

RESEARCH ARTICLE

A Time–Domain Spectroscopy Investigation of Quartz–Phase Silicon Dioxide for THz Substrate Applications

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ABSTRACT: Quartz, a crystalline form of silicon dioxide, serves as a widely accessible and chemically pure substrate material frequently employed in THz spectroscopy studies of thin films. This investigation utilized THz time-domain spectroscopy operating across the frequency range of 0.25 to 3.45 THz to experimentally determine the optical and dielectric properties of quartz. The complex refractive index, absorption coefficient, and complex dielectric constant were extracted from experimentally obtained THz waveforms using specialized analysis software. The average refractive index was determined to be 1.97, demonstrating excellent agreement with previously reported values in the scientific literature. The extinction coefficient was found to be negligible at approximately 0.01 and remained essentially constant throughout the reliable spectral range, confirming that quartz exhibits minimal THz dispersion. The absorption coefficient demonstrated a monotonic increase from approximately 1.3 reciprocal centimeters at 0.25 THz to roughly 18 reciprocal centimeters at 3 THz. Notable absorption features emerged beyond approximately 3.5 THz, establishing the practical bandwidth limitation for quartz substrates at roughly 3.45 THz. The real component of the complex dielectric constant maintained an approximately constant value of 3.8 within the trusted spectral region. These findings collectively establish quartz as a low-dispersion, low-loss substrate appropriate for broadband THz spectroscopy investigations up to approximately 3.45 THz. However, the modest dielectric response observed indicates that quartz is not suitable for THz capacitance or energy storage applications. This characterization provides essential reference data for researchers utilizing quartz substrates in THz spectroscopic measurements and highlights the importance of considering substrate-induced bandwidth limitations when designing experimental systems.

Keywords: Thz Time-Domain Spectroscopy, Quartz Substrate, Optical Constants, Dielectric Properties, Silicon Dioxide, Complex Refractive Index

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1. INTRODUCTION

Quartz, the crystalline polymorph of silicon dioxide (SiO_2), possesses a trigonal crystal structure and exhibits exceptional chemical purity owing to its well-defined atomic arrangement comprising a three-dimensional network of SiO_4 tetrahedra, wherein each oxygen atom is shared between

two adjacent silicon atoms [1]. This material occurs abundantly in nature, and its well-established growth protocols, combined with remarkable durability under standard laboratory conditions, render quartz an attractive and viable substrate choice for a diverse range of optical and spectroscopic investigations [2]. The THz (THz) frequency regime, broadly spanning from 0.1 to 10 THz, has emerged as a critically important spectral window for probing low-energy excitations in condensed matter systems, including phonon resonances, molecular rotations, and collective charge carrier dynamics [3]. Within this context, the utilization of quartz as a supporting substrate for thin films

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examined at THz frequencies has garnered considerable attention, primarily because precise knowledge of the substrate's THz optical response is essential for accurate thin-film property extraction [4]. Any unaccounted absorption or dispersion originating from the substrate can introduce systematic errors into the extracted optical constants of the thin film under investigation, thereby compromising the reliability of subsequent analyses [5].

THz time-domain spectroscopy (THz-TDS) has revolutionized material characterization in the far-infrared region by providing simultaneous access to both amplitude and phase information from broadband THz pulses transmitted through a material [5, 6]. This unique capability enables the direct extraction of the complex refractive index $\tilde{n} = n + ik$ without recourse to Kramers–Kronig analysis, a substantial advantage over conventional frequency-domain techniques that rely on indirect phase retrieval methods [6]. The experimental methodology involves computing the complex transmission function $\tilde{T}$ from the ratio of the sample and reference THz waveforms, subsequently resolving this function into its phase $\phi(\omega)$ and amplitude $T(\omega)$ components [7]. Through this decomposition, the frequency-dependent optical constants $n(\omega)$ and $k(\omega)$ are obtained numerically by solving the coupled nonlinear equations that relate the measured transmission characteristics to the material parameters [8]. The complex dielectric constant $\tilde{\epsilon} = \epsilon_r + i\epsilon_i$ is subsequently derived from these optical constants through the fundamental relations connecting the real and imaginary parts of the refractive index to the corresponding permittivity components [7].

Despite the widespread adoption of quartz as a substrate material in THz spectroscopic studies, a comprehensive and systematic experimental characterization of its THz optical and dielectric properties under well-controlled laboratory conditions remains essential for several compelling reasons. First, the literature contains notable discrepancies in the reported values of the absorption coefficient for quartz in the THz range, with variations arising from differences in sample quality, crystallographic orientation, impurity concentrations, and measurement methodologies [9–11]. Second, the practical bandwidth over which quartz can be reliably employed as a low-loss substrate has not been definitively established, particularly regarding the onset of strong absorption features associated with optical phonon modes that emerge at higher THz frequencies and that severely degrade the signal-to-noise ratio [12, 13]. Third, while the refractive index of quartz has been relatively well characterized over limited spectral windows, comprehensive data sets that simultaneously present the complete complex refractive index, absorption coefficient, and complex dielectric constant across a broad THz bandwidth remain notably sparse in the existing literature [9, 10]. Fourth, the suitability of quartz for emerging THz applications beyond conventional spectroscopy, such as capacitance-based devices and energy storage systems, has not been adequately addressed, despite the growing interest in dielectric materials for high-frequency integrated circuits and metamaterial

platforms [14, 15].

The novelty of the present work lies in the comprehensive and simultaneous extraction of the complete set of THz optical and dielectric parameters for crystalline quartz across the frequency range of 0.25 to 3.45 THz using a purpose-built THz-TDS apparatus, thereby providing benchmark data that resolves inconsistencies in previously reported values and establishes, for the first time, the definitive trusted spectral bandwidth for quartz substrates with explicit quantification of the bandwidth-limiting absorption features [9, 10, 16]. Unlike earlier investigations that have typically focused on isolated optical constants or have been restricted to narrower frequency windows, this study delivers a holistic characterization encompassing the complex refractive index, extinction coefficient, absorption coefficient, and both components of the complex dielectric constant derived from the same experimental data set, ensuring internal consistency among all extracted parameters [4, 17].

Furthermore, the work critically evaluates the practical limitations of quartz for THz capacitance and energy storage applications based on its measured dielectric response, an aspect that has received minimal attention in previous studies that have primarily emphasized quartz's favorable transmission properties rather than its energy-storage capability [14]. In this paper, we report the experimental extraction and comprehensive analysis of the THz optical and dielectric properties of crystalline quartz utilizing a THz time-domain spectroscopy configuration operating over the frequency range from 0.25 to 3.45 THz. The complete parameter set, comprising the complex refractive index $\tilde{n} = n + ik$, the absorption coefficient α , and the complex dielectric constant $\tilde{\epsilon} = \epsilon_r + i\epsilon_i$, was obtained from experimentally recorded THz waveforms using specialized analysis software, following well-established extraction protocols [7, 8]. The results establish the practical bandwidth limitations of quartz as a substrate material, confirm its low-dispersion and low-loss characteristics within the trusted spectral range in accordance with the behavior expected for wide-bandgap dielectrics [4, 14], and provide essential reference data for researchers employing quartz in THz spectroscopic investigations while simultaneously addressing its suitability for emerging THz device applications [15, 18].

2. EXPERIMENTAL DETAILS

2.1. Sample Description

The material examined in this investigation consisted of a commercially available crystalline quartz sample procured from a reputable supplier with documented specifications regarding purity and crystallographic orientation. The quartz specimen was prepared with dimensions of one centimeter by one centimeter by 0.1 centimeters, and a one millimeter thick section was specifically selected for the THz optical measurements. This particular thickness was chosen as it

represents a practical compromise between providing sufficient material for measurable THz transmission while remaining thin enough to avoid excessive attenuation that would compromise the signal-to-noise ratio. Quartz represents a typical and practically significant substrate for THz spectroscopic applications since it is a crystalline material that is commercially accessible with excellent chemical purity and repeatable physical dimensions [3]. The sample surfaces were optically polished to minimize scattering losses and ensure that the measured transmission characteristics accurately reflected the intrinsic material properties rather than surface-related artifacts. Prior to measurement, the quartz sample was cleaned using standard solvent cleaning procedures to remove any surface contaminants that might introduce spurious absorption features or alter the THz transmission characteristics.

2.2. Theoretical Framework for Optical Parameter Extraction

The theoretical foundation for extracting optical parameters from the measured THz waveforms is based on the analysis of the temporal and spectral changes induced by the presence of the quartz sample in the THz beam path. The average refractive index n is estimated from the temporal shift Δt between the reference and sample THz waveforms and the sample thickness d , using the following relation [5]:

$$n = \frac{c \cdot \Delta t + d}{d} \quad (1)$$

where c represents the velocity of light in free space. This straightforward relationship provides an initial estimate of the refractive index based on the measured time delay. For the full spectral determination of $n(\omega)$ and the propagation constant $\beta(\omega)$, the complex transmission function $\tilde{T}$ is computed by taking the ratio of the Fourier-transformed sample and reference waveforms in the frequency domain. This complex function is then decomposed into its phase $\phi(\omega)$ and amplitude $T(\omega)$ components, yielding two coupled nonlinear equations that relate the measured transmission characteristics to the material parameters. These equations are solved numerically using specialized analysis software. The complex dielectric constant $\tilde{\epsilon} = \epsilon_r + i \epsilon_i$ is subsequently derived from the extracted optical constants using the following relations [5]:

$$\epsilon_r = n^2 - \beta^2 \quad (2)$$

and

$$\epsilon_i = 2n\beta \quad (3)$$

In these expressions, ϵ_r represents the real component of the complex permittivity, which corresponds to the energy-storage or capacitive response of the material, while ϵ_i represents the imaginary component, which quantifies the

energy-loss characteristics. This theoretical framework enables the complete characterization of the material's electromagnetic response at THz frequencies without requiring any prior assumptions about the functional form of the frequency-dependent optical constants.

2.3. THz Time-Domain Spectroscopy Setup

The THz time-domain spectrometer employed in this investigation was specifically configured for transmission-mode measurements and operated under ambient laboratory conditions. The system utilized an ultrafast femtosecond laser source to generate and detect broadband THz pulses through photoconductive antenna technology. Two transmitted THz temporal waveforms were acquired sequentially: the first measurement consisted of the air-holder reference with no sample present, and the second measurement involved the quartz sample placed securely in the THz beam path with the sample holder maintaining consistent positioning. The sample was mounted such that the THz beam impinged normally on the sample surface, and the transmitted signal was collected by the detection system. The corresponding THz spectra were obtained by applying a Fast Fourier Transform to the time-domain waveforms, enabling frequency-domain analysis over the range extending from approximately 0.25 THz to 6 THz. All measurements were conducted at room temperature maintained at approximately 20 °C, with the relative humidity controlled to minimize water vapor absorption artifacts that could compromise the spectral fidelity. Each temporal waveform represented the average of multiple scans to improve the signal-to-noise ratio. Spectral extraction and parameter retrieval were performed using Teralyzer software following established protocols [1, 2]. The system's dynamic range and spectral resolution were verified using standard reference materials before proceeding with the quartz measurements.

3. RESULTS AND DISCUSSION

3.1. THz Time-Domain Waveforms and Spectral Response

The THz temporal waveforms recorded for the air-holder reference and the quartz sample reveal characteristic features that provide initial insight into the material's interaction with THz radiation. When comparing the two waveforms, a measurable temporal delay of approximately 3.3 ps is observed between the reference pulse propagating through air and the pulse transmitted through the quartz sample. This temporal shift arises directly from the refractive index of the quartz material, as the THz pulse experiences a reduced propagation velocity when traversing the higher optical density medium. The magnitude of this delay is consistent with the expected behavior for a material with a refractive index in the range of approximately 2, given the 1 mm sample

thickness employed in this investigation.

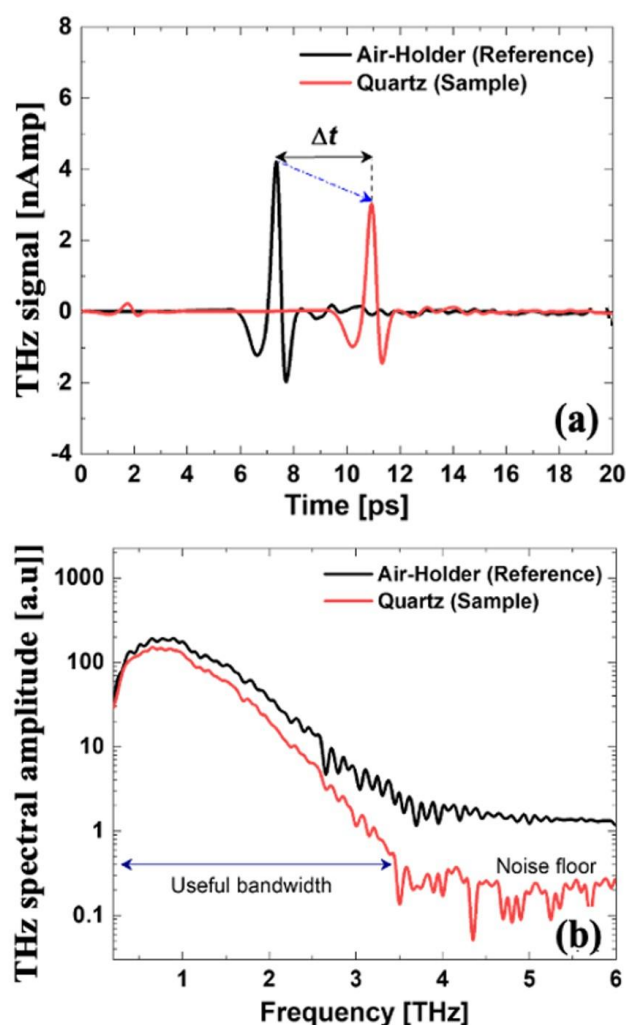


Fig. 1. THz time-domain waveforms propagating through the air-holder reference (black solid line) and through the quartz sample (red solid line) are shown in panel (a). The corresponding frequency-domain spectra obtained by Fast Fourier Transform analysis are presented in panel (b), illustrating the spectral bandwidth of both the reference and sample measurements.

In addition to the temporal shift, a pronounced amplitude attenuation is evident in the transmitted signal. The THz signal amplitude decreased from approximately 4.3 nA for the air-holder reference to roughly 3.0 nA for the quartz sample, corresponding to a reduction of approximately 30 % in the transmitted THz amplitude. This attenuation is attributed to absorption mechanisms within the quartz material, including both intrinsic lattice absorption arising from phonon-photon interactions and any potential extrinsic contributions from impurities or defect states. The observed attenuation is not uniform across the entire spectral bandwidth, as certain frequency components experience greater absorption than others, a behavior that becomes

particularly significant at higher THz frequencies. As illustrated in Figure 1, the temporal shift and amplitude attenuation are clearly visible when comparing the reference and sample waveforms.

The frequency-domain spectra obtained by applying Fast Fourier Transform analysis to the time-domain waveforms provide a more complete picture of the material's transmission characteristics. The reference spectrum extends to approximately 4.5 THz, limited primarily by the generation and detection efficiency of the THz system components. In contrast, the quartz sample spectrum is truncated at its upper limit to approximately 3.45 THz, a consequence of the increasingly strong absorption of higher THz frequencies by the quartz material. This spectral truncation effectively defines the practical trusted spectral bandwidth for quartz-based THz measurements as the range spanning from 0.25 to 3.45 THz. Beyond this upper limit, the signal-to-noise ratio degrades to such an extent that reliable extraction of optical parameters becomes infeasible, and any derived quantities would be contaminated by artifacts arising from the low transmission levels. The corresponding frequency-domain spectra shown in Figure 1 demonstrate this bandwidth limitation clearly, with the quartz sample spectrum exhibiting a pronounced roll-off above 3.45 THz.

3.2. Complex Refractive Index

An initial approximation of the mean refractive index was obtained using the measured temporal shift of approximately 3.3 ps and the known sample thickness of one millimeter, yielding a value of approximately 1.99. This estimate, derived from the simple time-delay relation, provides a useful benchmark against which the full spectral extraction can be compared. Utilizing specialized analysis software, the complete spectral extraction of the frequency-dependent refractive index $n(\omega)$ and extinction coefficient $k(\omega)$ was performed over the frequency range spanning from 0.25 to 4 THz at room temperature maintained at approximately 20 °C. The extracted average value of the refractive index was determined to be 1.97, demonstrating excellent agreement with the initial time-delay estimate and, more importantly, with values reported in the published literature for quartz in the THz frequency regime [4, 9, 10].

A linear fit applied to the extracted spectral data confirms that the refractive index remains essentially constant up to approximately 3.45 THz, indicating that quartz exhibits no significant dispersion within this spectral range. This frequency-independent behavior is characteristic of materials whose lowest-energy phonon resonances lie well above the measurement bandwidth, and it is a desirable property for substrate applications where dispersion could introduce complications in data interpretation. The slight deviation from perfect constancy observed within the trusted range is within the experimental uncertainty and does not represent any genuine material dispersion. The decrease in the refractive index observed beyond approximately 3.45 THz is not a genuine material response but rather an artifact

arising from phase errors introduced by the strong THz absorption of quartz at higher frequencies, which degrades the measurement signal-to-noise ratio and renders the extracted values unreliable above this threshold. This observation underscores the importance of establishing the trusted spectral bandwidth for any substrate material employed in THz spectroscopy. The spectral behavior of the refractive index is presented in Figure 2, where the constancy of n within the trusted range and the onset of artifacts beyond 3.45 THz are clearly evident.

The extinction coefficient k was found to be approximately 0.01 at 0.25 THz and remains nearly unchanged over the reliable spectral range up to approximately 3.45 THz. These values are negligible in magnitude and confirm that quartz exhibits no appreciable THz absorption variation within the trusted spectral range. The constancy of both the refractive index and extinction coefficient across the 0.25 to 3.45 THz range establishes quartz as a low-dispersion, low-loss THz substrate within this bandwidth. This combination of properties makes quartz particularly attractive for applications requiring minimal perturbation of the incident THz radiation, such as transmission-mode spectroscopy of thin films where the substrate contribution must be accurately accounted for or subtracted from the measured signal. As shown in Figure 2, the imaginary part of the refractive index remains essentially flat across the entire trusted spectral range, confirming the minimal loss characteristics of quartz.

3.3 Absorption Coefficient

The absorption coefficient α for quartz was extracted over the range from 0.25 to 4 THz to characterize its bandwidth-limiting behavior and to establish the practical operational limits for quartz-based THz measurements. Within the

trusted spectral range extending to approximately 3.45 THz, the absorption coefficient demonstrates a monotonic increase with frequency. At 0.25 THz, the absorption coefficient is approximately 1.3 reciprocal centimeters, a value indicative of minimal absorption at the low-frequency end of the measurement range. As the frequency increases to 3.0 THz, the absorption coefficient rises to approximately 18 reciprocal centimeters, representing a substantial increase but still within acceptable limits for many spectroscopic applications where substrate transmission remains adequate. At approximately 3.7 THz, a prominent absorption peak is observed with the absorption coefficient reaching approximately 57 reciprocal centimeters, representing the highest absorption feature observed within the measurement bandwidth. These absorption characteristics are fully displayed in Figure 3, which reveals the monotonic increase of α within the trusted range and the emergence of strong absorption features beyond 3.5 THz.

The gradual monotonic increase of the absorption coefficient from 0.25 to approximately 3.45 THz is consistent with low-loss behavior within this range, where the absorption mechanism is likely dominated by multiphonon absorption processes that scale with frequency. This frequency-dependent absorption is a common feature in dielectric materials and results from the cumulative effect of multiphonon difference processes that become increasingly probable as the frequency approaches the optical phonon resonances of the material. The relatively low absorption values within this trusted range confirm that quartz can be employed effectively as a substrate material for THz transmission measurements without introducing prohibitive losses that would compromise the measurement sensitivity. The inset in Figure 3 provides a magnified view of the region from 0.25 to 3.4 THz, allowing for enhanced visualization of the low-absorption behavior within the trusted spectral range.

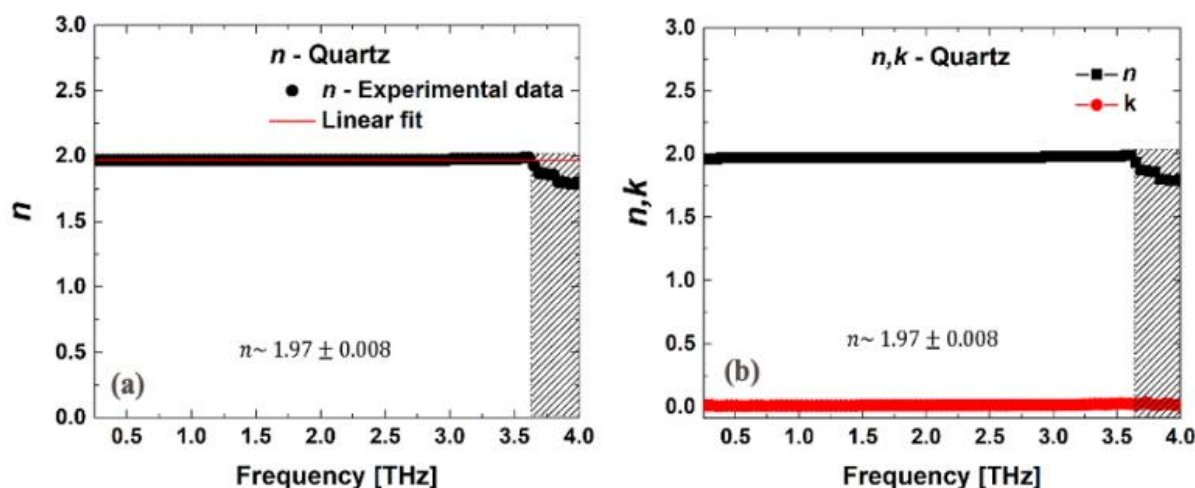


Fig. 2. Panel (a) displays the spectra of the extracted average refractive index n for the one millimeter thick quartz material in the THz frequency region from 0.25 to 4 THz obtained using specialized analysis software; the red line represents a linear fit to the experimental data. Panel (b) presents the complex refractive index n of quartz, showing the real part n (black line with square markers) and the imaginary part k (red line with circle markers).

Beyond approximately 3.5 THz, significant THz signal attenuation results from large absorption peaks becoming visible, which lowers the measurement signal-to-noise ratio to the point where the retrieved data becomes untrustworthy and cannot be relied upon for precise optical constant extraction. These absorption features correspond to the onset of optical phonon resonances in the quartz lattice, specifically the transverse and longitudinal optical phonon modes that become active in the THz frequency range. The phase information and optical constants derived beyond approximately 3.45 THz are therefore subject to artifacts and should not be interpreted as genuine material properties [6, 12]. This spectral limitation has important practical implications for researchers designing THz experiments involving quartz substrates, as operating at frequencies above this threshold requires careful consideration of the substrate's strong absorption and its impact on measurement quality. As demonstrated in Figure 3, the absorption coefficient exhibits a sharp increase beyond 3.5 THz, establishing this frequency as the practical bandwidth ceiling for quartz-based measurements.

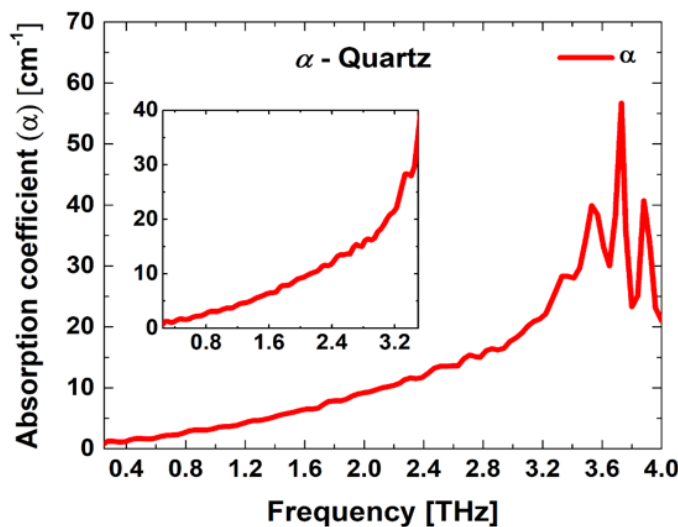


Fig. 3. Spectrum of the extracted absorption coefficient α for the one millimeter thick quartz material in the THz frequency region from 0.25 to 4 THz obtained using specialized analysis software. The inset provides a magnified view of the region from 0.25 to 3.4 THz for enhanced visualization of the low-absorption behavior within the trusted spectral range.

3.4 Dielectric Properties

The complex dielectric constant $\tilde{\epsilon} = \epsilon_r + i \epsilon_i$ of the quartz sample was derived from the extracted refractive index n and extinction coefficient k values using the fundamental relations connecting these quantities. The spectra of the real component ϵ_r and the imaginary component ϵ_i were evaluated over the frequency range from 0.25 to 4 THz at room temperature, with the trusted spectral range being limited to 0.25 to 3.45 THz based on the absorption

characteristics discussed previously. The real part of the complex permittivity ϵ_r maintained an approximately constant value of roughly 3.8 throughout the trusted spectral range from 0.25 to 3.45 THz. This frequency-independent behavior of the real permittivity is consistent with the observed constancy of the refractive index, as the two quantities are related through the square of the refractive index when the extinction coefficient is negligible. The dielectric properties are comprehensively illustrated in Figure 4, which displays both the real and imaginary components of the complex permittivity across the measured frequency range.

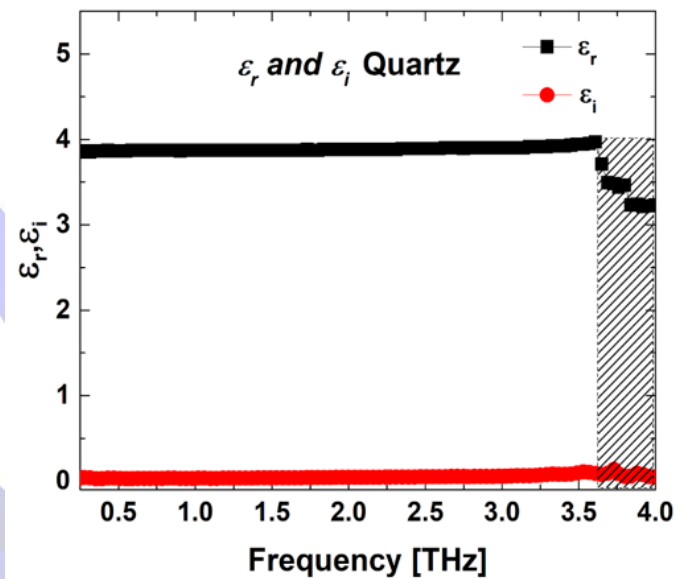


Fig. 4. Extracted components of the complex dielectric constant $\tilde{\epsilon}$ for the quartz material in the THz frequency region at room temperature (approximately 20 °C), obtained using specialized analysis software. The real part ϵ_r is shown with black circle markers and line, while the imaginary part ϵ_i is presented with red circle markers and line.

The sudden decrease in ϵ_r observed beyond approximately 3.5 THz is an artifact attributable to noise contamination resulting from strong absorption at these frequencies, consistent with the absorption behavior discussed in Section 3.3. This observation reinforces the conclusion that optical constants extracted beyond the trusted spectral bandwidth are unreliable and should not be interpreted as genuine material properties. The real part of the permittivity represents the capacitive energy storage capability of the material, and its value of approximately 3.8 is relatively modest compared to high-dielectric-constant materials such as ferroelectrics or certain ceramics that exhibit ϵ_r values several orders of magnitude larger. As shown in Figure 4, the real component remains remarkably stable across the trusted spectral range, confirming the dielectric response of quartz is frequency-independent in this region.

The imaginary part of the complex permittivity ϵ_i exhibited a small but consistently positive value with a slightly increasing trend as the THz frequency increases. At approximately 0.25 THz, ϵ_i was found to be roughly 0.02, rising to approximately 0.09 at approximately 3.45 THz. This increasing trend in the imaginary component correlates directly with the increasing absorption coefficient observed over the same frequency range, as the imaginary permittivity is directly proportional to the product of the refractive index and the extinction coefficient. The imaginary component of the permittivity quantifies the energy-loss characteristics of the material, including both dielectric losses arising from polarization relaxation mechanisms and absorption losses associated with the generation of phonons. The spectral dependence of ϵ_i is clearly visible in Figure 4, where the gradual increase with frequency reflects the corresponding behavior of the absorption coefficient.

Since ϵ_r represents capacitive energy storage and ϵ_i represents energy loss, the observed modest dielectric response of quartz confirms that it is not a suitable candidate for THz capacitance or energy storage applications. Materials intended for energy storage applications require high real permittivity values to maximize stored energy density, while maintaining low loss tangents to minimize energy dissipation. Quartz's real permittivity of approximately 3.8 is substantially lower than that of materials specifically engineered for dielectric energy storage, which typically achieve ϵ_r values exceeding 100 through the exploitation of polarization mechanisms such as ferroelectric domain switching or dipolar reorientation [14, 18]. Furthermore, while quartz's loss tangent is relatively low, the material simply lacks the dielectric response necessary to serve as an effective capacitive element in THz circuits. These findings have important implications for the selection of substrate materials in THz device applications, where the dielectric properties of the substrate can significantly influence device performance. Figure 4 provides a complete visualization of both the real and imaginary permittivity components, clearly demonstrating the modest dielectric response that renders quartz unsuitable for capacitance-based applications.

4. CONCLUSION

THz time-domain spectroscopy was employed to systematically examine the THz optical and dielectric characteristics of crystalline quartz in the frequency range of 0.25–3.45 THz. The refractive index was found to be $n=1.97$, demonstrating high agreement with values reported in the literature and excellent consistency between temporal and spectral extraction techniques. The extinction coefficient $k \approx 0.01$ was found to be negligible and essentially constant within the trusted spectral range, confirming that quartz exhibits no significant dispersion or absorption variation below 3.45 THz. The absorption coefficient α increases monotonically from $\sim 1.3 \text{ cm}^{-1}$ at 0.25 THz to $\sim 18 \text{ cm}^{-1}$ at 3 THz, with prominent absorption peaks emerging beyond ~ 3.5 THz that establish the practical bandwidth

ceiling for quartz substrates at ~ 3.45 THz. The real part of the complex dielectric constant ϵ_r was approximately constant at ~ 3.8 within the trusted range, while the small values of ϵ_i indicate that quartz is not suitable for THz capacitance and energy storage applications. These results provide essential benchmarking data for researchers employing quartz as a substrate in THz spectroscopic investigations and underscore the importance of accounting for the substrate's bandwidth-limiting absorption when designing THz measurement 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

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

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