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RESEARCH ARTICLE

Terahertz Optical and Dielectric Properties of BK7 Silicate Glass: Characterization of the Complex Refractive Index and Dielectric Response in the Terahertz Frequency Region

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ABSTRACT: BK7 is a widely available borosilicate glass composition (74.3SiO_2-9.5B_2O_3-9.2Na_2O-5.8K_2O-1.2BaO) commonly employed as an amorphous substrate material in various laboratory environments. This study investigates the terahertz (THz) frequency properties of a standard BK7 glass substrate using a purpose-built THz time-domain spectroscopy (THz-TDS) system. The complex refractive index $\tilde{n} = n + ik$, absorption coefficient α, and complex dielectric constant $\tilde{\varepsilon} = \varepsilon_1 + i\varepsilon_2$ were extracted from experimentally obtained THz transmission data using Teralyzer software. The BK7 sample (dimensions: 7.5 cm × 2.5 cm × 1 mm) exhibited a real refractive index of $n = 2.549 \pm 0.002$ across the 0.25-1.2 THz range, with minimal dispersion. The absorption coefficient demonstrated a monotonic increase from approximately 9.4 cm^{-1} at 0.25 THz to 149 cm^{-1} at 1.4 THz. The reliable spectral bandwidth of BK7 was established as 0.25-1.2 THz, beyond which strong absorption renders measurements unreliable. The real part of the complex permittivity ε_1 remained nearly constant at approximately 6.5 within the trusted bandwidth, while ε_2 exhibited small positive values increasing with frequency. These results demonstrate that although BK7 is a convenient substrate material, its strong THz absorption above 1.2 THz significantly limits its applicability for broadband THz spectroscopic measurements, establishing critical constraints for experimental design.

Keywords: BK7 glass; Terahertz time-domain spectroscopy; Complex refractive index; Absorption coefficient; Complex permittivity; THz substrate characterization.

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1. INTRODUCTION

Glass materials have long served as fundamental components in optical systems due to their excellent transparency, mechanical stability, chemical durability, and cost-effectiveness. Among the various glass compositions available, borosilicate glasses occupy a particularly important position owing to their low thermal expansion coefficients, high chemical resistance, and favorable optical transmission properties across broad spectral ranges [1, 2]. BK7, a specific borosilicate glass formulation (74.3SiO_2-9.5B_2O_3-9.2Na_2O-5.8K_2O-1.2BaO), has emerged as a ubiquitous substrate material in optical and photonics laboratories worldwide. Its amorphous nature, combined with exceptional optical homogeneity and minimal birefringence, makes BK7 an ideal candidate for thin-film deposition substrates, optical windows, beam splitters, and reference samples in various spectroscopic configurations [3, 4].

The terahertz (THz) frequency regime, conventionally defined as spanning 0.1 to 10 THz, has experienced remarkable growth in scientific and technological importance over the past two decades [5, 6]. This spectral

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region bridges the gap between microwave electronics and infrared photonics, offering unique capabilities for non-destructive testing, biomedical imaging, security screening, chemical sensing, and high-speed wireless communications [7, 8]. The development of THz time-domain spectroscopy (THz-TDS) has been particularly transformative, enabling direct measurement of both amplitude and phase information of THz pulses, thereby allowing comprehensive extraction of complex optical constants without requiring Kramers-Kronig analysis [9, 10].

The accurate characterization of optical materials in the THz region has become increasingly critical as THz technologies mature from laboratory demonstrations to practical applications [11, 12]. For substrate materials routinely employed in THz experiments, knowledge of their frequency-dependent refractive indices and absorption coefficients is essential for proper interpretation of transmission measurements, elimination of Fabry-Pérot etalon effects, and correction of signal distortions arising from substrate-induced temporal delays and amplitude attenuations [13, 14]. Despite extensive documentation of BK7 optical properties in the visible and near-infrared spectral regions, its THz optical response remains comparatively less explored in the peer-reviewed literature [15, 16].

Several investigations have reported THz characterization of common glass substrates using THz-TDS techniques [17-19]. Naftaly and Miles conducted comprehensive surveys of various optical materials including BK7, providing baseline values for refractive indices and absorption coefficients at selected THz frequencies [20]. However, detailed spectral characterization across broad THz bandwidths, including the identification of reliable measurement ranges and the quantification of parameter uncertainties, has been limited. The strong frequency-dependent absorption exhibited by many oxide glasses in the THz region, attributed to vibrational modes of the glass network and phonon-assisted processes, necessitates careful experimental design and data validation [21, 22].

In THz-TDS measurements, the substrate material directly influences the transmitted signal through multiple mechanisms: temporal delay induced by the real refractive index, amplitude attenuation from absorption, and multiple internal reflections contributing to Fabry-Pérot etalon fringes [23, 24]. Comprehensive characterization of these contributions is a prerequisite for accurate material measurements when BK7 is employed as a sample carrier, reference window, or optical component in THz beam paths [25]. Without such characterization, systematic errors can propagate into the extracted optical constants of unknown materials deposited or mounted on BK7 substrates.

In this paper, we report THz-TDS measurements of a standard BK7 glass substrate conducted with a purpose-built THz setup designed for reliable optical parameter extraction. The principal parameters extracted from the experimental transmission data include the complex refractive index $\tilde{n} = n + ik$, the absorption coefficient α, and the complex dielectric constant $\tilde{\varepsilon} = \varepsilon_1 + i\varepsilon_2$. These quantities are systematically analyzed over the spectral range 0.25–4 THz, with particular emphasis on identifying the frequency interval within which reliable, noise-free measurements can be obtained. Special attention is devoted to establishing the trusted spectral bandwidth of BK7 and characterizing the frequency dependence of absorption that ultimately limits its applicability in broadband THz spectroscopy. The results provide practical guidance on the usable spectral bandwidth of BK7 in THz experiments and establish benchmark optical constants for this material, offering a valuable reference for researchers incorporating BK7 into THz measurement configurations.

2. EXPERIMENTAL DETAILS

2.1. Experimental Configuration

Figure 1 provides a schematic representation of the experimental THz time-domain spectroscopy (THz-TDS) system used to measure the optical and dielectric properties of the BK7 glass substrate. This diagram illustrates the key components of the setup and their interconnections, enabling readers to understand the experimental methodology and assess the reliability of the reported measurements. The schematic also serves to contextualize the subsequent experimental results by clarifying the measurement geometry, beam propagation paths, and signal detection mechanism.

The system is driven by a mode-locked Ti:sapphire oscillator (typically operating at 800 nm central wavelength) that generates ultrashort laser pulses with durations of approximately 100 femtoseconds at a repetition rate of 80 MHz. This laser provides the optical excitation necessary for both THz generation and detection. The ultrashort pulse duration is critical for achieving broadband THz emission and high temporal resolution in the time-domain measurements.

The output from the femtosecond laser is divided into two separate beams, pump and probe, using a beam splitter. The pump beam (typically comprising ~80-90% of the laser power) is directed toward the THz emitter, where it triggers the generation of THz radiation. The probe beam (the remaining ~10-20%) is directed toward the detector via a controlled optical delay line, enabling synchronized sampling of the THz electric field.

The pump beam is focused onto the PCA emitter, which consists of a semiconductor substrate (typically low-temperature-grown GaAs or InGaAs) patterned with metal electrodes. Upon illumination by the femtosecond laser pulses, photoexcited carriers are accelerated by a bias voltage applied across the electrodes, generating an ultrafast transient current that radiates a THz pulse. The emitted THz radiation is collimated and focused onto the sample position using off-axis parabolic mirrors.

The BK7 glass substrate (dimensions: 7.5 cm × 2.5 cm × 1 mm) is mounted in a sample holder positioned at the focal point of the THz beam. The holder is designed to maintain the sample perpendicular to the beam propagation direction

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to minimize reflection losses and ensure reproducible measurements. For reference measurements, the holder is left empty (air-filled), allowing the incident THz waveform to be recorded without the sample.

The probe beam path includes an optical delay line comprising a retroreflector mounted on a motorized translation stage. By varying the optical path length of the probe beam relative to the pump beam, the system can sample different temporal positions of the THz waveform with sub-picosecond resolution. The delay line enables the reconstruction of the complete time-domain waveform by recording the THz electric field as a function of time delay.

The transmitted THz pulse is focused onto the PCA detector, which operates on the principle of photoconductive sampling. The probe beam arrives at the detector with a controlled time delay relative to the THz pulse, gating the photoconductive response. The THz electric field modulates the conductivity of the semiconductor gap, generating a photocurrent that is proportional to the instantaneous THz field amplitude. By scanning the optical delay line, the entire THz waveform is sampled point-by-point.

The photocurrent from the PCA detector is amplified and demodulated using a lock-in amplifier synchronized to the laser repetition rate or an optical chopper. This phase-sensitive detection significantly improves the signal-to-noise ratio by rejecting uncorrelated noise sources. The digitized signals are processed and stored by a computer for subsequent Fourier transformation and optical parameter extraction.

In each measurement, two THz time-domain waveforms were recorded: (i) a reference waveform, consisting of the THz pulse propagating through an air-filled sample holder (air-holder reference), and (ii) a sample waveform, consisting of the THz pulse transmitted through the BK7 substrate placed in the sample holder. The temporal THz waveforms and their corresponding amplitude spectra — obtained via fast Fourier transform (FFT) were used for subsequent data extraction [1-10].

All optical parameter extraction was performed at room temperature (~ 20°C) using Teralyzer software, which implements standard THz-TDS analysis algorithms based on the complex transmission function formalism.

2.2. Theoretical Framework for Optical Parameter Extraction

The fundamental observable in THz-TDS is the transmitted time-domain electric field waveform. A comparison of the reference (air-holder) and sample (BK7) waveforms yields the complex transmission function $\tilde{T}(\omega)$, from which the optical constants of the sample are extracted.

A first-order estimate of the average real refractive index n is obtained directly from the temporal delay Δt between the reference and sample waveforms, together with the known sample thickness L, via the following relation

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

where c is the speed of light in free space.

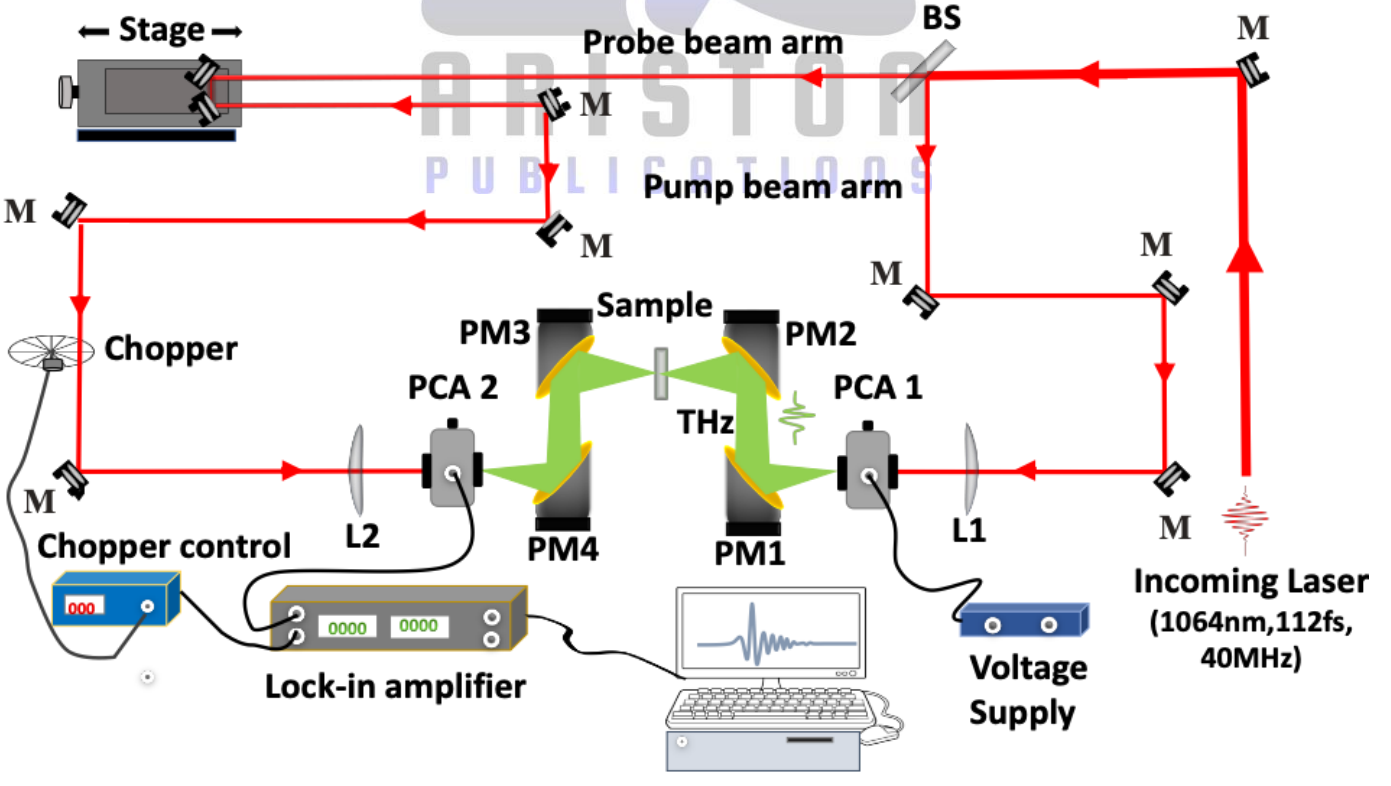


Fig. 1. Schematic of THz experimental setup used in this study.

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This temporal-domain estimate provides a rapid, model-independent approximation of n prior to the full spectral extraction.

The frequency-domain analysis employs the complex transmission function $\tilde{T}(\omega)$, defined as the ratio of the Fourier-transformed sample field to the Fourier-transformed reference field. This function is separated into its phase component $\phi(\omega)$ and amplitude component $|\tilde{T}(\omega)|$, yielding two coupled nonlinear equations for $n(\omega)$ and $k(\omega)$ that are solved numerically using Teralyzer software.

The complex refractive index is defined as:

$$\tilde{n}(\omega) = n(\omega) + ik(\omega) \quad (2)$$

where $n(\omega)$ is the real (dispersive) part and $k(\omega)$ is the extinction coefficient (absorptive part). The absorption coefficient $\alpha(\omega)$ is related to $k(\omega)$ through:

$$\alpha(\omega) = \frac{2\omega k(\omega)}{c} \quad (3)$$

The complex dielectric constant $\tilde{\varepsilon}(\omega)$ is related to the complex refractive index by:

$$\tilde{\varepsilon}(\omega) = \tilde{n}^2(\omega) \quad (4)$$

From which the real and imaginary parts of the permittivity are obtained as:

$$\varepsilon_1(\omega) = n^2(\omega) - k^2(\omega) \quad (5)$$

$$\varepsilon_2(\omega) = 2n(\omega)k(\omega) \quad (6)$$

where ε_1 characterizes the energy storage (capacitive) response of the material, and ε_2 characterizes the energy loss (dissipative) response

3. RESULTS AND DISCUSSION

3.1. Time-Domain Waveforms and Spectral Characterization

The transmitted THz time-domain waveforms for both the air-holder reference and the BK7 sample are presented in Figure 2(a). Their corresponding amplitude spectra, obtained by FFT, are displayed in Figure 2(b). Two characteristic features are immediately evident from the temporal waveforms (Figure 2(a)). First, a temporal shift Δt of ~5.2 ps is observed between the reference and sample waveforms. This delay is caused by the reduced phase velocity of the THz pulse propagating through BK7 glass (thickness L = 1 mm) relative to air and is a direct manifestation of the refractive index of the material. Second, a significant reduction in THz electric field amplitude is observed, from ~42 nA in the air-holder reference to ~4.8 nA in the BK7 transmission, corresponding to an amplitude attenuation of ~88.5%. This attenuation is attributable to the absorption of THz radiation by the BK7 material.

The amplitude spectra (Figure 2(b)) reveals that the air-holder reference spectrum extends from ~0.25 THz to ~4.5 THz. In contrast, the BK7 sample spectrum is truncated at its upper frequency limit to ~1.2 THz, a reduction that is directly caused by the strong absorption of higher THz frequencies by BK7 glass. Consequently, the trusted spectral bandwidth for measurements employing BK7 as a substrate is established to be 0.25–1.2 THz. This bandwidth limitation must be carefully accounted for in any THz spectroscopic measurement utilizing BK7.

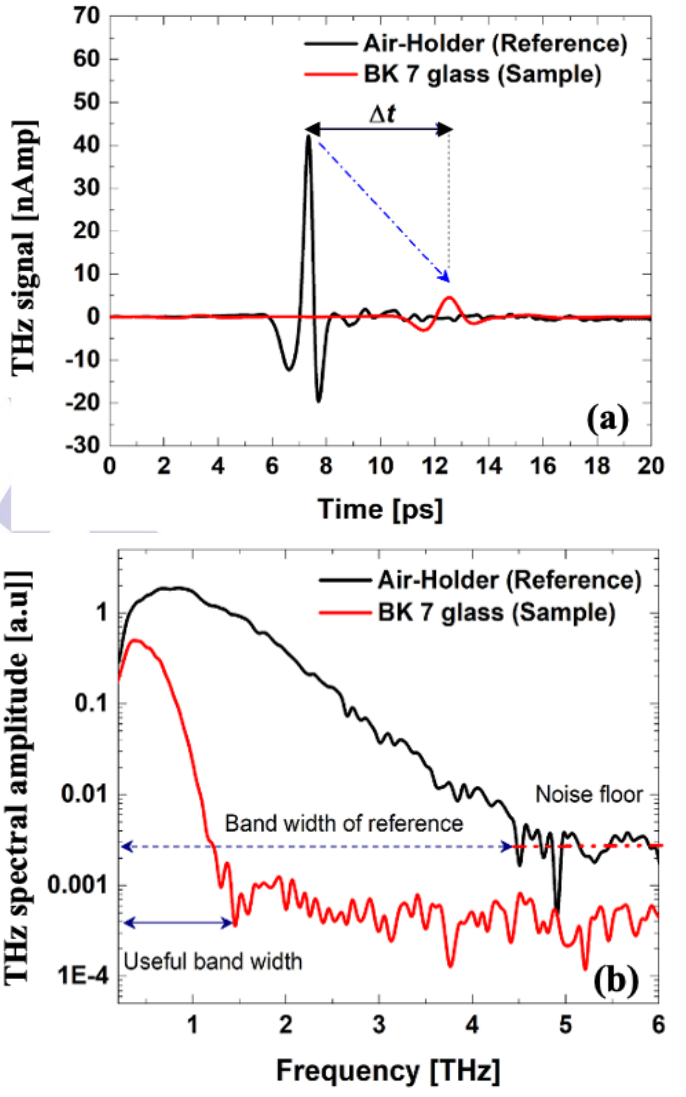


Fig. 2. THz Temporal waveforms propagating via air-holder (reference – black solid line) and the BK7 (sample – red solid line) (a). Their corresponding spectra are obtained by taking Fourier transformation (b).

3.2. Complex Refractive Index

A preliminary estimate of the real refractive index was derived from the temporal waveform delay $\Delta t = 5.15$ ps

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and the BK7 sample thickness $L = 1$ mm using Equation (1), yielding $n \approx 2.545$.

The spectrally resolved real refractive index $n(\omega)$, extracted numerically using Teralyzer software over the frequency range 0.25–1.4 THz, is shown in Figure 3(a). The extracted value is $n = 2.549 \pm 0.002$, found to be essentially constant across the trusted bandwidth of 0.25–1.2 THz, as indicated by the linear fit overlaid in Figure 3(b). The close agreement between the temporal-domain estimate ($n \approx 2.545$) and the spectral-domain result ($n = 2.549 \pm 0.002$) confirms the internal consistency of the measurement. These values are furthermore in excellent agreement with published THz refractive index values for BK7 in the same spectral region [11].

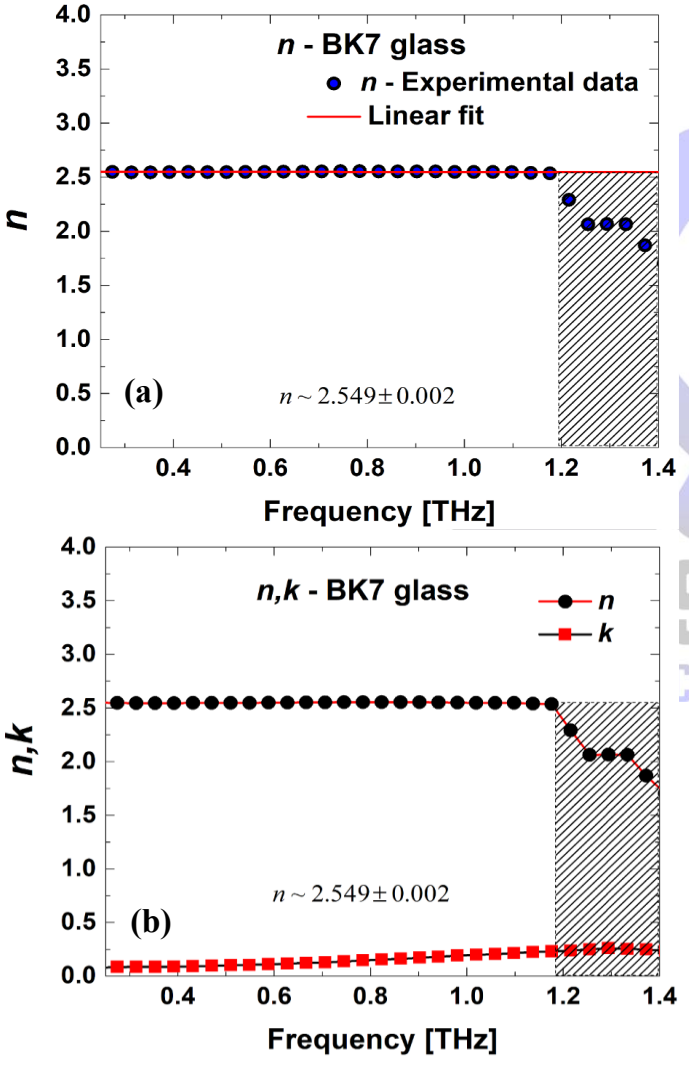


Fig. 3. Spectra of the extracted average real refractive index n for a 1 mm thick BK7 substrate in the THz frequency range 0.25–1.4 THz at room temperature (~20°C), obtained using Teralyzer software. The red line is a linear fit (a). The components of the complex refractive index $\tilde{n}$: real part n (black dots — red solid line) and imaginary part (extinction coefficient) k (red squares — black solid line) (b).

The constancy of n across the 0.25–1.2 THz range signifies the absence of noticeable material dispersion in BK7 within this frequency window. The apparent decrease in n observed beyond 1.2 THz is not a physical behavior of the material; rather, it is an artifact of the phase errors introduced by the poor signal-to-noise ratio (SNR) resulting from the strong absorption of THz frequencies above 1.2 THz. Data in this region are consequently unreliable and are presented only to illustrate this spectral limitation.

The spectra of both components of the complex refractive index $\tilde{n} = n + ik$ over the range 0.25–1.4 THz are shown in Figure 2(b). The extinction coefficient k is ~0.08 at 0.25 THz and increases to ~0.20 at 1.2 THz. These values of k are small and confirm that within the trusted bandwidth, THz absorption in BK7 is modest and reasonably well-behaved. As with n, the values of k beyond 1.2 THz are not physically meaningful [1].

3.3. Absorption Coefficient

The spectrum of the extracted absorption coefficient α for the 1 mm BK7 sample is shown in Figure 4 over the extended frequency range 0.25–4 THz. The inset provides a magnified view of the trusted region 0.25–1.4 THz for improved visualization. A monotonically increasing trend in α with frequency is the dominant feature of this spectrum. Within the trusted bandwidth (0.25–1.2 THz), α increases from ~9.4 cm^{-1} at 0.25 THz to ~149 cm^{-1} at 1.4 THz. At 1 THz, the measured value of $\alpha \approx 81.25$ cm^{-1} is in good agreement with literature values reported for BK7 in the THz region.

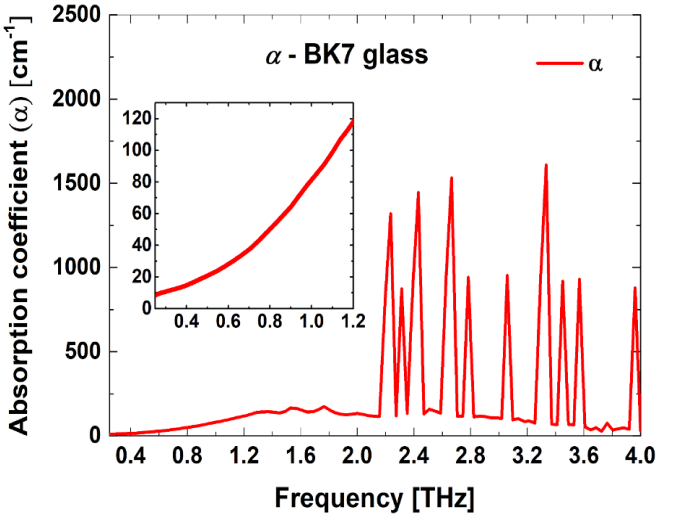


Fig. 4. Spectrum of the extracted absorption coefficient α for a 1 mm thick BK7 substrate in the THz frequency range 0.25–4 THz, obtained using Teralyzer software. The inset shows a magnified view of the 0.25–1.4 THz region.

Beyond 1.2 THz, the absorption rises rapidly, with minor spectral features (absorption peaks) observed at ~1.55 THz

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and ~1.76 THz. Above 2 THz, major absorption peaks dominate the spectrum; for instance, at ~2.67 THz, α reaches a peak value of $\sim 1.5 \times 10^3\ cm^{-1}$. This dramatic increase in α at higher THz frequencies is the principal cause of the spectral bandwidth limitation of BK7 observed in Figure 2(b). The significantly degraded SNR beyond ~1.2 THz renders the extracted phase information and derived optical constants unreliable, leading to artifacts in all extracted parameters in this spectral range. The usable THz spectral bandwidth for BK7 substrates is therefore confirmed to be 0.25–1.2 THz.

3.4. Complex Dielectric Response

The dielectric response of BK7 glass was characterized through the extraction of the complex permittivity $\tilde{\varepsilon}(\omega) = \varepsilon_1(\omega) + i\varepsilon_2(\omega)$, computed from the measured n and k values using Equations (5) and (6). The spectra of both components over the range 0.25–1.4 THz at room temperature are presented in Figure 5.

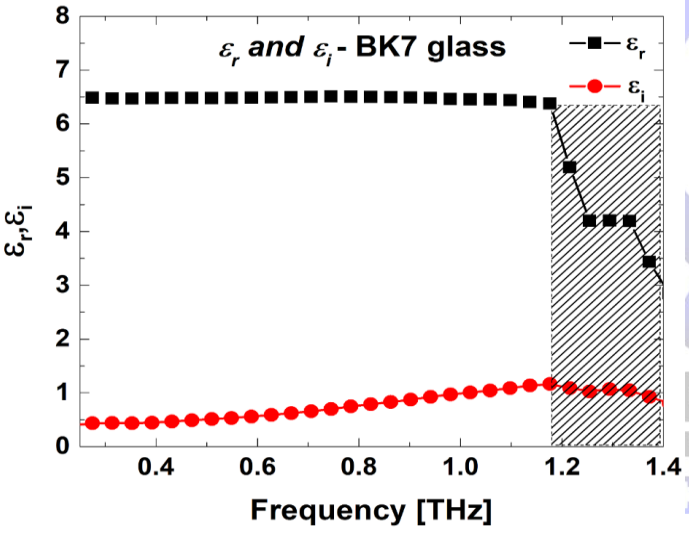


Fig. 5. Spectra of the extracted complex dielectric constant components: real part ε_1 (black square — line) and imaginary part ε_2 (red circle — line) for BK7 glass in the THz frequency region at room temperature (~ 20°C), obtained from experimental data using Teralyzer software.

The real part of the complex permittivity, ε_1, is observed to sustain a nearly constant value of ~6.5 throughout the trusted spectral bandwidth (0.25–1.2 THz). The apparent sharp decrease in ε_1 beyond ~1.2 THz is an artifact driven by the noise-contaminated measurement in this frequency range and does not represent an intrinsic physical property of BK7.

The imaginary part of the complex permittivity, ε_2, assumes small positive values ($\varepsilon_2 > 0$) throughout the measured range, with an increasing trend as frequency rises: $\varepsilon_2 \approx 0.4$ at 0.25 THz and $\varepsilon_2 \approx 1.1$ at 1.2 THz. The physical significance of these components is well established: ε_1 governs the energy storage (capacitive) behavior of the material, while ε_2 represents the energy dissipation (loss). The small values of ε_2 relative to ε_1 across the trusted bandwidth are consistent with the moderately low THz absorption of BK7 in this spectral window. Taken together, the measured dielectric response indicates that BK7 is not a high-performing candidate for THz energy storage or capacitance applications, given its relatively modest and essentially frequency-independent permittivity in the 0.25–1.2 THz range.

4. CONCLUSIONS

This comprehensive THz time-domain spectroscopy investigation of a standard BK7 borosilicate glass substrate has successfully established its key optical and dielectric parameters across the terahertz frequency region, providing essential reference data for researchers utilizing this common material in THz spectroscopy applications. The measured real refractive index of n = 2.549 ± 0.002 exhibits remarkable stability across the 0.25-1.2 THz range, confirming the absence of significant material dispersion within this spectral window and demonstrating excellent agreement with previously reported values in the literature. The absorption characteristics of BK7 glass reveal a fundamentally limiting property for THz applications: the absorption coefficient increases monotonically from approximately 9.4 cm^{-1} at 0.25 THz to 81.25 cm^{-1} at 1 THz, with a dramatic escalation beyond 1.2 THz reaching peak values of approximately 1.5 × 10^3 cm^{-1} at 2.67 THz. This severe absorption at higher frequencies directly causes the spectral truncation observed in the transmitted THz signal, establishing the reliable usable bandwidth of BK7 substrates as 0.25-1.2 THz. The dielectric response analysis reveals a stable real permittivity $\varepsilon_1 \approx 6.5$ with minimal frequency dependence, complemented by a small imaginary component ε_2 ranging from 0.4 to 1.1 within the trusted bandwidth, consistent with the moderate energy dissipation characteristics of the material. These findings carry significant practical implications for THz spectroscopy experimental design. While BK7 remains an accessible and convenient substrate material for thin-film deposition and optical mounting applications, researchers must carefully account for its inherent spectral bandwidth limitation when employing this material in THz measurement configurations. The material is unsuitable for applications requiring broadband THz characterization extending beyond 1.2 THz, particularly for time-resolved spectroscopy, broadband imaging, or high-frequency dielectric studies. For experiments requiring accurate THz transmission measurements above 1.2 THz, alternative substrate materials such as high-resistivity silicon, quartz, or polymer-based substrates should be considered. The comprehensive optical constants presented in this work serve as benchmark reference values for BK7 in the THz regime, enabling more accurate data interpretation and improved experimental design in future THz spectroscopic studies utilizing this

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common laboratory material

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

All authors contributed equally in the preparation of this manuscript.

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