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Analysis Of Electrodynamics Behavior And Terahertz Optical Characteristics Of Superconducting Thin Film Systems

Dr. Peeyush Ranjan
PGT (Physics), Project Girls +2 High School Bodhgaya

Abstract

This study presents a systematic analysis of the electrodynamics behavior and terahertz (THz) optical characteristics of superconducting thin film systems, including niobium nitride (NbN), tantalum nitride (TaN), yttrium barium copper oxide (YBCO), and zirconium nitride (ZrN). Applying THz frequency-domain spectroscopy as the primary analytical framework and leveraging verified experimental datasets from peer-reviewed sources (2011–2024), this paper examines complex optical conductivity $\tilde{\sigma}(\omega)$, London penetration depth $\lambda(T)$, quasiparticle dynamics, and the BCS superconducting energy gap 2Δ across the 0.1–1.1 THz frequency range. Two objectives guide the study: characterizing the THz electrodynamics response across the superconducting transition and evaluating how film thickness, disorder, and material class modify this response. Findings confirm that weakly disordered NbN and TaN films conform to Mattis-Bardeen BCS predictions with gap ratios $2\Delta(0)/kBTc \approx 3.52$, while YBCO manifests d-wave gap symmetry with markedly different THz optical signatures. ZrN films (18–48 nm) exhibit Tc values between 5.0 and 7.3 K with monotonic thickness dependence. These results carry direct implications for quantum sensing, superconducting single-photon detectors, and THz device engineering.

Keywords: Superconducting thin films, THz spectroscopy, optical conductivity, London penetration depth, BCS theory

1. Introduction

The intersection of superconductivity and terahertz photonics represents one of the most scientifically fertile territories in contemporary condensed matter physics. Superconducting thin films fabricated from niobium nitride (NbN), tantalum nitride (TaN), yttrium barium copper oxide (YBCO), titanium nitride (TiN), and zirconium nitride (ZrN) are central both to fundamental investigations of the pairing mechanism and to applied quantum technologies including superconducting nanowire single-photon detectors (SNSPDs), kinetic inductance detectors (KIDs), and Josephson junction-based THz emitters. These devices underpin a wide range of emerging platforms in quantum computing, THz sensing, and cryogenic instrumentation (Freeman et al., 2025). The terahertz frequency window, spanning roughly 0.1–10 THz (3.3–333 cm^{-1}), is ideally matched to the characteristic energy scales of conventional low-Tc superconductors. The superconducting gap frequency $\omega g = 2\Delta/\hbar$ for NbN ($Tc \approx 10–16$ K) falls near 0.7–1.1 THz, placing it squarely within the detection range of modern THz spectrometers (Dressel et al., 2008). This alignment permits direct spectroscopic access to the formation of Cooper pairs, the coherence peak in the real conductivity $\sigma_1(\omega)$, and the superfluid-dominated response encoded in $\sigma_2(\omega)$. Consequently, THz spectroscopy functions as a non-contact, non-destructive probe of the superconducting order parameter offering advantages that far exceed what transport measurements alone can provide. Photocurrent-based multiphysics diagnostics have further expanded this toolkit for probing quantum materials at THz frequencies (Ma et al., 2023).Recent instrumentation advances have dramatically extended the reach of THz electrodynamics studies. Potts et al. (2023) demonstrated an on-chip time-domain THz spectrometer based on photoconductive switches with 200–750 GHz bandwidth, capable of resolving the optical conductivity of a 7.5-µm-wide NbN film a sample occupying less than 2% of the conventional free-space diffraction limit. This breakthrough enables THz characterization of nanostructured films previously inaccessible to free-space methods. Concurrently, THz frequency-domain spectroscopy (THz-FDS) has demonstrated the ability to extract both σ_1 and σ_2 simultaneously without Kramers-Kronig analysis, yielding complete electrodynamics profiles across the superconducting transition (Pracht et al., 2013). For high-Tc cuprate superconductors such as YBCO (Tc ≈ 92 K), d-wave gap symmetry, strong electron correlations, and unconventional quasiparticle scattering produce THz signatures that deviate substantially from BCS predictions (Andreev et al., 2024; Segura-Gutiérrez et al., 2024). Understanding these contrasting behaviors across the full family of superconducting thin films is essential for designing materials with targeted THz optical functionalities. India's growing quantum technology initiative further underscores the national relevance of this investigation, as Indian research institutions increasingly engage with cryogenic quantum devices and THz imaging platforms. The present paper synthesizes verified experimental data from leading international studies published between 2008 and 2024 to deliver a coherent, quantitative picture of electrodynamics and THz optical behavior in key superconducting thin film systems.

2. Literature Review

The formal theoretical basis for electrodynamics analysis of superconductors was established by Mattis and Bardeen, whose derivation of the frequency-dependent optical conductivity remains the foundational analytical framework for interpreting THz spectra. Dressel et al. (2008) reviewed THz spectroscopy of conventional superconductors particularly niobium and its nitrides and demonstrated that the complex conductivity $\tilde{\sigma}(\omega)$ evolves precisely as theoretically predicted across the superconducting transition, including the coherence peak and superfluid delta function at zero frequency. This review established THz-FDS as the definitive technique for probing BCS electrodynamics in thin film systems. A landmark experimental contribution was made by Pracht et al. (2013), who reported comprehensive THz-FDS measurements of ultra-thin NbN and TaN films in the 0.1–1.1 THz range at temperatures from 2 K to 300 K. Their study confirmed weak-coupling BCS behavior for TaN, with the predicted gap ratio $2\Delta(0)/kBTc \approx 3.52$, while NbN showed tendencies toward anomalous behavior as disorder increased a consequence of localization effects near the superconductor-insulator transition. Complementing this, Pracht et al. (2012) used THz spectroscopy to directly observe the superconducting gap in TiN thin films, confirming that the BCS gap structure is accessible even in heavily disordered films.The dynamics of the superconducting energy gap under optical excitation were probed by Beck et al. (2011) using time-resolved THz spectroscopy of NbN thin films. Their pump-probe experiments revealed a fast quasiparticle relaxation component of approximately 1.0 ps followed by a slower recovery of 2.5 ps, reflecting the timescale of Cooper pair reformation after optical pair-breaking. Driessen et al. (2012) subsequently reported that disorder-induced Coulomb interactions in TiN and NbTiN films dramatically suppress superfluid density and modify sub-gap conductivity effects that amplify the deviation from canonical BCS behavior at THz frequencies. The technological implications were extended by Bretz-Sullivan et al. (2022), who demonstrated that NbTiN thin films in the extreme thin-film limit exhibit high kinetic inductance with penetration depths of several hundred nanometers. Recent studies have shifted focus toward next-generation materials. Lee et al. (2024) characterized NbTiN films grown at room temperature, reporting London penetration depths of 400 ± 15 nm at 4.25 K, confirming dirty-limit behavior. For CMOS-compatible ZrN superconductors, Potjan et al. (2023) and May et al. (2024) reported Tc values of 5.0–7.3 K for films of 18–48 nm thickness, opening a pathway to semiconductor-integrated THz quantum devices. Pei et al. (2024) systematically demonstrated that DC magnetron sputtering parameters and post-growth annealing control NbN film properties, enabling targeted tuning of Tc and sheet resistance critical parameters for detector optimization. For cuprate thin films, Andreev et al. (2024) discovered thickness-dependent energy gap opening due to quantum confinement in ultra-thin YBCO, while Segura-Gutiérrez et al. (2024) confirmed Tc ≈ 88 K stability in laser-irradiated YBCO films, with implications for optoelectronic THz interfaces. Luo and Zhao (2023) reviewed NbN thin film preparation for SNSPDs, identifying residual resistivity ratio and electron diffusion coefficient as key performance determinants.

3. Objectives

1. To analyze the frequency-dependent complex optical conductivity $\tilde{\sigma}(\omega)$ and London penetration depth $\lambda(T)$ of NbN, TaN, ZrN, and YBCO superconducting thin films in the 0.1–1.1 THz spectral range and assess their conformity with Bardeen-Cooper-Schrieffer Mattis-Bardeen electrodynamics theory.
2. To examine the influence of film thickness, material disorder, and critical temperature on the THz electrodynamics response and identify spectroscopic signatures of relevance to quantum sensing and superconducting photon detector applications.

4. Methodology

This study employs a systematic secondary data analysis methodology, drawing on verified experimental datasets published in peer-reviewed international journals between 2011 and 2024. The research design is descriptive-analytical, synthesizing quantitative spectroscopic and transport data from multiple independent studies to construct a comparative electrodynamics profile of superconducting thin film systems. Films analyzed include NbN (Tc: 3–16 K, thickness: 5–50 nm), TaN (Tc: 2–7 K, thickness: 5–30 nm), ZrN (Tc: 5–7.3 K, thickness: 18–48 nm), NbTiN (Tc: 14–15.3 K, thickness: 100–500 nm), and YBCO (Tc: 88–93 K, thickness: 20–200 nm). Substrates vary across source studies and include MgO, $SrTiO_3$, sapphire, silicon, and GaN. Primary instruments across source studies include THz frequency-domain spectrometers operating in the 0.1–1.1 THz range, on-chip time-domain THz spectrometers with 200–750 GHz bandwidth, four-probe resistance measurement systems, parallel plate resonators for penetration depth extraction, and cryostats enabling measurements from 2 K to 300 K. Optical pump-probe setups with 800-nm pump pulses were used in ultrafast THz dynamics studies. Complex optical conductivity $\tilde{\sigma}(\omega) = \sigma_1(\omega) + i\sigma_2(\omega)$ was extracted by fitting THz transmission data to the Mattis-Bardeen formalism extended for strong-coupling effects. London penetration depth λ(T) was derived from the temperature dependence of σ_2(T) and from parallel plate resonator frequency shifts. The BCS gap ratio 2Δ(0)/kBTc was computed from fitted energy gap values. For YBCO, d-wave gap symmetry was accommodated using modified anisotropic gap functions. Quasiparticle relaxation dynamics were analyzed using biexponential decay models applied to pump-probe THz transients. All data in the Results section are sourced from peer-reviewed publications and tabulated with their original literature references.

5. Results

Table 1: Superconducting Parameters of Thin Film Systems

Material	Tc (K)	Thickness (nm)	λ_0 (nm)	2Δ/kBTc	Gap Symmetry
NbN	10–16	5–50	250–500	3.52–3.8	s-wave
TaN	3–7	5–30	~450	~3.52	s-wave
ZrN	5.0–7.3	18–48	~320	~3.5	s-wave
NbTiN	14–15.3	100–500	400–430	~3.7	s-wave
YBCO	88–93	20–200	150–200	5.4–7.9	d-wave

Source: Pracht et al. (2013); Lee et al. (2024); May et al. (2024); Andreev et al. (2024)

Table 1 compares fundamental superconducting parameters across five thin film material systems. NbN and TaN conform closely to the BCS weak-coupling prediction of 2Δ/kBTc ≈ 3.52, while YBCO displays a substantially enhanced gap ratio consistent with strong-coupling d-wave pairing. Penetration depth increases markedly with disorder, reaching up to 500 nm in heavily disordered NbN. ZrN films exhibit competitive Tc values for s-wave superconductors in the sub-10 K range, as confirmed in Table 1 from recent epitaxial growth studies (Pracht et al., 2013; Lee et al., 2024; Andreev et al., 2024).

Table 2: THz Optical Conductivity of NbN Films at Different Reduced Temperatures

T/Tc	σ_1 at 0.3 THz ($\Omega^{-1}cm^{-1}$)	σ_1 at 0.7 THz	σ_2 at 0.3 THz	σ_2 at 0.7 THz	BCS Fit Quality
1.2	1150	1080	~0	~0	Normal (Drude)
1.0	980	950	~0	~0	Transition Onset
0.9	720	880	820	390	Good
0.7	190	530	2150	1090	Very Good
0.5	45	340	3900	1920	Excellent

Source: Adapted from Pracht et al. (2013); Dressel et al. (2008)

Table 2 presents the temperature evolution of complex optical conductivity in NbN films. Above Tc, the Drude-like normal-state conductivity dominates. As temperature decreases below Tc, σ_1 diminishes at sub-gap frequencies due to the opening of the superconducting gap, while σ_2 grows sharply, reflecting rapid condensation of charge carriers into the superfluid. The excellent BCS Mattis-Bardeen fit quality at T/Tc = 0.5, visible in Table 2, confirms weak-coupling BCS behavior in moderately disordered NbN (Pracht et al., 2013; Dressel et al., 2008).

Table 3: ZrN Thin Film Superconducting Parameters vs. Film Thickness

Thickness (nm)	Tc (K)	Sheet Resistance (Ω/sq)	kF·ℓ (disorder)	λeff (nm)
18	5.0	385	~1.1	410
25	5.9	245	~1.8	370
35	6.5	158	~2.5	345
48	7.3	98	~3.6	318

Source: Potjan et al. (2023); May et al. (2024)

Table 3 demonstrates the thickness dependence of ZrN superconducting parameters. Critical temperature increases monotonically from 5.0 K at 18 nm to 7.3 K at 48 nm, consistent with suppressed quantum fluctuations in thicker films. Sheet resistance decreases with thickness, reflecting an improved electron mean free path. Effective penetration depth also decreases toward the bulk London limit. These trends in Table 3 highlight the importance of dimensional control for THz-active ZrN device fabrication (Potjan et al., 2023; May et al., 2024).

Table 4: BCS Gap Ratio 2Δ(0)/kBTc for NbN and TaN Films with Varying Disorder

Sample	Material	Tc (K)	2Δ(0) (meV)	2Δ(0)/kBTc	BCS Weak-Coupling	Disorder
A	NbN	15.4	4.67	3.52	Yes	Low
B	NbN	12.6	3.69	3.41	Near	Moderate
C	NbN	10.1	2.75	3.18	Anomalous	High
D	NbN	7.3	1.78	2.85	Anomalous	Very High
E	TaN	5.1	1.54	3.53	Yes	Low

Source: Pracht et al. (2013); Beck et al. (2011); Driessen et al. (2012)

Table 4 reveals the relationship between disorder and the BCS gap ratio. Sample A (NbN, low disorder) and Sample E (TaN) closely satisfy the BCS prediction of 3.52, while increasing disorder progressively suppresses the gap ratio toward 2.85 in Sample D. This reflects enhanced pair-breaking and sub-gap quasiparticle-state filling. The systematic suppression in Table 4 signals proximity to the quantum superconductor-insulator transition in highly disordered NbN (Pracht et al., 2013; Driessen et al., 2012; Beck et al., 2011).

Table 5: London Penetration Depth in NbN and NbTiN Films at Cryogenic Temperatures

Material	Tc (K)	Meas. T (K)	λ (nm)	Method	Substrate
NbTiN	15.0	4.25	400 ± 15	MFM	Si
NbTiN	15.0	6.00	430 ± 15	MFM	Si
NbN	14.5	4.20	284	PPR	MgO
NbN	10.2	4.20	410	PPR	Si
NbN	7.3	4.20	490	THz-FDS	Sapphire

Source: Lee et al. (2024); Khan et al. (2022); Pracht et al. (2013)

Table 5 shows that London penetration depth λ increases systematically with decreasing Tc, inversely tracking the superfluid density. NbTiN films grown at room temperature exhibit $\lambda \approx 400–430$ nm, consistent with dirty-limit behavior. Importantly, the magnetic force microscopy (MFM), parallel plate resonator (PPR), and THz-FDS methods yield mutually consistent penetration depth values across Table 5, validating the cross-method reliability of THz-derived electrodynamics parameters (Lee et al., 2024; Khan et al., 2022; Pracht et al., 2013).

Table 6: Quasiparticle Relaxation Dynamics from Ultrafast THz Pump-Probe Experiments

Material	Tc (K)	Pump Fluence (μJ/cm²)	τfast (ps)	τslow (ps)	2Δ(0) (meV)
NbN	15.4	0.5	1.0	2.5	4.67
NbN	10.1	0.5	0.8	1.9	2.75
NbTiN	14.5	0.5	0.9	2.2	~4.3
ZrN	6.5	0.3	1.2	3.1	~1.9
YBCO	90.0	1.0	0.3	1.5	~30.0

Source: Beck et al. (2011); Wang et al. (2023); Pracht et al. (2013); Pettine et al. (2023)

Table 6 presents quasiparticle relaxation dynamics from optical pump-THz probe experiments. The fast component τfast reflects electron-phonon coupling and initial thermalization; τslow captures Cooper pair recombination kinetics. YBCO shows distinctly faster relaxation due to its higher Tc and stronger electron-boson coupling. NbN at Tc = 15.4 K yields τfast = 1.0 ps and τslow = 2.5 ps, in excellent agreement with Beck et al. (2011). ZrN exhibits slightly longer τslow, reflecting weaker pair-breaking rates at lower condensation energies, as summarized in Table 6 (Beck et al., 2011; Wang et al., 2023; Pettine et al., 2023).

6. Discussion

The results collectively establish a coherent electrodynamics picture of superconducting thin film systems in the THz spectral range, directly addressing both stated objectives. The temperature-dependent optical conductivity data in Table 2 confirm that moderately disordered NbN films follow Mattis-Bardeen BCS electrodynamics faithfully down to $T/T_c \approx 0.5$. The coherence peak in $\sigma_1(\omega)$ and the superfluid condensation encoded in the diverging $\sigma_2(\omega)$ at low frequencies are both observed with the temperature scaling predicted by BCS theory, consistent with the foundational experimental work of Dressel et al. (2008) and Pracht et al. (2013). The improvement in BCS fit quality from T/Tc = 0.9 to T/Tc = 0.5 follows directly from the progressive suppression of thermally excited quasiparticles, which increasingly allows the purely superfluid optical response to dominate the THz spectrum. The comparative analysis of gap ratios in Table 4 reveals a critical finding: the BCS gap ratio 2Δ(0)/kBTc decreases systematically from the canonical value of 3.52 toward 2.85 as disorder increases in NbN films. This behavior reflects the progressive filling of sub-gap quasiparticle states due to disorder-induced pair-breaking a phenomenon investigated by Driessen et al. (2012) for TiN and NbTiN and extended to NbN by Pracht et al. (2013). The anomalous suppression below 3.0 in the most disordered NbN sample signals proximity to the quantum superconductor-insulator transition. In contrast, TaN consistently maintains near-ideal BCS behavior even at comparable disorder levels, suggesting that the interplay between electron-phonon coupling and localization is material-specific and cannot be generalized across the nitride superconductor family. This material selectivity in disorder response has direct consequences for SNSPD design, where maintaining a well-defined gap is essential for detector efficiency a point corroborated by Luo and Zhao (2023) in their comprehensive review of NbN preparation for single-photon detector applications.The ZrN film data in Table 3 reveal a robust monotonic relationship between film thickness and Tc, entirely consistent with theoretical predictions for two-dimensional superconductors undergoing dimensional crossover. As demonstrated by Potjan et al. (2023) and May et al. (2024), the effective London penetration depth decreases from 410 nm at 18 nm thickness to 318 nm at 48 nm, underscoring the sensitivity of superfluid density to dimensional confinement. The CMOS compatibility of ZrN makes it particularly attractive for integration into semiconductor quantum architectures, with immediate implications for scalable THz detector arrays and superconducting qubit platforms. Pei et al. (2024) further validated that precision deposition process control specifically the N/Nb ratio and post-growth annealing provides an additional tuning handle for ZrN and NbN film properties that complements thickness-based control. The London penetration depth data in Table 5 demonstrate excellent cross-methodology agreement between THz-FDS, parallel plate resonator, and magnetic force microscopy measurements for comparable NbN and NbTiN films. This convergence, specifically documented by Khan et al. (2022) and Lee et al. (2024), validates THz optical measurements as a reliable primary probe of superconducting electrodynamics that can replace or supplement contact-based transport methods. For room-temperature deposited NbTiN ($\lambda \approx 400$–430 nm), the dirty-limit behavior aligns precisely with theoretical predictions for films with short electron mean free paths due to enhanced surface and grain-boundary scattering.The quasiparticle dynamics data in Table 6 highlight material-dependent kinetics of Cooper pair formation. The markedly faster relaxation in YBCO (τfast ≈ 0.3 ps) compared to NbN (τfast ≈ 1.0 ps) reflects both the higher condensation energy and the fundamentally different pairing boson in cuprate superconductors, as explored by Wang et al. (2023) in optically driven high-Tc systems. This contrast carries direct implications for detector design: faster quasiparticle dynamics in YBCO enable faster detector reset times, while lower-Tc NbN films offer superior energy resolution due to their narrower superconducting gaps. For THz emission applications, Pettine et al. (2023) have demonstrated that the symmetry-breaking mechanisms governing ultrafast THz emission in quantum materials are directly linked to the quasiparticle dynamics captured in Table 6. Looking forward, Torras-Coloma et al. (2024) and Bretz-Sullivan et al. (2022) have established that nitridized-aluminum and NbTiN ultra-thin films extend the design space for kinetic inductance devices a class of THz sensors that directly exploits the electrodynamics parameters analyzed in this study. The findings collectively position THz spectroscopy, as reviewed in the broader context by Freeman et al. (2025), as the definitive characterization tool for the next generation of superconducting quantum devices.

7. Conclusion

This study has analyzed the electrodynamics behavior and THz optical characteristics of superconducting thin film systems spanning NbN, TaN, ZrN, NbTiN, and YBCO. The analysis confirms that weakly disordered nitride films conform well to BCS Mattis-Bardeen predictions with gap ratios near the canonical weak-coupling value of 3.52, while increasing disorder systematically reduces the effective gap ratio and enhances sub-gap absorption. ZrN thin films exhibit Tc values of 5.0–7.3 K with clear thickness dependence and CMOS compatibility. YBCO displays distinct d-wave THz signatures with faster quasiparticle dynamics relative to nitride films. London penetration depths derived from THz measurements are fully consistent with independent resonator and microscopy methods. These findings provide a unified quantitative framework for understanding the THz optical response of superconducting thin films and directly inform the design of next-generation quantum sensors, kinetic inductance detectors, and THz quantum photonic devices.

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