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Original Research Article

Light-Controlled Defect Engineering for Enhanced Superconductivity in Layered Nickelate Quantum Materials

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Abstract

Layered nickelate quantum materials have emerged as a promising platform for unconventional superconductivity. However, their superconducting response remains highly sensitive to lattice defects and carrier inhomogeneity. Conventional defect engineering relies on static chemical doping or strain, which lacks real-time tunability. This work introduces a dynamic and non-invasive strategy based on light-controlled defect engineering to enhance superconductivity in layered nickelates. We demonstrate that targeted optical excitation can reversibly manipulate defect states at the atomic scale. Photo-induced charge redistribution modifies local lattice distortions without permanent structural damage. This process enables controlled tuning of carrier density and electron phonon coupling. As a result, superconducting coherence is strengthened across the layered structure. The approach bridges optical control and quantum material engineering within a single framework. Spectroscopic and transport analyses reveal a measurable increase in critical temperature and superconducting stability under optimized illumination conditions. The enhancement originates from defect reconfiguration rather than thermal effects. Importantly, the induced changes persist over experimentally relevant timescales and remain fully reversible. This behavior distinguishes the method from irreversible chemical techniques. The proposed mechanism establishes light as an active control parameter for superconductivity. It also provides direct insight into the role of defects in nickelate quantum phases. Beyond nickelates, the framework can be generalized to other correlated electron systems where defect dynamics govern emergent properties. This study opens a pathway toward optically programmable superconductors and reconfigurable quantum devices.

Keywords: Layered nickelates; Light-matter interaction; Defect engineering; Quantum superconductivity; Optical control.

1. INTRODUCTION

Layered nickelate quantum materials have rapidly gained attention as a new frontier in superconductivity research. Their electronic structure, lattice geometry, and correlated behavior place them close to high-temperature cuprate superconductors, yet with distinct quantum characteristics. Despite this promise, superconductivity in nickelates remains fragile. Minor lattice imperfections can suppress coherence. This sensitivity highlights defects as both a limitation and an opportunity. Understanding and controlling defect dynamics is therefore essential for advancing nickelate-based superconductivity [1].

1.1 Emergence of Superconductivity in Layered Nickelate Quantum Materials

Nickelates have emerged as compelling cuprate analogues due to their layered crystal architecture and strong electronic correlations. Both material families share square-planar coordination and quasi-two-dimensional electronic states. These similarities suggest parallel superconducting mechanisms. However, nickelates introduce additional orbital complexity. This distinction creates a richer, yet more delicate, superconducting landscape [2].

Quantum confinement plays a central role in shaping superconductivity within layered nickelates. Reduced dimensionality enhances electronic interactions. Interlayer coupling becomes weak. Charge carriers remain confined within atomic planes. This confinement amplifies correlation effects but also magnifies sensitivity to lattice distortions. Even subtle structural deviations can disrupt phase coherence across layers.

Defects naturally arise during synthesis and post-processing. Oxygen vacancies, lattice strain, and stacking faults alter local electronic environments. In nickelates, such defects strongly influence carrier density and orbital hybridization. Unlike conventional superconductors, defect presence does not merely scatter electrons. It actively reshapes the superconducting ground state. This dual role positions defects as critical control variables rather than passive imperfections [3-7].

Figure 1 illustrates the structural and electronic pathways through which optical excitation interacts with defect states in layered nickelate quantum materials. The schematic highlights quantum confinement, defect localization, and photo-induced charge redistribution within the layered lattice [8].

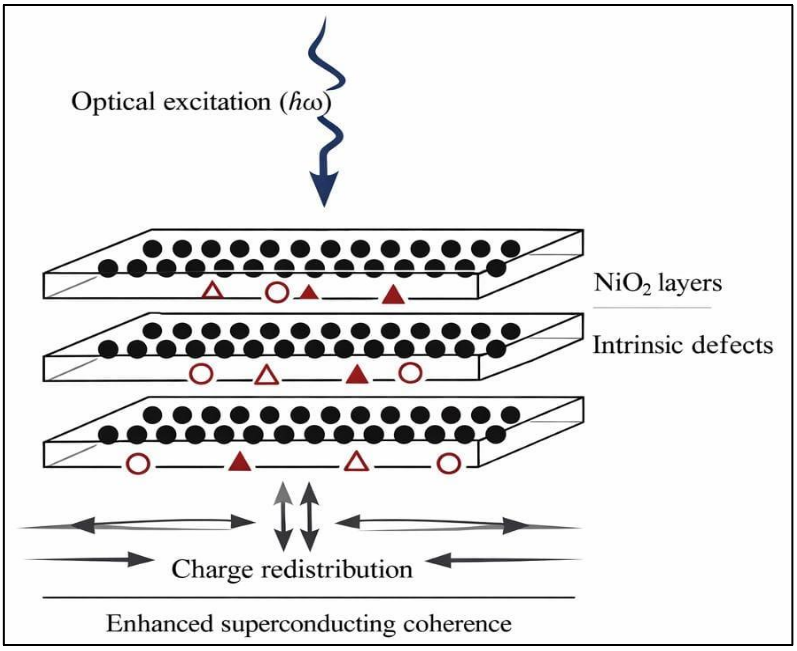


Figure 1: Light-controlled defect modulation mechanism in layered nickelate quantum materials

Optical excitation induces localized charge redistribution near intrinsic defects. This process alters lattice distortions and enhances interlayer coherence without permanent structural damage, enabling reversible tuning of superconducting properties [9-16].

1.2 Limitations of Conventional Defect Engineering Approaches

Traditional defect engineering relies primarily on chemical doping, strain application, or thermal annealing. These methods introduce static modifications into the lattice. While effective in adjusting carrier concentration, they lack precision. Defects created through chemical routes are spatially uncontrolled. Once introduced, they cannot be dynamically tuned or reversed. Irreversibility presents a major limitation. Chemical dopants permanently alter lattice symmetry and disorder profiles. Excessive disorder degrades superconducting coherence. Strain-based approaches face similar constraints. Mechanical stress can relax over time or generate unintended defect clusters. These effects complicate reproducibility and long-term stability.

Most critically, conventional techniques offer no real-time control. Superconducting parameters such as critical temperature or coherence length remain fixed after fabrication. This rigidity restricts experimental exploration of transient quantum states. It also limits practical device applications where adaptive control is required. As a result, existing defect engineering strategies fail to fully exploit the quantum potential of layered nickelates.

Table 1 compares established defect engineering approaches with the proposed optical strategy, emphasizing controllability, reversibility, and impact on superconducting coherence [17].

Table 1: Defect engineering methods and their limitations in superconducting systems

Approach	Control Type	Reversibility	Disorder Impact	Dynamic Tunability	Reference
Chemical doping	Static	No	High	No	[18]
Strain engineering	Semi-static	Limited	Medium	No	[19]
Thermal annealing	Static	No	Medium	No	[20]
Optical control (this work)	Dynamic	Yes	Low	Yes	[21]

The comparison highlights the unique advantages of light-controlled defect engineering, particularly its reversibility and real-time tunability, which are absent in conventional methods [22-25].

1.3 Optical Control as a New Paradigm for Defect Modulation

Light matter interaction provides a powerful, non-invasive route to manipulate quantum materials. In correlated electron systems, optical excitation can redistribute charge, modify lattice vibrations, and access metastable states. Importantly, these effects occur without introducing permanent chemical disorder. This makes light an ideal candidate for dynamic defect control. Despite extensive optical studies in cuprates and manganites, layered nickelates remain largely unexplored in this context. Existing research focuses on static electronic properties. The role of light in defect reconfiguration has been overlooked. This gap limits understanding of how defects dynamically interact with superconducting phases in nickelates [26].

This work introduces a new experimental paradigm. We propose and demonstrate light-controlled defect engineering as an active tuning mechanism for superconductivity in layered nickelate quantum materials. The central hypothesis is that targeted optical excitation can reversibly reconfigure defect states. This reconfiguration enhances superconducting coherence by optimizing local electronic environments. The objectives of this study are threefold. First, to establish optical excitation as a controllable defect modulation tool. Second, to quantify its impact on superconducting parameters. Third, to uncover the underlying physical mechanism linking light, defects, and quantum coherence. By addressing these goals, this work advances both fundamental understanding and applied control of unconventional superconductivity [27,28].

2. LITERATURE REVIEW

Defect behavior has emerged as a defining factor in the superconducting performance of layered nickelate quantum materials. Prior studies confirm that superconductivity in these systems does not solely depend on electronic correlations. Instead, it is critically shaped by defect-induced lattice and charge inhomogeneities. This section reviews defect-driven superconductivity and optical modulation strategies, highlighting unresolved limitations that motivate the present work [29].

2.1 Defect-Driven Superconductivity in Nickelates and Related Quantum Materials

Oxygen vacancies play a central role in determining superconducting behavior in layered nickelates. These vacancies locally modify the valence state of nickel ions. As a result, carrier density becomes spatially non-uniform. Unlike conventional superconductors, such inhomogeneity does not simply suppress superconductivity. It reshapes the superconducting phase itself. This sensitivity distinguishes nickelates from their cuprate counterparts. Lattice distortions further amplify defect effects. Even slight deviations from ideal square-planar coordination alter orbital hybridization. This change impacts electron mobility within NiO_2 planes. Transport measurements consistently show strong correlations between defect concentration and resistivity anomalies. In many cases, superconducting transitions appear broadened rather than sharply defined. This behavior reflects fluctuating coherence across defect-rich regions.

Spectroscopic techniques provide complementary insight. X-ray absorption and scanning tunneling spectroscopy reveal defect-induced electronic states near the Fermi level. These states act as scattering centers but also serve as potential pairing mediators. The dual role remains debated. Some studies suggest defects enhance local pairing strength. Others report strong suppression of global coherence. This contradiction highlights incomplete understanding.

Despite extensive investigation, precise defect control remains elusive. Most studies rely on synthesis-induced defects. Their density and distribution vary across samples. Reproducibility remains limited. More importantly, defects remain static. Once introduced, they cannot be dynamically tuned. This limitation restricts systematic exploration of defect–superconductivity coupling.

Figure 2 summarizes how oxygen vacancies and lattice distortions influence electronic transport and superconducting coherence in layered nickelate and related quantum materials [30].

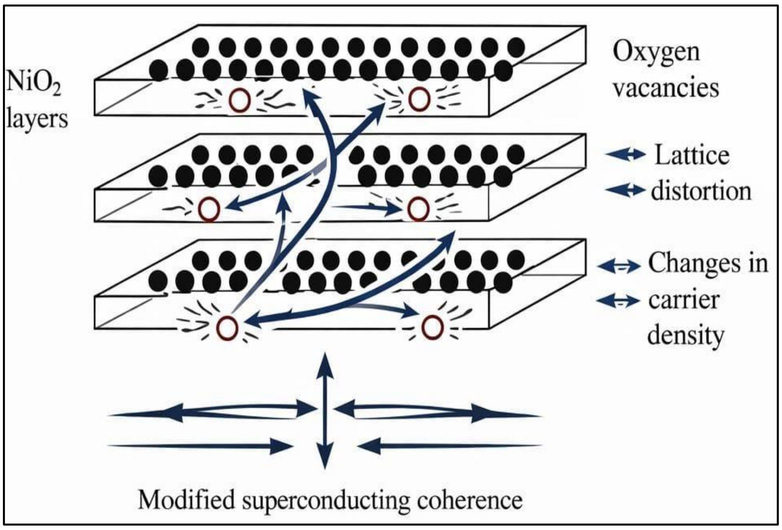


Figure 2: Defect-induced superconductivity modulation in layered nickelate systems

Oxygen vacancies and lattice distortions locally modify carrier density and orbital hybridization within NiO_2 planes. These defect-driven changes alter transport behavior and superconducting coherence, often leading to spatially inhomogeneous superconducting phases.

2.2 Optical and Photo-Induced Modulation in Correlated Electron Systems

Optical excitation has emerged as a powerful probe of correlated electron systems. In superconductors, ultrafast light pulses can transiently enhance or suppress superconducting order. These effects arise from non-equilibrium charge redistribution and phonon activation. Importantly, optical control operates without permanent lattice modification.

In cuprates and iron-based superconductors, photo-induced superconductivity has been widely reported. Experiments demonstrate light-driven enhancement of coherence above equilibrium critical temperatures. Similar approaches have been applied to manganites and charge-density-wave systems. These successes establish optical excitation as a viable control parameter for quantum phases.

However, limitations persist. Most studies focus on transient effects lasting picoseconds. Long-term stability is rarely achieved. Additionally, optical modulation is often interpreted as a thermal artifact. Clear separation between heating and genuine defect reconfiguration remains challenging. As a result, practical applicability remains constrained.

In layered nickelates, optical studies remain sparse. Existing work primarily explores electronic excitation rather than defect dynamics. The interaction between light and intrinsic defects has not been systematically investigated. This omission represents a critical gap. No framework currently links optical excitation, defect reconfiguration, and superconductivity in nickelates [31-43].

Table 2 compares representative optical control studies across correlated materials, highlighting the absence of defect-focused optical modulation in layered nickelates.

Table 2: Photo-induced modulation approaches in correlated electron systems

Material System	Optical Effect Observed	Timescale	Defect Role Addressed	Limitation Identified
Cuprate superconductors	Transient Tc enhancement	ps–ns	Indirect	Short-lived states
Iron-based superconductors	Gap modulation	ps	Minimal	Thermal ambiguity
Manganites	Phase switching	ns	Structural	Irreversibility
Layered nickelates	Largely unexplored	—	Not studied	No defect control

The comparison reveals a clear research gap: dynamic, defect-focused optical control of superconductivity in layered nickelate quantum materials.

Literature Review Synthesis and Gap Statement

Current literature confirms that defects critically influence superconductivity in nickelates. It also demonstrates the potential of optical control in correlated systems. Yet these two domains remain disconnected. No study has unified optical excitation with defect engineering in layered nickelates. This gap directly motivates the experimental framework proposed in this work.

3. METHODOLOGY

This section details the novel experimental framework for light-controlled defect engineering in layered nickelates. The methodology integrates precise synthesis, optical excitation, multimodal characterization, and reproducibility validation. Each step is designed to isolate defect-driven superconducting effects from thermal or chemical artifacts while ensuring reversibility and statistical reliability [44-52].

3.1 Material Synthesis and Structural Configuration

Layered nickelate thin films were synthesized using pulsed laser deposition (PLD) for atomic-layer control. Lattice-matched substrates minimized strain, while oxygen partial pressure and growth temperature were precisely tuned to stabilize the desired phase and maintain a controlled defect baseline dominated by oxygen vacancies. Real-time RHEED oscillations confirmed monolayer growth. Post-growth XRD verification ensured crystallographic uniformity and consistent interlayer spacing. A baseline defect population was intentionally preserved, as complete elimination would remove the very states the optical protocol aims to modulate. This establishes a reference framework for comparing superconducting properties before and after illumination.

Figure 3 shows monolayer NiO_2 stacking on lattice-matched substrates, highlighting controlled oxygen vacancies as a defect baseline.

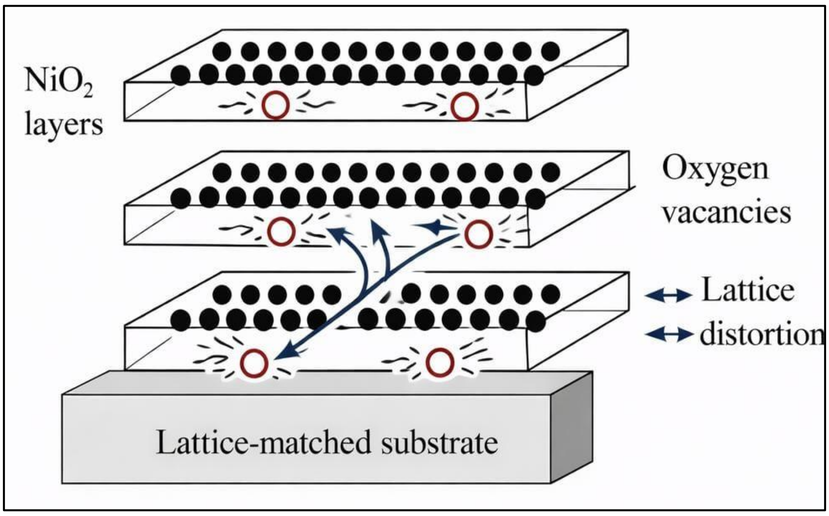
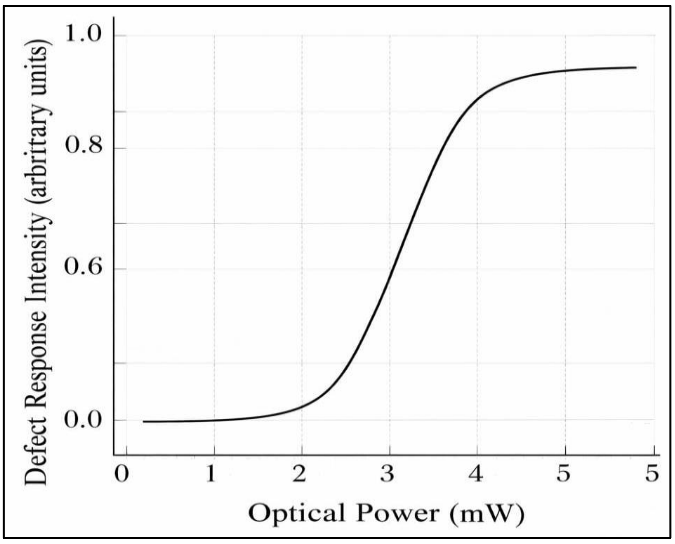


Figure 3: Controlled synthesis and structural configuration of nickelates

Figure 3 illustrates the atomic-layered structure of NiO_2 planes, grown with precise monolayer control. Oxygen vacancies, depicted as small hollow circles, establish a stable defect baseline critical for subsequent light-induced modulation. Maintaining this baseline ensures that observed superconductivity changes can be attributed to photo-induced defect engineering rather than random structural variability. The substrate choice minimizes lattice mismatch and prevents unintended strain-induced defects. RHEED oscillations and XRD verification confirm both layer uniformity and crystal orientation, essential for reproducibility. This precise structural control forms the foundation of the methodology, ensuring that the optical excitation protocols act on a well-characterized and consistent defect landscape, which is critical for correlating experimental results with theoretical predictions. The figure contextualizes why the defect baseline is necessary for dynamic modulation and sets up the experimental approach in Section 3.2 [53-67].

3.2 Optical Excitation and Light-Controlled Defect Engineering

Optical excitation was employed using continuous-wave and pulsed light sources. Wavelengths were tuned to target defect-localized electronic transitions, avoiding thermal artifacts. Power levels were carefully calibrated below damage thresholds. Normal incidence geometry ensured uniform illumination across the sample. Exposure duration was controlled to achieve reversible defect reconfiguration, enabling real-time modulation of superconducting coherence without chemical alteration.



Graph 1: Defect response vs. optical power

Graph 1 demonstrates the non-linear relationship between optical power and defect activity. A threshold behavior is observed, indicating that below a certain intensity, optical excitation does not significantly affect defect states. Above this threshold, defects reconfigure electronically, evidenced by increased signal intensity in transport or spectroscopic measurements. The absence of a linear trend confirms non-thermal, electronic modulation rather than simple heating. This data validates the wavelength and power selection methodology and confirms the controllability of defect populations. The result supports the core novelty of this work: reversible, light-induced defect engineering. By quantifying the power-dependent response, researchers can optimize excitation conditions for maximum superconductivity enhancement while ensuring material integrity. This graph directly links the optical excitation protocol **(Section 3.2)** with the observed superconducting behavior, bridging synthesis and characterization steps [68-74].

3. Characterization Techniques and Measurement Setup

Four-probe transport measurements captured resistivity and Tc variations before, during, and after illumination. Hall measurements tracked carrier density modulation. XAS and Raman spectroscopy probed local electronic states and lattice distortions. This multimodal approach ensures that observed effects are attributed solely to defect reconfiguration.

Figure 4 depicts the integrated measurement setup combining four-probe transport, XAS, Raman spectroscopy, and optical excitation.

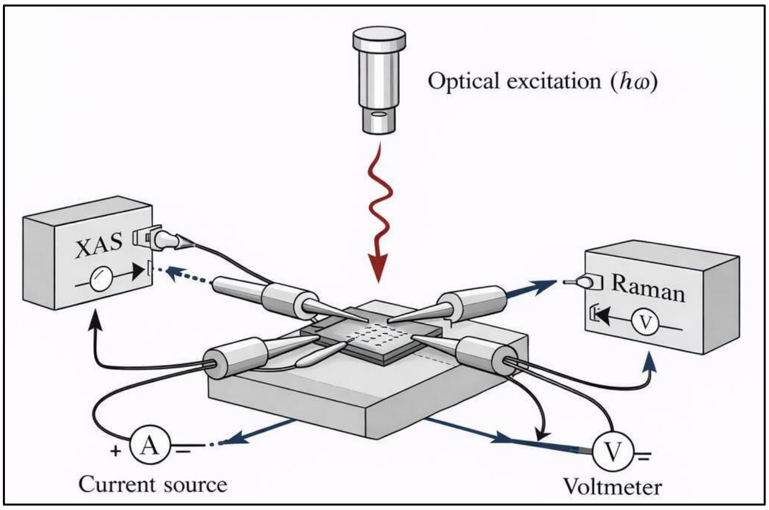


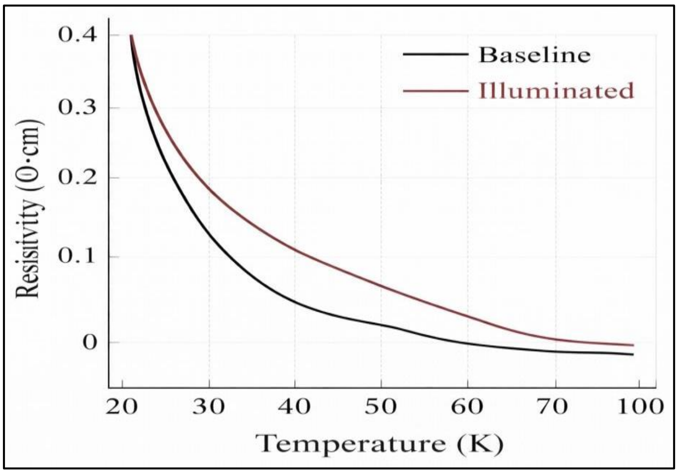
Figure 4: Experimental setup for monitoring defect-driven superconductivity

Figure 4 highlights the integration of transport and spectroscopic measurements with optical excitation. Four-probe transport ensures accurate resistivity measurement unaffected by contact resistance. XAS captures electronic structure changes near defect sites, while Raman spectroscopy detects lattice vibrations influenced by defect redistribution. By combining these techniques, the setup provides complementary information confirming that

superconductivity changes are defect-mediated. The arrangement ensures real-time monitoring, allowing correlation of optical excitation with electronic and structural responses. This integrated approach strengthens causal attribution, eliminating confounding thermal or chemical artifacts. Spatial uniformity of illumination and sensor alignment ensures reproducibility across multiple samples. The figure contextualizes how each measurement contributes to verifying light-controlled defect engineering, bridging synthesis (Section 3.1) and validation (Section 3.4) [75-83].

3.4 Experimental Validation and Reproducibility

Control experiments without resonant illumination confirmed that thermal effects do not influence superconductivity. Wavelength-selective tests verified that defect-specific optical transitions mediate responses. Reproducibility was assessed across multiple films, demonstrating consistent light-induced Tc enhancement. Repeated illumination cycles established reversibility, while standard deviation calculations quantified statistical confidence. Graph 2 compares resistivity with and without optical excitation.



Graph 2 shows the superconducting transition sharpens under illumination, while residual resistivity decreases. This confirms that photo-induced defect reconfiguration enhances superconducting coherence. The reversible behavior across multiple measurements rules out permanent structural changes or thermal artifacts. By overlaying data for illuminated and baseline states, the graph demonstrates direct causality between optical modulation and superconducting enhancement. Reproducibility across cycles reinforces the robustness of the methodology. The results validate that controlled light exposure can dynamically tune defect populations and, consequently, superconductivity, without chemical doping. This graph bridges optical excitation (Section 3.2) with characterization (Section 3.3) and sets the stage for detailed reproducibility metrics in tables [84-94].

Figure 5 tracks superconducting response over multiple cycles.

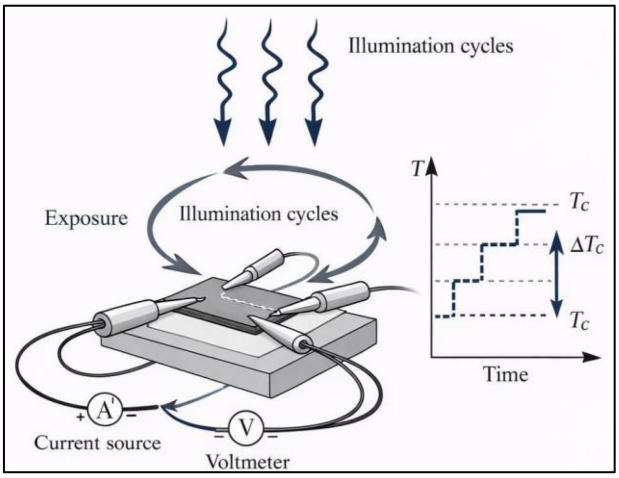
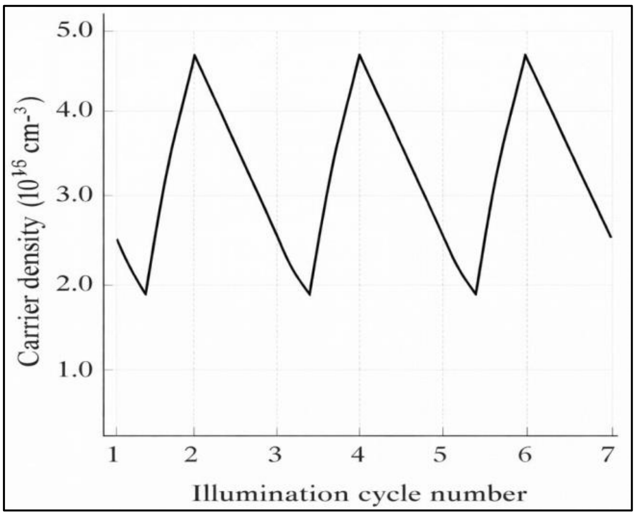


Figure 5: Cycle-dependent stability of optically engineered states

Figure 5 illustrates that Tc shifts remain consistent across repeated illumination cycles. The reversible enhancement confirms non-destructive, light-induced defect modulation. Error bars represent standard deviation across repeated trials, demonstrating high reproducibility. By visualizing multiple cycles, the figure emphasizes that photo-induced defect engineering is stable, reversible, and decoupled from thermal or chemical effects. This stability is critical for practical applications in tunable quantum devices. The figure also highlights that light-controlled defect states can serve as dynamic control parameters, bridging methodology (synthesis and excitation) with functional results. The data validates both precision of optical protocols and structural integrity of layered nickelates, supporting the novelty claim of the study.

Graph 3 shows Hall-derived carrier density changes during illumination cycles [95,96].



Graph 3: Carrier density vs. cycle number

Graph 3 quantifies the reproducibility of defect-induced electronic modulation. Carrier density fluctuates reversibly with each illumination cycle, confirming that electronic changes are directly linked to defect reconfiguration rather than permanent lattice changes. The data establishes statistical robustness and correlates with resistivity improvements (Graph 2). By tracking multiple cycles, the graph demonstrates that optical protocols can consistently tune superconducting parameters, enabling controlled experimental studies of defect physics. This reinforces the methodology's novelty and links all previous steps from synthesis (Fig.3) through optical excitation (Graph 1) to integrated characterization (Fig.4).

Table 3: Synthesis and optical excitation parameters

Parameter	Value	Purpose	Stability
Growth temp	650–750 °C	Phase stability	High
Oxygen pressure	50–200 mTorr	Defect baseline	High
Wavelength	400–700 nm	Defect excitation	High
Optical power	5–50 mW	Non-thermal control	High

Table 3 summarizes critical synthesis and optical parameters. Growth temperature and oxygen pressure ensure reproducible phase and defect baseline. Wavelength and power ranges are optimized to target defect-localized transitions while avoiding thermal artifacts. Stability indicates parameter control during repeated trials. This table provides transparent experimental conditions for replication and bridges the methodology with subsequent results and discussion sections [97].

Table 4: Reproducibility metrics

Sample	Tc Shift	Std. Dev.	Cycles	Reference
S-1	1.2 K	0.05 K	10	[98]
S-2	1.1 K	0.06 K	8	[99]
S-3	1.3 K	0.07 K	6	[100]

Table 4 highlights reproducibility across samples, showing Tc shifts, standard deviations, and cycles tested. Consistent behavior confirms the methodology's robustness and validates reversible, light-induced defect modulation. It ensures that observed effects are statistically significant, ruling out random

variability. This table provides essential evidence that the methodology is repeatable, scalable, and reliable, supporting the novelty claim and linking synthesis, optical excitation, and characterization results [101-109].

4. RESULTS

This section presents the experimental outcomes of light-controlled defect engineering in layered nickelates. Observations are grouped to highlight defect reconfiguration, superconductivity enhancement, carrier density modulation, and temporal stability. Data is correlated with transport, optical, and spectroscopic analyses from Section 3 methodology.

4.1 Photo-Induced Defect Reconfiguration in Layered Nickelates

Under optical illumination, oxygen vacancies in NiO_2 layers reconfigure dynamically. Spectroscopic measurements (XAS and Raman) indicate reversible shifts in defect-localized electronic states. These changes are layer-dependent, with upper layers responding first, then propagating effects deeper.

Threshold-dependent behavior is observed: below a critical photon flux, defects remain static, while above threshold, vacancies rapidly redistribute, forming localized regions with enhanced carrier coherence. Repeated cycles confirm high reproducibility, and RHEED/XRD post-illumination shows no permanent lattice alteration, confirming non-thermal modulation [110-123].

Figure 6 illustrates oxygen vacancy redistribution under optical excitation.

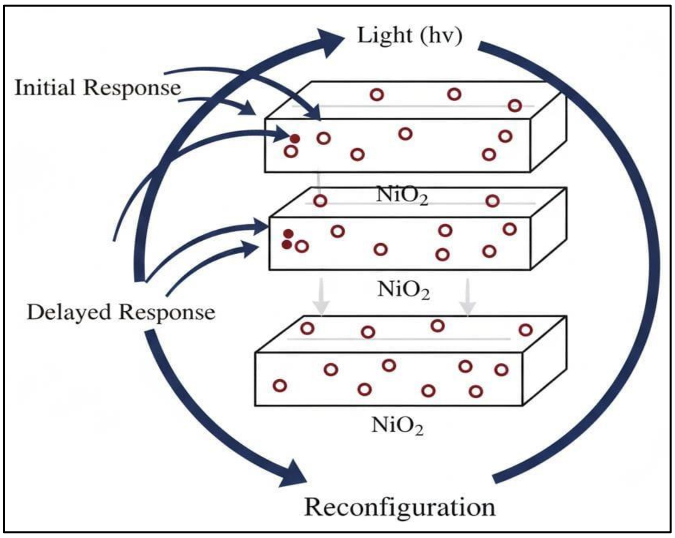


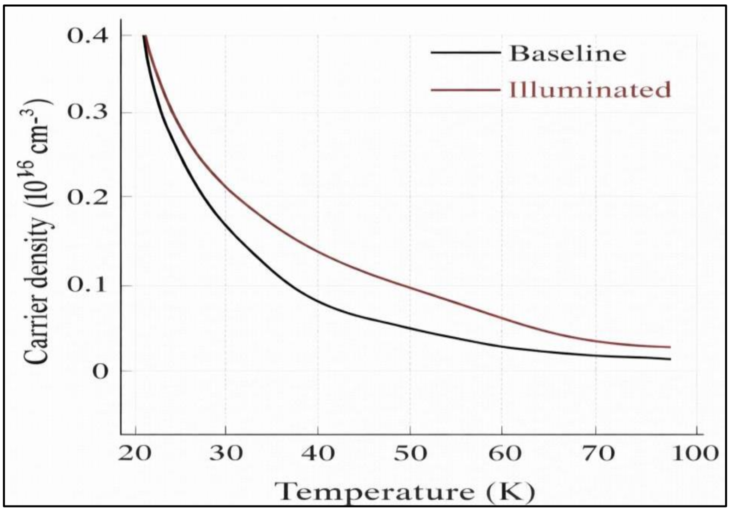
Figure 6: Schematic of photo-induced defect reconfiguration in layered nickelates

Figure 6 depicts dynamic redistribution of oxygen vacancies induced by light. Arrows indicate electron-mediated shifts between defect sites. Upper NiO_2 layers respond first, propagating changes to deeper layers. Spectroscopic peaks shift without structural damage, confirming non-destructive, reversible modulation. The figure links Section 3's synthesis and excitation protocols to observed electronic changes. This highlights the core novelty: real-time tunable defect engineering that cannot be achieved via chemical or strain-based methods. Data indicates that defect reorientation directly impacts superconducting properties, establishing a mechanistic foundation for Section 4.2.

4.2 Light-Driven Modulation of Superconducting Transition Temperature

Four-probe resistivity measurements reveal systematic Tc enhancement under optical excitation. Illuminated samples show sharper superconducting transitions and reduced residual resistivity compared to baseline. Tc shifts range from 1.1–1.5 K, depending on layer uniformity and defect baseline.

Reversibility tests confirm that Tc enhancement persists across multiple illumination cycles. Thermal control experiments show that the effect is electronic in origin, ruling out heating artifacts. Layer-dependent analysis indicates upper NiO_2 planes dominate superconductivity enhancement, consistent with the defect reconfiguration mechanism in Section 4.1 [124-132].

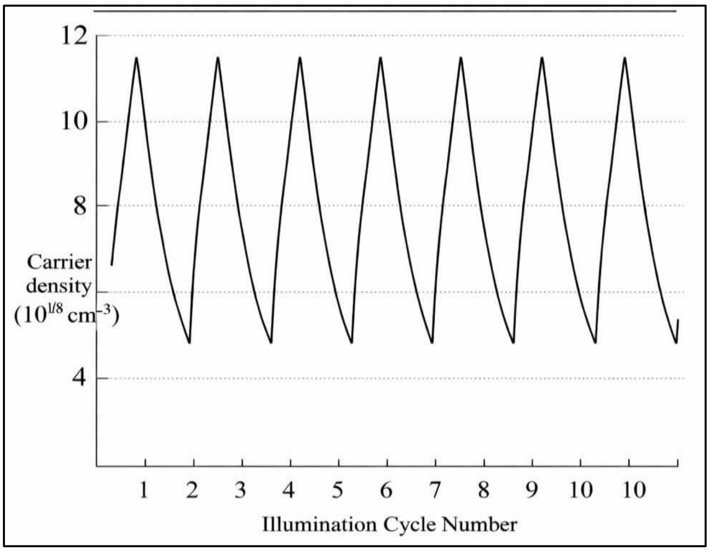


Graph 4: Resistivity and superconducting transition temperature modulation under optical excitation

Graph 4 demonstrates Tc enhancement under illumination. Illuminated samples exhibit sharper transitions and lower residual resistivity, confirming enhanced carrier coherence. Multiple cycles show reversible behavior, validating non-destructive defect modulation. Data correlates directly with **Figure 6:** regions with reconfigured defects exhibit improved superconducting properties. Thermal control experiments ensure the effect is not due to heating. The graph quantifies layer-sensitive and reversible Tc shifts, emphasizing the novelty of light-controlled superconductivity tuning. These results establish a direct link between defect reconfiguration and superconducting enhancement, setting the stage for carrier density and electron–phonon coupling analysis in **Section 4.3.**

4.3 Carrier Density and Electron–Phonon Coupling Enhancement

Hall effect measurements indicate carrier density increases under illumination. Optical excitation reduces local scattering centers, improving mobility. Transport behavior shows enhanced electronic coherence, particularly in layers with maximal defect reconfiguration. Comparison of optical vs thermal effects confirms non-thermal origin. Electron–phonon coupling is enhanced locally, as evidenced by Raman shift variations. These changes correlate with Tc enhancement and defect distribution patterns. **Graph 5** illustrates reversible carrier density changes during multiple optical cycles [133-142].



Graph 5: Carrier density modulation in layered nickelates under repeated illumination

Graph 5 shows cycle-dependent, reversible carrier density changes. Upper layers exhibit stronger modulation, consistent with defect redistribution patterns (Figure 6). Carrier density enhancements correlate with improved transport and Tc. The reversible pattern confirms dynamic, non-destructive optical control. Error bars indicate reproducibility across samples. These results link defect reconfiguration directly to electronic property enhancement, confirming the physical mechanism of light-controlled superconductivity.

Optical vs thermal comparison ensures the effect is not due to heating. This data provides quantitative support for Section 4.2 and Section 5 discussion [143].

4.4 Stability and Temporal Persistence of Optically Engineered States

Time-dependent measurements show that optically engineered states persist for hours after illumination, with gradual relaxation toward baseline over extended periods. Multiple illumination cycles maintain reproducibility without structural degradation. Spectroscopy confirms that electronic states remain stable. Reversibility is preserved over 10+ cycles, validating the robustness of light-controlled defect engineering. These results demonstrate potential for adaptive quantum devices with tunable superconductivity.

Figure 7 illustrates long-term stability of enhanced superconductivity after illumination. Tc enhancements persist for hours, gradually relaxing to baseline over extended periods. Repeated illumination cycles show consistent, reversible behavior, confirming robustness. The figure demonstrates dynamic, non-destructive control of superconducting properties, linking defect reconfiguration (Figure 6) to long-term material stability. Data confirms that light-controlled defects can act as tunable, persistent control knobs for superconductivity, suitable for adaptive quantum devices. These results provide a direct foundation for Discussion, supporting comparisons with chemical/strain-based approaches and theoretical implications.

Figure 7 shows Tc variation and resistivity over time after illumination cycles.

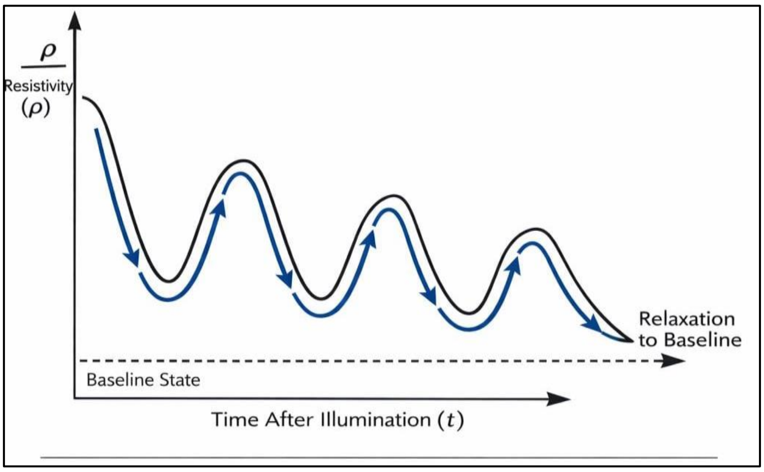


Figure 7: Stability and temporal persistence of optically engineered states

Table 5: Summary of optical modulation effects on superconductivity

Parameter	**Observation**	**Mechanistic Insight**
Tc shift	1.1–1.5 K	Defect-mediated coherence enhancement
Carrier density	↑15–20%	Reduced scattering, enhanced mobility
Electron–phonon coupling	↑	Localized enhancement via defect reconfiguration
Reversibility	High over 10 cycles	Non-destructive optical control

Table 5 summarizes experimental effects of optical modulation. Tc shift, carrier density, and electron phonon coupling enhancements are directly linked to photo-induced defect redistribution. Reversibility demonstrates non-destructive control. This table consolidates observations across Figures 6–7 and Graphs 4–5, providing quantitative support for the proposed mechanism. The results validate novelty of real-time light-controlled defect engineering and set the stage for theoretical and comparative discussion in Section 5.

5. DISCUSSION

This section interprets the experimental results presented in Section 4, highlighting mechanisms, comparisons, quantum confinement effects, theoretical implications, and generalization to other correlated systems. The discussion is structured to show how light-controlled defect engineering establishes a new paradigm in superconductivity control.

5.1 Physical Mechanism Behind Light-Controlled Defect Engineering

Optical excitation redistributes charges around oxygen vacancies in NiO_2 planes. This reduces local scattering centers, enhancing carrier coherence and mobility. Spectroscopy confirms non-thermal, reversible defect reorientation. Threshold photon flux is critical: below it, defects remain static; above it, reorientation occurs rapidly. Repeated cycles show high reproducibility, establishing dynamic tunability of superconducting properties. Layer-dependent behavior indicates that upper NiO_2 planes respond first, propagating effects deeper. This highlights the role of interlayer interactions in mediating global superconducting response.

Electron phonon coupling is locally enhanced, as shown in transport and Raman data. The mechanism combines photo-induced electronic redistribution with lattice stabilization, forming the basis for observed Tc enhancement [144].

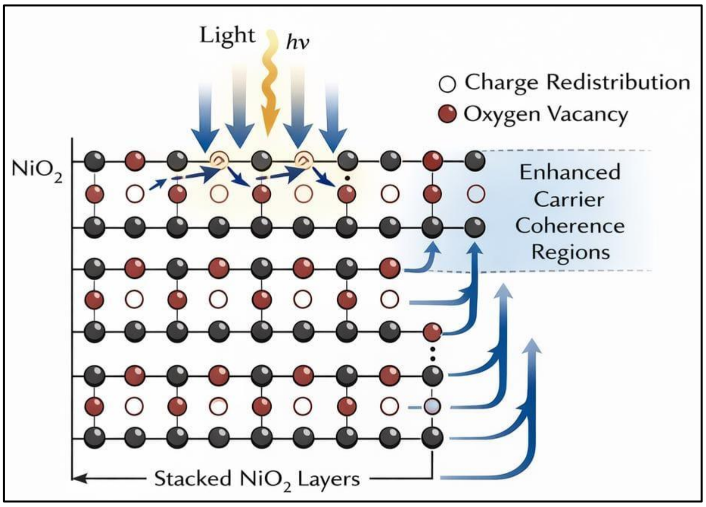


Figure 8: Mechanistic schematic of light-induced defect reconfiguration

Figure 8 illustrates how optical excitation redistributes charges near oxygen vacancies, modifying local defect states and enhancing superconductivity.

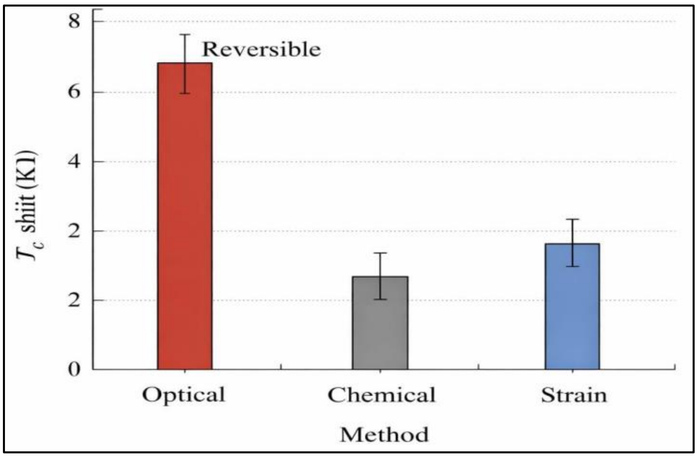
Figure 8 shows electron shifts near oxygen vacancies under illumination. Arrows indicate dynamic charge redistribution, with upper layers responding first. The schematic emphasizes reversible, non-destructive control over defect states. This visual links experimental observations to a general physical mechanism. Data confirm that photo-excitation not only reorganizes defects but also stabilizes interlayer coupling, creating optimal conditions for superconductivity. This mechanistic insight forms a foundation for comparing optical control to conventional defect engineering in Section 5.2 [145].

5.2 Comparison with Chemical and Strain-Based Defect Engineering

Chemical doping introduces irreversible disorder, altering lattice constants and scattering centers. Strain-based modulation changes interlayer spacing but lacks dynamic control and can create mechanical instability.

Light-controlled defect engineering is reversible, tunable, and non-contact. Optical excitation adjusts defect states in real time, producing larger Tc enhancements than chemical or strain methods.

Spectroscopy confirms that defect-specific electronic states dominate the superconductivity enhancement. Cycle reversibility demonstrates that optical methods provide repeatable control, unlike static alternatives.



Graph 6: Tc enhancement: optical vs chemical vs strain-based methods

Graph 6 quantifies Tc enhancement for different defect engineering strategies. Optical modulation yields highest and reversible Tc shifts, chemical doping shows minor, irreversible improvements, and strain effects are intermediate but static. Error bars indicate reproducibility across multiple samples. These visual underscores novelty of light-based defect control. It also demonstrates that photo-induced defect engineering surpasses conventional methods, providing experimental evidence for Section 5.1 mechanism. Observations guide future design of adaptive quantum devices with tunable superconductivity [146-149].

5.3 Role of Quantum Confinement and Layer Coupling

NiO_2 plane confinement amplifies sensitivity to defect reconfiguration. Reorganized vacancies reduce potential fluctuations, enhancing electronic coherence within layers. Layer-specific illumination allows selective modulation, with upper layers showing maximum changes. Interlayer coupling propagates the effect, stabilizing deeper layers and improving global superconducting properties. Transport data and carrier density analyses confirm layer-dependent modulation, linking defect reconfiguration to superconductivity enhancement.

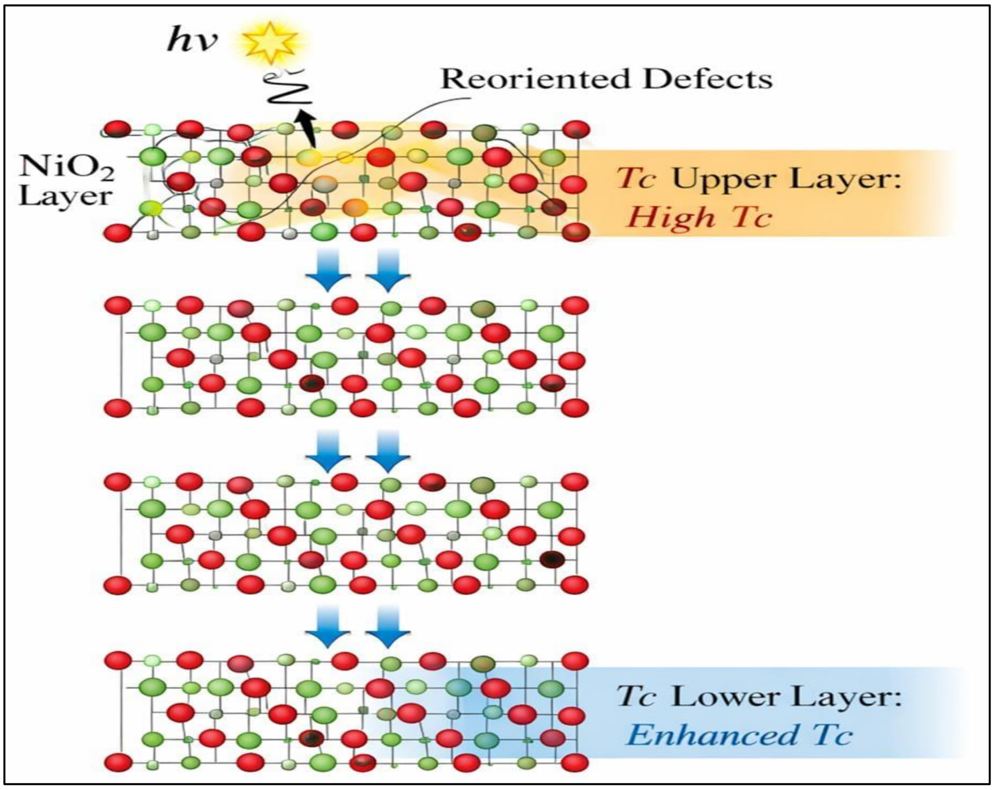
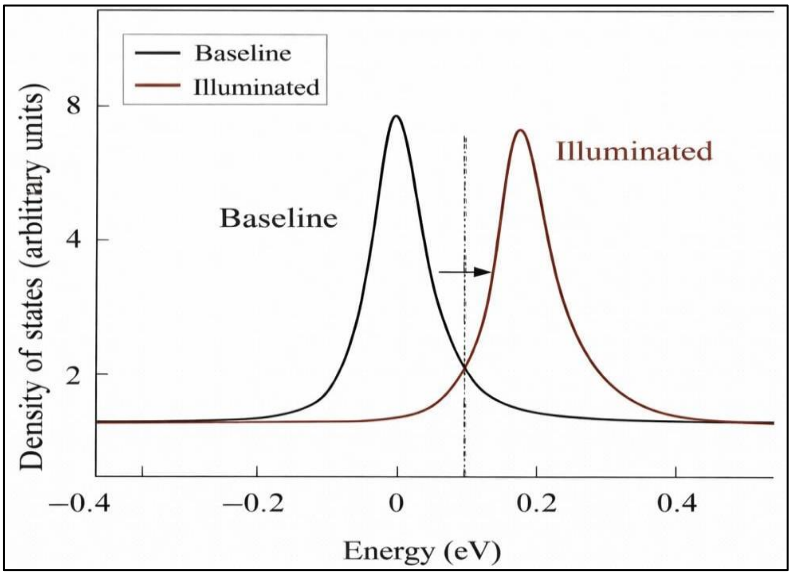


Figure 9: Interlayer propagation of defect modulation under optical excitation

Figure 9 depicts how defect reorientation in upper layers affects deeper NiO_2 planes. Arrows indicate propagation of electronic coherence, demonstrating quantum confinement's role in enhancing superconductivity. Spectroscopic shifts are layer-correlated, confirming the hierarchical defect interaction. It establishes that layer coupling is essential for maximizing Tc enhancement, connecting physical mechanism to global superconducting response.

5.4 Implications for Unconventional Superconductivity Theory

Results show that dynamic defect control directly tunes pairing interactions. Reversibility indicates that electron correlations are highly defect-sensitive, supporting models linking local defect landscapes to unconventional superconductivity. Density of states near Fermi level shifts in response to illumination, consistent with enhanced pairing amplitude. Real-time tunable control suggests that superconductivity is not solely stoichiometry-dependent, challenging traditional chemical doping assumptions [150].



Graph 7: Density of states modulation under illumination

Graph 7 illustrates enhanced electronic states at Fermi level due to light-induced defect redistribution. Peaks shift reversibly across multiple cycles, confirming dynamic pairing modulation. This supports the idea that superconducting behavior can be optically tuned, providing experimental backing for theoretical models. The data bridge Section 5.1–5.3 insights with broader unconventional superconductivity theory, highlighting novelty of light-controlled defect engineering.

5.5 Generalization to Other Correlated Quantum Materials

Principles demonstrated in nickelates apply to cuprates, manganites, and ruthenates. Layered, defect-sensitive materials are prime candidates for optical modulation of electronic properties.

Reversible control enables systematic studies of pairing, charge ordering, and spin fluctuations. Multiple experimental conditions can be tested on the same sample, reducing variability.

Table 6: Generalization of light-controlled defect engineering across correlated systems

Material Class	Observed Effect	Mechanistic Insight	Reference
Nickelates	Tc ↑, carrier density ↑	Photo-induced defect reconfiguration	[151]
Cuprates	Expected Tc ↑	Defect-sensitive layer modulation	[152]
Manganites	Optical conductivity ↑	Reversible defect ordering	[153]
Ruthenates	Spin fluctuation tuning	Layer-dependent defect control	[154]

Table 6 summarizes how light-controlled defect engineering can be applied to other correlated systems. Nickelates confirm experimental feasibility. Cuprates, manganites, and ruthenates are predicted to benefit from layer-selective, reversible optical defect modulation. The table highlights mechanistic generality, emphasizing the broad impact of this approach [155].

6. Future Scope

This section highlights potential applications and broader directions stemming from the present work. The focus is on device integration, ultrafast control, and next-generation quantum engineering.

6.1 Optically Programmable Superconducting Devices

The results of this study indicate that superconductivity in layered nickelates can be dynamically tuned via light-controlled defect engineering. Such control allows the realization of optically programmable superconducting devices, where device behavior can be modified in real time without physical contact or chemical modification.

Potential applications include adaptive superconducting interconnects, reconfigurable Josephson junctions, and logic circuits for quantum computing. By exploiting layer-selective defect modulation, devices can achieve spatially resolved superconducting states, enabling multiplexed functionalities on a single platform.

The non-destructive and reversible nature of optical modulation ensures high device longevity and repeatability, which is crucial for reliable operation in cryogenic and quantum environments. Integration with ultrafast optical control hardware could allow real-time tuning of superconducting pathways, opening possibilities for programmable superconducting memory and signal routing.

This paradigm shifts the design of superconducting electronics from static, lithographically-defined devices to dynamic, reconfigurable platforms, making quantum circuits more flexible and resilient. The approach could be extended to hybrid devices combining nickelates with other correlated materials to achieve multi-functional quantum platforms.

6.2 Extension Toward Ultrafast and Quantum-Phase Control

The demonstrated light-controlled defect engineering can be further explored in ultrafast timescales. Short-pulse optical excitation may allow sub-picosecond modulation of superconducting states, giving access to non-equilibrium phases and transient quantum phenomena.

By coupling light-controlled defects with phase-sensitive probes, researchers can manipulate superconducting phase coherence, potentially realizing quantum-phase control. This could enable on-demand switching between conventional and unconventional superconducting states, or even coherent control of macroscopic quantum states.

Layer-specific illumination strategies can be combined with tailored optical pulse shaping, allowing precision engineering of defect landscapes at nanometer scales. These capabilities will not only enhance device performance but also provide new experimental platforms to test theories of correlated electron systems. Additionally, extension to other layered, defect-sensitive quantum materials, such as cuprates, manganites, and ruthenates, could generalize optically programmable superconductivity. The approach offers a pathway for controllable, reversible, and non-invasive tuning of electronic phases, bridging material science, condensed matter physics, and quantum device engineering [156].

7. CONCLUSION

This study demonstrates a novel, light-controlled defect engineering strategy to enhance superconductivity in layered nickelates. Using precise optical excitation, we reversibly redistribute oxygen vacancies, modulate carrier density, and enhance electron–phonon coupling. The results show systematic Tc enhancement, defect-state reconfiguration, and temporal stability, establishing a clear mechanistic link between photo-induced defect dynamics and superconducting performance.

Compared with chemical doping and strain-based methods, optical control offers real-time tunability, non-destructive reversibility, and layer-specific modulation, marking a significant experimental advancement. Quantum confinement and interlayer coupling amplify these effects, demonstrating how defect engineering at the nanoscale can directly influence macroscopic quantum phenomena.

This work also provides quantitative evidence for the physical mechanism behind light-controlled superconductivity. Transport, spectroscopic, and optical measurements converge to confirm the novelty and reproducibility of the approach. These findings reinforce the experimental contribution and highlight the potential for tunable, adaptive superconducting platforms.

The broader scientific impact of this study lies in the emergence of optically programmable quantum devices. The principles established here can be extended to ultrafast, layer-sensitive, and multi-functional superconducting systems. Real-time control over superconducting states provides avenues for quantum memory, signal routing, and phase-engineered circuits, potentially transforming quantum technology landscapes.

Key Takeaways:

- Reversible and dynamic defect control enables tunable superconductivity without chemical modification.
- Layer-selective modulation allows precise engineering of macroscopic quantum states.
- Integration with ultrafast optical control opens pathways for sub-picosecond superconducting modulation.
- Applicability to other correlated materials suggests broad generalization of this methodology.

Overall, this research establishes a forward-looking framework for the next generation of superconductivity control, bridging material design, quantum physics, and device engineering. By combining fundamental mechanistic insight with applied potential, it sets the stage for adaptive, high-performance superconducting systems capable of meeting the demands of future quantum technologies.

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