracted absorption coefficient exhibits a smooth, monotonically increasing trend. At the lower end of the spectrum, approximately 0.25 THz, the absorption coefficient is about 5.5 cm^{-1} . As the frequency increases to 4.0 THz, the absorption coefficient rises to approximately 19 cm^{-1} . This gradual increase is consistent with the phonon absorption

processes that become more pronounced at higher THz frequencies in oxide materials.

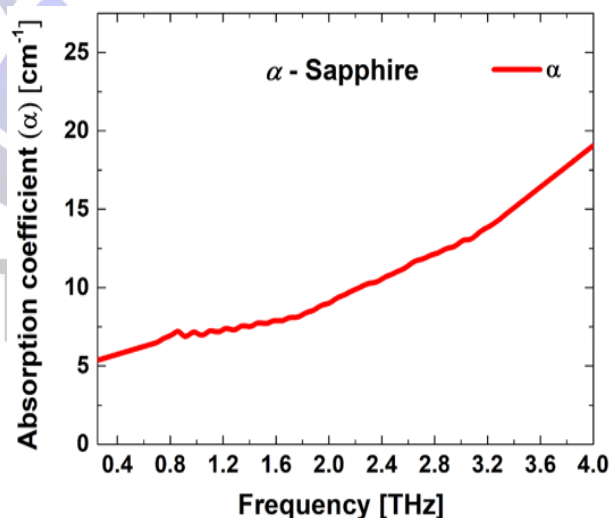


Fig. 3. Spectrum of the absorption coefficient α extracted for a 0.4 mm thick sapphire sample across the THz frequency range 0.25–4 THz, obtained from experimental data using Teralyzer software.

A particularly noteworthy feature of the absorption spectrum is the complete absence of any distinct or noticeable absorption peaks. The spectral profile remains smooth and free of resonance-like features throughout the entire measurement range. This characteristic is highly favorable for substrate applications, as it ensures that the substrate does not selectively suppress specific THz frequency components or introduce spectrally localized artefacts into thin-film measurements. The continuously low absorption coefficient

values across the full range further substantiate the designation of 0.25 to 4.3 THz as a trusted and reliable measurement bandwidth for sapphire substrates.

3.4. Dielectric Properties

The complex dielectric constant $\tilde{\epsilon} = \epsilon_r + i \epsilon_i$ was computed from the extracted n and k spectra using equations (2) and (3), covering the frequency range from 0.25 to 4 THz at room temperature (approximately 20°C) [8]. The real part of the dielectric constant, ϵ_r , which represents the material's capacity to store electromagnetic energy, demonstrated remarkable stability over the measured frequency range. The value of ϵ_r was approximately 9.8 at 2.25 THz and increased marginally to about 10 at 4 THz. This near-invariance of ϵ_r with frequency corresponds directly with the flat dispersion profile observed for the refractive index, and together these data imply a remarkably homogeneous dielectric response of sapphire over the THz spectral window.

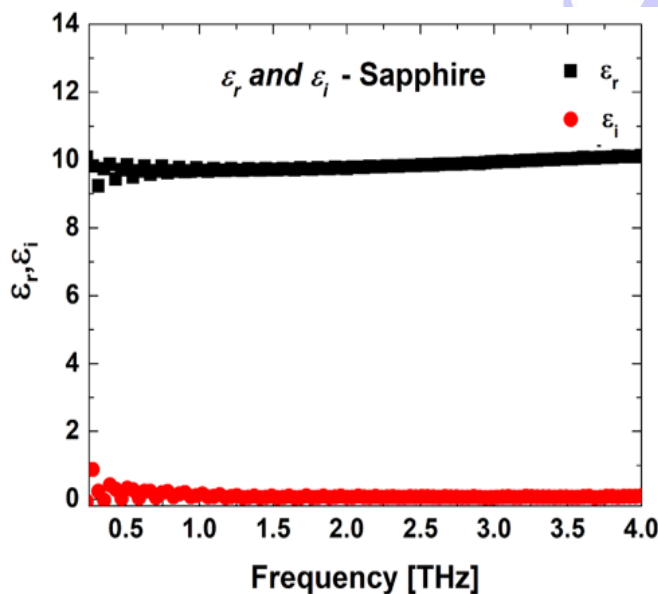


Fig. 4. Spectra of the extracted complex dielectric constant $\tilde{\epsilon}$: real part ϵ_r (black circle-line) and imaginary part ϵ_i (red circle-line) for the sapphire sample at room temperature (approximately 20 °C), obtained using Teralyzer software.

The imaginary component of the dielectric constant, ϵ_i , which governs dielectric energy dissipation, was recorded at approximately 0.6 at 2.25 THz and approximately 0.1 at 4 THz. The relatively minor variation in ϵ_i across this range is practically insignificant and does not indicate any meaningful change in the material's energy-loss characteristics. The small magnitude of ϵ_i throughout the measured range confirms that sapphire exhibits low dielectric loss in the THz region. Since ϵ_r reflects the energy storage capacity while ϵ_i reflects losses, the overall modest dielectric response of sapphire suggests that it is not well-suited for

applications requiring high THz capacitance or energy storage performance. However, this same characteristic makes sapphire an excellent choice as a substrate material, where minimal dielectric loss and stable dielectric properties are of primary importance.

The consistency of the dielectric data with the refractive index and absorption coefficient results reinforces the overall picture of sapphire as a material with stable, predictable optical properties across the THz frequency range. The combination of a flat refractive index, low extinction coefficient, smooth absorption spectrum, and stable dielectric constant makes sapphire an outstanding candidate for use as a broadband THz substrate. These properties ensure that sapphire does not introduce frequency-dependent distortions into THz measurements, allowing for high-fidelity characterization of thin films and devices deposited on this substrate.

4. CONCLUSION

A detailed experimental study of the THz optical and dielectric properties of sapphire was conducted using THz time-domain spectroscopy across the 0.25 to 4 THz frequency range [8]. The refractive index was consistently determined to be $n = 3.10 \pm 0.001$ through both temporal and spectral analysis methods, confirming the reliability of the extraction procedure. The extinction coefficient remained essentially flat at $k \approx 0.03$ to 0.04, verifying that sapphire exhibits no discernible THz dispersion or frequency-dependent absorption variation [5]. The absorption coefficient α showed a gradual rise from approximately 5.5 cm^{-1} to 19 cm^{-1} across the measured range, with no sharp absorption resonances detected. This smooth spectral profile is a hallmark of a spectrally clean, broadband-compatible substrate. The real part of the dielectric constant ϵ_r proved highly stable at approximately 9.8 to 10 across the entire range, while the small magnitude of ϵ_i confirmed a low-loss dielectric character throughout. Taken together, these results establish sapphire as an outstanding THz substrate material, offering a broad and reliable spectral bandwidth of approximately 4.3 THz, minimal dispersion, and spectrally uniform transmission. These qualities are essential for high-fidelity THz thin-film and device characterization, and the data presented here provide a valuable reference for future work involving sapphire in THz photonic systems.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has

been mutually agreed upon.

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Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

Abdulaziz. A. Asiri: Formal Analysis, Data Curation, interpretation of results and Original draft preparation; A. Ibrahim: Sample preparation, Experimental Work, Data collection, and interpretation of results. Ali. Alshehri: Data Curation, Write and Review.

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