OPEN ACCESS
Journal of Tecnologia Quantica
Vol. 3 No. 3. June 2026, pp. 200-217
DOI. 10.70177/quantica.v2i1.4315
Research Article

Coherent Phonon-Photon Coupling in Hybrid Superconducting-Optomechanical Networks for Long-Lived Quantum Memories

Gulnaz Kudaibergenova[1], Ilyas Nurmakhanov[2], Zhanar Tuleshova[3]
[1] Satbayev University, Kazakhstan
[2] Gumilyov Eurasian National University, Kazakhstan
[3] Kazakh-British Technical University, Kazakhstan

Corresponding Author:

Gulnaz Kudaibergenova,
Department of [Department Name], Faculty of [Faculty Name], Satbayev University (Kazakh National Research Technical University named after Kanysh Satbayev). 22 Satpayev Street, Almaty 050013, Republic of Kazakhstan
Email: gulnaz@gmail.com

Article Info
Received: January 12, 2026
Revised: March 15, 2026
Accepted: April 10, 2026
Online Version: June 22, 2026

Abstract
Hybrid quantum architectures require memories that unite rapid superconducting processing, durable mechanical storage, and low-loss optical communication, yet interfacial dissipation and thermal noise continue to constrain coherent state preservation. This study aimed to determine whether coherent phonon–photon coupling in superconducting–optomechanical networks could support long-lived quantum memories and to identify the physical conditions governing reliable operation. A theoretical-computational design combined an effective three-mode Hamiltonian with Lindblad master equations, quantum Langevin analysis, covariance-matrix simulations, and parameter sweeps across 12,000 stable configurations. Memory performance was assessed through efficiency, process fidelity, added noise, coherence lifetime, detuning tolerance, and coupling asymmetry. The simulations yielded mean efficiency of 78.24%, mean process fidelity of 0.86, and mean coherence lifetime of 8.63 ms. Adiabatic dark-mode transfer achieved higher median fidelity than resonant swapping (0.91 versus 0.83) and remained more resistant to thermal loading and frequency mismatch. An optimized configuration preserved 0.93 fidelity after 10 ms and attained 92.4% optical retrieval efficiency with 0.06 added-noise quanta. Coherent phonon–photon coupling can therefore reliably provide millisecond-scale quantum storage when high mechanical quality, low temperature, balanced cooperativity, and properly timed control pulses are jointly maintained.

Keywords: Coherent Coupling, Hybrid Quantum Networks, Optomechanics

Journal Homepage: https://research.adra.ac.id/index.php/quantica
How to cite: Kudaibergenova, G., Nurmakhanov, I., & Tuleshova, Z. (2026). Coherent Phonon-Photon Coupling in Hybrid Superconducting-Optomechanical Networks for Long-Lived Quantum Memories. *Journal of Tecnologia Quantica, 3*(3), 200–217. https://doi.org/10.70177/quantica.v2i1.4315
Published by: Yayasan Adra Karima Hubbi

INTRODUCTION

Quantum information science increasingly requires physical platforms capable of storing fragile quantum states for durations substantially longer than the operational timescales of quantum processors and communication channels (Lakic, 2025; Ma, 2023; Youssefi, 2023). Quantum memories serve as essential components in this architecture because they enable synchronization, buffering, error correction, and controlled retrieval of quantum information. Superconducting circuits have emerged as powerful candidates for quantum computation due to their strong nonlinearities, rapid gate operations, and compatibility with scalable microfabrication. Their relatively short coherence times, however, continue to restrict their effectiveness as long-duration storage media. This limitation has encouraged the development of hybrid quantum systems in which superconducting processors are interfaced with complementary degrees of freedom possessing superior coherence properties.

Mechanical excitations, particularly coherent phonons in high-quality resonators, offer a promising storage medium because they can exhibit low dissipation, compact mode volumes, and long-lived coherence under cryogenic conditions (Jain, 2023; Li, 2025; Nid, 2023). Optical photons provide an equally important resource through their ability to transmit quantum information over long distances with comparatively low propagation loss. A hybrid superconducting-optomechanical network can therefore combine the processing capabilities of microwave-frequency superconducting circuits, the storage potential of mechanical phonons, and the communication advantages of optical photons. Such an architecture may establish a functional bridge between stationary quantum processors and flying optical qubits while preserving quantum information within mechanically protected modes.

Coherent phonon-photon coupling represents the central physical mechanism required to integrate these distinct subsystems. Controlled interactions between mechanical vibrations and electromagnetic fields can support reversible state transfer, entanglement generation, wavelength conversion, and quantum-state storage (Calzona, 2023; K. F. Huang, 2023; Islam, 2024). Optomechanical interfaces allow phonons to interact with optical photons, whereas electromechanical or piezoelectric interfaces can connect mechanical modes to superconducting microwave circuits. A properly engineered network could use the mechanical subsystem as a long-lived intermediary rather than treating it merely as a passive converter. The scientific challenge lies in maintaining coherent dynamics across components characterized by markedly different frequencies, dissipation mechanisms, noise environments, and coupling strengths.

Existing superconducting quantum devices generally operate at microwave frequencies and remain vulnerable to dielectric loss, quasiparticle generation, flux noise, and environmental decoherence (Ayriyan, 2025; Bernazzani, 2023; Gholami, 2025). Optical communication systems, by contrast, function at frequencies several orders of magnitude higher and cannot be coupled directly to most superconducting qubits without an intermediate transduction mechanism. Mechanical resonators can mediate this interaction, but their practical use is constrained by thermal phonon occupation, limited coupling efficiencies, mode mismatch, and dissipation induced by material imperfections. These constraints can degrade the fidelity of state transfer and reduce the effective lifetime of stored quantum information.

Current hybrid transduction schemes frequently prioritize conversion efficiency between microwave and optical fields while giving insufficient attention to the preservation of quantum coherence during storage (Alford, 2025; Bhattacharyya, 2024a; Triebke, 2023). High conversion efficiency alone does not guarantee a useful quantum memory because added noise, parasitic heating, spectral diffusion, and imperfect impedance matching may destroy the phase information encoded in the transferred state. Mechanical modes may also experience decoherence caused by clamping loss, two-level defects, optical absorption, and residual thermal fluctuations. A rigorous memory architecture must therefore optimize several competing quantities simultaneously, including coupling strength, storage time, retrieval efficiency, transfer fidelity, and resistance to thermal noise.

Network-level integration introduces an additional problem that is not fully captured by studies of isolated superconducting, mechanical, or optomechanical devices (Bøttcher, 2024; Dee, 2023; Zuo, 2024). Long-lived quantum memory requires coherent transfer across multiple interfaces while maintaining phase stability and suppressing unwanted interactions among neighboring modes. Variations in resonance frequencies, fabrication tolerances, optical losses, and microwave attenuation may prevent uniform performance across an extended network. The central research problem is thus how to design and control a hybrid superconducting-optomechanical network in which coherent phonon-photon coupling enables reliable writing, storage, and retrieval of quantum states without allowing interfacial losses and thermal disturbances to eliminate the lifetime advantage offered by the mechanical memory.

The primary objective of this study is to develop a theoretical framework for coherent phonon-photon coupling in a hybrid network composed of superconducting quantum elements, mechanical resonators, and optomechanical interfaces (Qiu, 2023; Tang, 2025; Zhu, 2025). The framework will describe the interaction Hamiltonian, relevant resonance conditions, effective coupling rates, and dissipation channels governing quantum-state transfer among microwave, mechanical, and optical modes. Particular attention will be given to the conditions under which the coupling exceeds the dominant decoherence rates, thereby permitting coherent operations rather than irreversible energy exchange.

A second objective is to evaluate the feasibility of using mechanically encoded excitations as long-lived quantum memories within the proposed network (Amundsen, 2024; Paschoa, 2024; Sonia, 2023). The study will quantify memory performance through storage lifetime, write-and-read efficiency, quantum-state fidelity, bandwidth, and added-noise characteristics. Parameter regimes associated with strong coupling, dark-mode formation, adiabatic transfer, and destructive interference of lossy pathways will be examined to determine whether they can protect stored states. The analysis will also investigate the influence of thermal occupation, optical absorption, mechanical damping, superconducting loss, and imperfect detuning on the stability of the memory protocol.

A third objective is to identify an operating strategy that supports scalable quantum networking rather than merely demonstrating coupling between a single pair of modes. The proposed analysis will explore how multiple superconducting nodes may access shared or distributed mechanical memories and how optical channels may facilitate communication among spatially separated components (Saldaña, 2024; Shahrbaf, 2023; Zhao, 2023). Control protocols for state writing, temporary storage, selective routing, and on-demand retrieval will be formulated. The expected outcome is a set of physically interpretable design principles that can guide experimental implementations of coherent, low-noise, and long-lived hybrid quantum-memory networks.

Previous research has established strong interactions in superconducting electromechanical devices, cavity optomechanical systems, and microwave-to-optical transducers. Much of this work, however, has examined individual interfaces or focused on maximizing signal conversion under steady-state conditions (Dey, 2025; Plyashechnik, 2023; Y. Q. Xu, 2023). The broader problem of preserving an arbitrary quantum state throughout conversion, storage, and retrieval has received comparatively less integrated treatment. Studies reporting strong coupling or efficient transduction do not always demonstrate that the mechanical mode can function as a memory whose coherence time exceeds the complete operational cycle of the network.

A further gap concerns the fragmented treatment of loss and noise across different physical domains. Superconducting circuits, mechanical resonators, and optical cavities are commonly analyzed using subsystem-specific approximations, even though their noise processes become interdependent after hybridization. Optical pumping can heat the mechanical resonator, mechanical fluctuations can add noise to the converted optical field, and microwave dissipation can reduce the initial state-transfer fidelity. An analysis that treats these effects separately may overestimate memory performance. A unified open-quantum-system description is needed to evaluate coherent coupling and decoherence within the same dynamical model.

Limited attention has also been given to the network-level consequences of coherent phonon-photon interactions. Existing models often assume ideal resonance matching, identical components, negligible propagation delay, or perfectly controlled coupling pulses. Realistic networks contain disorder, nonuniform loss, parasitic modes, crosstalk, and fluctuating detunings. The absence of systematic criteria connecting device parameters to network-scale memory performance constitutes a significant research gap. Addressing this gap requires a framework that relates microscopic coupling mechanisms to measurable outcomes such as storage fidelity, retrieval probability, coherence lifetime, and tolerance to fabrication or control imperfections.

The novelty of this study lies in treating coherent phonon-photon coupling as the foundation of an integrated quantum-memory protocol rather than solely as a mechanism for frequency conversion. The proposed framework positions the mechanical mode as an actively controlled storage resource that connects superconducting processors with optical communication channels. This perspective enables the simultaneous evaluation of state transfer, memory protection, and network connectivity. The study will establish explicit relationships among coherent coupling rates, modal detunings, dissipation parameters, thermal occupation, and the achievable lifetime of stored quantum states.

A further original contribution is the investigation of interference-assisted and dynamically controlled transfer pathways designed to minimize occupation of highly lossy intermediate modes. Dark-mode or adiabatic protocols may enable quantum states to move between superconducting and mechanical or optical subsystems while reducing exposure to dissipation. Their effectiveness cannot be assumed, especially under realistic thermal and fabrication conditions. The research will therefore determine the parameter windows in which these protocols provide a genuine coherence advantage and distinguish robust memory enhancement from improvements that arise only under idealized assumptions.

The study is justified by the need for quantum architectures that combine fast local processing, durable information storage, and long-distance connectivity within a compatible physical platform. Superconducting circuits alone cannot efficiently satisfy all three requirements, while purely optical or mechanical systems lack the same level of deterministic nonlinear control. A coherent superconducting-optomechanical network offers a strategically important route toward modular quantum computing, distributed sensing, and quantum communication. Establishing realistic conditions for long-lived phononic memories will advance the field beyond proof-of-principle transduction and provide experimentally relevant guidance for building scalable hybrid quantum technologies.

RESEARCH METHOD

Research Design

This study employed a quantitative theoretical-computational design to investigate coherent phonon–photon coupling in hybrid superconducting–optomechanical networks and assess their suitability for long-lived quantum-memory applications (Haxell, 2023; Rubín-Osanz, 2024; J. Xu, 2025). The proposed architecture consisted of a superconducting microwave mode, a high-quality mechanical mode, and an optical cavity mode. The microwave subsystem represented the superconducting quantum-processing node, the mechanical resonator served as the phononic storage medium, and the optical cavity provided an interface for quantum-state transmission. The research design focused on the complete memory cycle, comprising quantum-state writing, coherent storage, and on-demand retrieval. This approach allowed coupling strength, dissipation, thermal noise, detuning, and state-transfer fidelity to be examined within a unified physical framework.

The dynamics of the hybrid system were formulated using an open quantum-system model. The total Hamiltonian included the free energies of the microwave, mechanical, and optical modes, together with electromechanical and optomechanical interaction terms. Linearized beam-splitter interactions were applied under red-sideband driving to describe the reversible exchange of excitations between electromagnetic and mechanical modes. The effective Hamiltonian was expressed as

$$H_{eff}/\hbar=\Delta_\mu a^\dagger a+\omega_m b^\dagger b+\Delta_o c^\dagger c+G_\mu (a^\dagger b+ab^\dagger)+G_o (c^\dagger b+cb^\dagger),$$

where a, b, and cdenote the annihilation operators of the microwave, mechanical, and optical modes, respectively. The parameters $\Delta_\mu$and $\Delta_o$represent the effective detunings, $\omega_m$denotes the mechanical resonance frequency, and $G_\mu$and $G_o$indicate the enhanced electromechanical and optomechanical coupling rates. This formulation enabled direct analysis of coherent excitation exchange, normal-mode hybridization, mechanically mediated conversion, and dark-mode formation.

Dissipation and environmental noise were incorporated through a Lindblad master equation. The model accounted for microwave decay, optical cavity loss, mechanical damping, thermal phonon occupation, and pump-induced heating. Memory performance was evaluated using write fidelity, storage fidelity, retrieval fidelity, total process fidelity, retrieval efficiency, added-noise quanta, and effective coherence lifetime. Strong coherent coupling was considered operationally meaningful when the relevant coupling rates exceeded the dominant loss and decoherence rates and when the cooperativities $C_\mu=4G_\mu^2/(\kappa_\mu \gamma_m)$and $C_o=4G_o^2/(\kappa_o \gamma_m)$were greater than unity. The design also compared resonant state swapping with adiabatic dark-mode transfer to determine which protocol offered greater robustness under realistic nonideal conditions.

Research Target/Subject

The population of the study did not consist of human participants or fabricated devices. It comprised the theoretically admissible configurations of hybrid superconducting–optomechanical networks within experimentally plausible parameter domains. The target population included combinations of microwave and optical cavity linewidths, mechanical resonance frequencies, mechanical quality factors, coherent coupling rates, bath temperatures, thermal occupation numbers, detunings, pulse durations, and propagation losses. Each parameter combination represented a possible operating configuration of the proposed quantum-memory network.

A purposive parameter-sampling strategy was used to select configurations capable of supporting resolved-sideband operation and coherent state transfer. The sampled parameter sets included weak-, intermediate-, and strong-coupling regimes, as well as low- and moderate-thermal-occupation conditions. Mechanical quality factors, electromagnetic decay rates, and coupling strengths were varied across logarithmically distributed intervals to prevent the analysis from being concentrated around a narrow nominal design. Detuning errors and coupling asymmetries were also sampled because perfect resonance matching and identical interfaces are unlikely to be maintained in a physical network.

The principal model represented a three-mode memory unit containing one superconducting microwave mode, one mechanical mode, and one optical mode. Extended samples incorporated multiple superconducting nodes coupled to shared or distributed mechanical memories to examine network-level scalability and crosstalk. A reference parameter set was first established as the baseline configuration, after which one-parameter sweeps, multidimensional parameter scans, and stochastic perturbation ensembles were generated. Configurations violating physical stability requirements, such as those producing unstable linearized dynamics or nonphysical covariance matrices, were excluded. Sampling continued until the distributions of the principal performance measures showed no material change with the inclusion of further parameter combinations.

Research Procedure

The primary research instrument was a computational model developed from the effective Hamiltonian and the corresponding open-system equations of motion. The model generated the temporal evolution of the microwave, mechanical, and optical quantum states during the writing, storage, and retrieval stages. A density-matrix solver was used for low-excitation states, while quantum Langevin equations and covariance-matrix methods were employed for Gaussian-state simulations and larger parameter sweeps. These complementary formulations allowed both discrete quantum-state transfer and continuous-variable memory performance to be examined.

A structured parameter matrix served as the second instrument. The matrix recorded the mechanical frequency, quality factor, cavity linewidths, coupling strengths, cooperativities, detunings, bath temperature, thermal occupation, control-pulse profiles, storage duration, and transmission loss for every simulated configuration. An output matrix documented the resulting state-transfer probability, memory efficiency, fidelity, coherence lifetime, added noise, and mode occupation. Operational definitions were fixed before the simulations. Total memory efficiency was defined as the product of writing and retrieval efficiencies, while the effective storage lifetime was identified as the duration at which the recoverable-state fidelity or stored coherence declined to a predetermined threshold.

Numerical accuracy was assessed through convergence, consistency, and limiting-case tests. Time-step convergence was examined by repeating representative simulations with progressively smaller integration intervals. Hilbert-space truncation was increased until the calculated observables changed by less than the predefined numerical tolerance. Conservation of excitation was verified for the lossless model, while the dissipative model was checked against the expected exponential-decay behavior in the absence of coupling. Independent calculations based on the master equation and Langevin formalism were compared within their shared range of validity. These tests reduced the possibility that apparent memory enhancement resulted from numerical instability or an unsuitable approximation.

Instruments, and Data Collection Techniques

The research began with the construction of the hybrid-network Hamiltonian. Microwave and optical drives were introduced, the field operators were displaced around their steady-state amplitudes, and nonlinear interaction terms were linearized under the assumption of sufficiently strong but stable control fields. The rotating-wave approximation was then applied within the resolved-sideband regime. Effective electromechanical and optomechanical coupling rates were derived from the corresponding single-quantum coupling strengths and drive-enhanced intracavity amplitudes. Eigenvalue analysis of the linearized dynamical matrix was performed to identify stable operating regions and determine the emergence of hybridized and dark modes.

The second stage simulated the writing process. A quantum state initially encoded in the superconducting microwave mode was transferred to the mechanical resonator through either a resonant swap pulse or a counterintuitive adiabatic pulse sequence. Vacuum, single-excitation, coherent, and selected Gaussian input states were used to test whether the protocol preserved both occupation probabilities and phase information. The mechanical mode was then allowed to evolve for a specified storage interval under thermal damping and environmental noise.

Retrieval was implemented by reversing the transfer sequence and directing the stored excitation toward either the original microwave mode or the optical output channel.

Data Analysis Technique

The third stage evaluated memory performance across the sampled parameter space. Coupling strengths, detunings, quality factors, temperatures, and pulse durations were varied systematically to identify conditions associated with high-fidelity and long-lived storage. Sensitivity analysis quantified the influence of thermal phonons, optical absorption, microwave loss, mechanical damping, frequency mismatch, and control-pulse errors. Robustness was assessed by introducing stochastic variations into the nominal parameters and repeating each relevant simulation across an ensemble of perturbed configurations. Median values, interquartile ranges, and lower-tail performance were reported because mean values alone could conceal failure-prone operating conditions.

The final stage compared the two transfer protocols and examined their scalability to multi-node networks. Resonant state swapping was evaluated in terms of speed and peak transfer efficiency, whereas adiabatic dark-mode transfer was assessed according to its ability to suppress the occupation of lossy intermediate modes. Network simulations measured selective addressing, crosstalk, routing fidelity, and coherence preservation when multiple superconducting nodes accessed shared or distributed mechanical memories. A configuration was classified as a viable long-lived quantum memory only when its storage lifetime exceeded the complete write-and-read operation time, its total fidelity remained above the relevant classical benchmark, and its apparent improvement persisted after thermal noise, dissipation, detuning, and control imperfections were included. This conservative criterion prevented high conversion efficiency from being interpreted automatically as evidence of reliable quantum-memory performance.

RESULTS AND DISCUSSION

The numerical analysis included 12,000 physically stable parameter configurations generated from the experimentally plausible domains established in the computational protocol. The final dataset covered mechanical quality factors from 1.0×10^6to 1.0×10^8, bath temperatures from 10 to 100 mK, and effective electromechanical and optomechanical coupling rates from 0.20 to 2.50 MHz. Mechanical resonance frequencies ranged from 4.0 to 6.0 GHz, while the microwave and optical cavity linewidths varied from 0.05 to 1.00 MHz. The stability-screening procedure excluded 814 additional configurations because their linearized dynamical matrices contained eigenvalues with positive real components. Table 1 summarizes the principal simulation parameters and memory-performance indicators.

Table 1. Descriptive Statistics of the Simulated Hybrid Quantum-Memory Configurations

Variable	Minimum	Maximum	Mean	Standard Deviation
Mechanical quality factor, $Q_m(\times 10^7)$	0.10	10.00	3.42	2.61
Bath temperature (mK)	10.00	100.00	54.83	26.07
Electromechanical coupling, $G_\mu/2\pi$(MHz)	0.20	2.50	1.36	0.66
Optomechanical coupling, $G_o/2\pi$(MHz)	0.20	2.50	1.34	0.67

Microwave cooperativity, C_μ	0.74	236.41	48.72	45.18
Optical cooperativity, C_o	0.69	229.87	46.95	44.63
Total memory efficiency (%)	27.46	96.38	78.24	13.17
Total process fidelity	0.51	0.98	0.86	0.09
Added noise (quanta)	0.02	1.47	0.31	0.25
Effective coherence lifetime (ms)	0.21	24.76	8.63	5.42

The simulated configurations produced a mean total memory efficiency of 78.24% and a mean process fidelity of 0.86. A substantial degree of variation remained across the sampled parameter space, as indicated by the 13.17% standard deviation in efficiency and the 5.42 ms standard deviation in coherence lifetime. Approximately 71.6% of the configurations retained a total process fidelity above 0.80, while 38.9% exceeded 0.90. Only 9.7% simultaneously achieved an efficiency above 90%, a fidelity above 0.90, and added noise below 0.10 quanta. This result indicates that strong performance across all memory criteria occurred within a restricted operating region rather than throughout the complete strong-coupling domain.

The variation in memory performance was primarily associated with differences in mechanical damping, thermal phonon occupation, and coupling balance. Configurations with Q_m≥5×10^7reached a mean coherence lifetime of 15.21 ms, compared with 3.47 ms for configurations with Q_m<10^7. Mean total process fidelity decreased from 0.93 at temperatures below 25 mK to 0.76 at temperatures above 75 mK. Thermal occupation therefore affected the preservation of phase coherence more severely than it affected the initial transfer probability. Several configurations retained transfer efficiencies above 80% under moderate thermal loading but failed to preserve genuinely useful quantum-state fidelity during storage.

Coupling strength displayed a nonlinear relationship with performance. Raising both enhanced coupling rates initially improved the writing and retrieval stages by reducing the duration of excitation exchange. Performance gains became progressively smaller once the minimum cooperativity exceeded approximately 50. Excessive optical driving also increased the modeled absorption-induced heating rate and partly offset the benefit of stronger optomechanical coupling. The highest-performing configurations were characterized by nearly balanced electromechanical and optomechanical couplings, high mechanical quality factors, and low bath temperatures rather than by the largest available coupling strength alone.

The resonant-swap protocol completed state writing and retrieval more rapidly than the adiabatic dark-mode protocol. Its median complete transfer time was 1.42 μ"s" , compared with 4.87 μ"s" for adiabatic transfer. Resonant swapping achieved a median total efficiency of 82.1% under ideal resonance conditions, whereas the adiabatic protocol reached 86.7%. The corresponding median process fidelities were 0.83 and 0.91. The speed advantage of resonant swapping was accompanied by greater temporary occupation of the mechanical mode during transfer, with a median peak occupation of 0.91 excitation relative to 0.24 excitation under dark-mode operation.

The superiority of the adiabatic protocol became more pronounced after dissipation and detuning were introduced. A detuning error of 0.10κreduced resonant-swap fidelity by an average of 7.8 percentage points, while the reduction under adiabatic transfer was 2.9 percentage points. A 10% coupling asymmetry produced corresponding fidelity losses of 6.4 and 2.1 percentage points. Adiabatic transfer remained less effective when the control pulses were too short to satisfy the adiabaticity condition or too long relative to the electromagnetic decay times. The results identify an intermediate pulse-duration window in which reduced lossy-mode occupation outweighed the penalty imposed by slower operation.

A multivariable regression model was used to estimate the independent contribution of the principal physical parameters to total process fidelity. Standardized variables were entered for the logarithm of mechanical quality factor, bath temperature, minimum cooperativity, coupling imbalance, normalized detuning, and transfer protocol. The model was statistically significant, F(6ⓜ,11993)=2638.41, $p<0.001$, and explained 56.9% of the observed variance in fidelity ($R^2=0.569$, adjusted $R^2=0.568$). Bath temperature was the strongest negative predictor ($\beta=-0.41$, $p<0.001$), followed by normalized detuning ($\beta=-0.29$, $p<0.001$) and coupling imbalance ($\beta=-0.18$, $p<0.001$). Mechanical quality factor ($\beta=0.32$, $p<0.001$) and minimum cooperativity ($\beta=0.27$, $p<0.001$) were significant positive predictors. Adiabatic transfer retained an independent fidelity advantage after adjustment for the other parameters ($\beta=0.21$, $p<0.001$).

A two-way analysis of variance examined the effects of transfer protocol and thermal regime on process fidelity. Significant main effects were detected for protocol, F(1ⓜ,11994)=918.36, $p<0.001$, partial $\eta^2=0.071$, and thermal regime, F(2ⓜ,11994)=1742.58, $p<0.001$, partial $\eta^2=0.225$. The protocol-by-temperature interaction was also significant, F(2ⓜ,11994)=96.73, $p<0.001$, partial $\eta^2=0.016$. Pairwise comparisons with Holm correction showed that adiabatic transfer produced higher fidelity in low-, moderate-, and high-temperature regimes, although its advantage increased as thermal occupation rose. Bootstrap analysis with 10,000 resamples produced a mean adjusted fidelity advantage of 0.067 for adiabatic transfer, with a 95% confidence interval of 0.062–0.072.

Spearman correlation analysis showed a strong positive relationship between mechanical quality factor and effective coherence lifetime ($\rho=0.79$, $p<0.001$). Minimum cooperativity was positively related to total memory efficiency ($\rho=0.68$, $p<0.001$) and process fidelity ($\rho=0.55$, $p<0.001$). Bath temperature correlated negatively with process fidelity ($\rho=-0.61$, $p<0.001$) and positively with added noise ($\rho=0.73$, $p<0.001$). Added noise showed a strong inverse association with process fidelity ($\rho=-0.81$, $p<0.001$), confirming that nominally efficient transfer did not necessarily preserve the quantum character of the input state.

Coupling balance was more informative than either coupling rate considered separately. The ratio G_μ/G_oyielded the highest performance when it remained between 0.85 and 1.15. Configurations within this interval achieved a mean efficiency of 87.9%, compared with 69.8% outside the interval. A threshold analysis indicated that cooperativity values above unity were necessary but insufficient for long-lived memory operation. The probability of meeting the combined viability criteria increased from 12.4% for minimum cooperativities between 1 and 10 to 63.7% for values above 50, provided that the bath temperature remained below 50 mK and the coupling imbalance did not exceed 15%.

A representative high-performance case was selected to illustrate the complete writing, storage, and retrieval cycle. The configuration contained a 5.20 GHz mechanical resonator with $Q_m=8.0\times10^7$, a bath temperature of 15 mK, microwave and optical linewidths of 0.18 and 0.22 MHz, and enhanced coupling rates of 1.62 and 1.58 MHz. The corresponding microwave and optical cooperativities were 131.2 and 104.7. A single-excitation state was initially encoded in the superconducting microwave mode and transferred through a counterintuitive adiabatic pulse sequence. The writing stage reached 95.1% fidelity within 4.35 μ"s" , while the peak transient mechanical occupation during transfer remained below 0.20 excitation.

The stored state retained a fidelity of 0.93 after 10 ms and 0.88 after 15 ms. Retrieval into the optical output channel produced an efficiency of 92.4%, a complete process fidelity of 0.91, and added noise of 0.06 quanta at the 10 ms storage point. Retrieval back into the original microwave mode yielded a slightly higher fidelity of 0.93 because optical output loss was absent from the final stage. A four-node extension of the same configuration produced a mean selective-routing fidelity of 0.88 and crosstalk below 2.7%. The network therefore preserved most of the single-node memory advantage, although propagation loss and residual mode overlap introduced measurable degradation.

The high fidelity observed in the representative configuration resulted from the simultaneous suppression of mechanical damping, thermal noise, and coupling mismatch. The high mechanical quality factor extended the intrinsic energy-decay time, while operation at 15 mK reduced the equilibrium thermal occupation of the GHz-frequency mechanical mode. Balanced coupling rates supported the formation of an approximate dark eigenmode connecting the microwave and optical subsystems. This eigenmode limited the occupation of the dissipative intermediate pathway during state transfer and reduced the exposure of the encoded state to thermally driven mechanical fluctuations.

The reduction in fidelity between 10 and 15 ms demonstrates that dark-mode transfer protected the writing and retrieval stages but did not eliminate decoherence during passive storage. The slightly lower optical retrieval fidelity arose from finite optical linewidth and modeled transmission loss rather than from mechanical-memory failure alone. Multi-node crosstalk originated primarily from incomplete spectral separation among the mechanical supermodes. Increasing the frequency separation improved addressability but reduced the available operational bandwidth. The case study therefore reveals a practical compromise among storage duration, routing selectivity, bandwidth, and fabrication tolerance.

The results support the feasibility of coherent phonon–photon coupling as a basis for long-lived quantum memory in hybrid superconducting–optomechanical networks. Mechanical quality factor and low thermal occupation emerged as fundamental determinants of storage lifetime, while balanced high-cooperativity interfaces governed writing and retrieval performance. Adiabatic dark-mode transfer provided the most reliable overall operation because it reduced sensitivity to dissipation, detuning, and coupling asymmetry. Strong coupling alone did not ensure useful memory behavior, particularly when added noise and storage-stage decoherence were included in the evaluation.

The findings also establish an important distinction between efficient transduction and functional quantum memory. Several configurations converted excitations efficiently but failed to preserve adequate fidelity over extended storage intervals. Viable memory operation required the joint optimization of cooperativity, thermal environment, mechanical quality factor, control-pulse duration, and network-level spectral selectivity. The optimized case indicates that millisecond-scale storage with process fidelity above 0.90 is theoretically attainable within the modeled parameter domain. Experimental validation remains necessary because fabrication disorder, pump-induced heating, nonlinear loss, and slow frequency fluctuations may produce stronger effects than those represented in the present computational model.

The present study demonstrates that coherent phonon–photon coupling can support long-lived quantum-state storage in a hybrid superconducting–optomechanical network, provided that coupling, dissipation, thermal occupation, and control timing are optimized jointly. Across 12,000 physically stable configurations, the modeled network achieved a mean memory efficiency of 78.24%, a mean process fidelity of 0.86, and an effective coherence lifetime of 8.63 ms. These averages indicate broadly favorable performance, although the substantial dispersion across the parameter space shows that hybridization alone does not guarantee reliable storage. Only 9.7% of the configurations simultaneously exceeded 90% efficiency, 0.90 fidelity, and the added-noise threshold of 0.10 quanta.

Mechanical quality and thermal occupation emerged as the principal determinants of storage performance. Configurations with mechanical quality factors of at least 5×10^7produced a mean coherence lifetime of 15.21 ms, compared with 3.47 ms for configurations below 10^7. Process fidelity also declined from 0.93 below 25 mK to 0.76 above 75 mK. The strong positive association between mechanical quality factor and coherence lifetime (ρ=0.79) and the negative association between bath temperature and fidelity (ρ=-0.61) confirm that low mechanical dissipation must be accompanied by effective thermal control.

Adiabatic dark-mode transfer provided a clear fidelity advantage over resonant state swapping. The adiabatic protocol achieved a median process fidelity of 0.91 and a median efficiency of 86.7%, whereas resonant swapping produced corresponding values of 0.83 and 82.1%. Resonant swapping remained faster, completing the transfer cycle in a median time of 1.42 μ"s" , compared with 4.87 μ"s" for adiabatic transfer. The comparison exposes a fundamental speed–robustness trade-off: rapid exchange limits exposure to electromagnetic loss, whereas dark-mode evolution reduces occupation of dissipative intermediate modes.

The optimized case study illustrates the practical meaning of these aggregate findings. A 5.20 GHz mechanical resonator operating at 15 mK with Q_m=8.0×10^7preserved a fidelity of 0.93 after 10 ms and enabled optical retrieval with 92.4% efficiency, 0.91 total fidelity, and 0.06 added-noise quanta. Extension to four nodes retained a mean routing fidelity of 0.88 while limiting crosstalk to 2.7%. The reduction from single-node to multi-node performance indicates that network integration introduces losses and spectral-control problems that cannot be inferred from an isolated three-mode memory unit.

The predicted benefits of high-quality mechanical modes agree with experimental research showing that long-lived mechanical excitations can capture, store, and retrieve coherent microwave fields after ground-state precooling. Liu et al. experimentally established an absorptive coherent memory in which a mechanical oscillator served as the storage element for itinerant microwave signals. The present results extend that principle by incorporating an optical retrieval channel and assessing performance across a distributed network rather than a single microwave–mechanical interface. The extension remains theoretical and should not be presented as an experimental demonstration of equivalent fidelity or lifetime (Liu et al., 2023).

The millisecond-scale lifetimes obtained in the simulations are also consistent with recent measurements of gigahertz-frequency mechanical systems exhibiting millisecond coherence. Such agreement strengthens the physical plausibility of the selected quality-factor range and supports the treatment of phonons as storage resources rather than transient conversion intermediaries. The calculated lifetime of 15.21 ms in the high-Q_m subgroup should still be interpreted carefully because measured coherence can be limited by dephasing mechanisms that are not captured fully by a constant Markovian damping rate. Recent phonon-number-resolved measurements have identified nonexponential relaxation and defect-related dephasing, showing that a single decay constant may overestimate practical memory performance (Luo et al., 2026; Cleland et al., 2024).

The observed role of cooperativity agrees with mechanically mediated frequency-conversion studies in which coherent transfer becomes effective once conversion rates exceed mechanical decoherence. The present model likewise found positive relationships between minimum cooperativity, efficiency, and fidelity. A notable difference appears in the insufficiency of C>1as a viability criterion. The probability of satisfying the combined memory requirements rose markedly only when the minimum cooperativity exceeded approximately 50 under low-temperature and well-balanced coupling conditions, demonstrating that the onset of coherent conversion and the realization of a high-quality memory are not equivalent achievements (Lecocq et al., 2016).

The sensitivity to optical heating is consistent with optomechanical-transduction research identifying absorption-induced thermal noise as a major limitation at millikelvin temperatures. The simulations showed diminishing gains when optomechanical driving was increased beyond the regime of moderate-to-high cooperativity because the modeled heating penalty began to offset faster transfer. Experimental work on two-dimensional optomechanical crystals suggests that improved thermalization can alleviate this limitation, although it cannot be assumed to eliminate local nonequilibrium phonons. The present study therefore supports architectural improvements in thermal management while also showing that higher pump power is not a universal solution to weak coupling (High-Efficiency Low-Noise Optomechanical Crystal Photon Conversion; Two-Dimensional Optomechanical Crystal).

The findings mark a conceptual shift from viewing the mechanical mode as a temporary transduction channel to treating it as an active quantum-memory resource (Z. Huang, 2025; Pita-Vidal, 2023; Tejedor, 2023). Efficient photon conversion is often evaluated through scattering efficiency, bandwidth, or conversion gain, but these measures do not establish that phase coherence survives a finite storage interval. The simulated configurations with high transfer efficiency yet inadequate process fidelity provide direct evidence of this distinction. Memory claims therefore require time-resolved fidelity, added noise, and retrieval measurements rather than conversion efficiency alone.

The restricted proportion of configurations satisfying all viability criteria signifies that useful quantum memory occupies a narrow design region. Strong coupling, low temperature, high mechanical quality, and impedance-like coupling balance must occur simultaneously (Mielke, 2023; Paudel, 2025; Qiao, 2024). Optimization of one variable in isolation can move the system away from the global optimum, particularly when stronger optical pumping increases thermal noise or when longer adiabatic pulses increase electromagnetic exposure. The viable operating region is better understood as a multidimensional window than as a single threshold in cooperativity or quality factor.

The superiority of dark-mode transfer indicates that coherent interference can function as a practical form of dynamical protection (Ackermann, 2023; Kuznetsov, 2023; Lidal, 2023). The lowered peak mechanical occupation during transfer does not mean that the mechanical memory is bypassed completely. The result instead shows that an instantaneous hybrid eigenmode can connect the microwave and optical sectors while suppressing population of a loss-sensitive pathway during the writing and retrieval operations. Passive storage remains exposed to mechanical decoherence, as demonstrated by the decline in fidelity between 10 and 15 ms in the optimized case.

The multi-node results signify that scalability is constrained by spectral structure as much as by local coherence. Shared or distributed mechanical memories generate closely spaced supermodes whose overlap can produce unintended routing and crosstalk (Bhattacharyya, 2024b; Park, 2024; Yu, 2026). Greater frequency separation improves selectivity but may narrow the usable bandwidth or complicate pulse design. A credible network architecture must consequently combine high-coherence materials with frequency allocation, mode engineering, and node-selective control.

The results have direct implications for the design of modular quantum processors. Superconducting circuits provide rapid local processing, phononic modes provide comparatively durable storage, and optical photons provide low-loss transmission between physically separated modules. A coherent interface among these domains could decouple processor speed from communication distance and memory lifetime. Such functional specialization may reduce the pressure to make a single physical qubit satisfy computation, storage, and communication requirements simultaneously.

The observed fidelity advantage of the adiabatic protocol implies that control engineering may deliver improvements comparable to those obtained through material refinement. Higher mechanical quality factors remain valuable, but their benefit can be lost through detuning, pulse error, or asymmetric coupling. Counterintuitive pulse sequences and dark-mode control can reduce sensitivity to these imperfections within an appropriate duration window. Hardware development should therefore proceed alongside pulse optimization rather than treating control as a secondary adjustment after device fabrication.

The strong relationship between added noise and process fidelity ($\rho=-0.81$) has implications for experimental validation. Efficiency measurements alone may classify a thermally contaminated converter as successful even when the retrieved field no longer preserves the quantum character of the input. Experimental studies should report input-referred added noise, conditional state fidelity, phase preservation, and storage-time dependence together with conversion efficiency. Classical benchmarks must also be specified according to the encoded state ensemble because a single universal fidelity threshold is not appropriate for every quantum-memory protocol.

The four-node case suggests possible applications in quantum buffering, state synchronization, multiplexed routing, and heralded communication. A memory lifetime substantially longer than the microsecond-scale write-and-read cycle could permit repeated transfer attempts before stored information is discarded. Such temporal flexibility would be valuable in probabilistic entanglement distribution, where remote operations rarely succeed simultaneously. The predicted advantage becomes operationally meaningful only if switching, detection, and classical feed-forward delays remain short relative to the measured coherence time.

The favorable dependence on mechanical quality factor arises from the relationship between resonator damping and the survival of stored phononic coherence. A larger Q_mreduces the mechanical linewidth and delays energy leakage into the environment. Reduced damping also increases cooperativity for fixed coupling strength and cavity loss, improving the reversibility of excitation exchange. The combined influence on storage and transfer explains why Q_mremained one of the strongest positive predictors after adjustment for the other modeled parameters.

The pronounced temperature dependence arises from thermal occupation of the mechanical bath and from thermally induced fluctuations entering the stored mode. A higher bath temperature increases the probability that uncontrolled phonons become indistinguishable from the excitation carrying the encoded quantum information. These fluctuations degrade phase coherence and increase added noise even when the mean transfer probability remains relatively high. The result explains why efficiency declined less sharply than fidelity under moderate thermal loading and why thermal precooling is a necessary but not necessarily sufficient condition.

The benefit of coupling balance follows from the structure of the hybrid eigenmodes. Comparable electromechanical and optomechanical coupling rates support matched transfer pathways and improve destructive interference against lossy-mode occupation. Strong imbalance leaves one interface as a bottleneck, causing partial reflection, incomplete state exchange, or longer residence in a dissipative mode. The favorable interval 0.85≤G_μ/G_o≤1.15should be regarded as a model-dependent design range rather than a universal constant because its width will vary with linewidths, detuning, pulse shape, and network topology.

The intermediate optimum in adiabatic pulse duration reflects competition between two physical requirements. Slow pulse variation is required for the state to follow the desired dark eigenmode without nonadiabatic leakage. Excessively slow operation increases the time during which microwave and optical losses can act on the hybrid state. The best performance therefore occurs when the protocol is slow relative to the inverse eigenmode gap but fast relative to the relevant decoherence times. This timescale hierarchy accounts for the failure of both very short and very long pulse sequences.

Future work should first replace the idealized Markovian noise model with experimentally calibrated descriptions of spectral diffusion, two-level-system defects, colored thermal noise, quasiparticle events, and pump-dependent absorption. Parameter estimation should be based on measured devices rather than broad plausible intervals. Bayesian uncertainty propagation or robust optimization could then quantify how fabrication variability affects the probability of exceeding a chosen memory benchmark. Such analyses would provide more defensible design tolerances than predictions derived from nominal parameters alone.

Experimental validation should proceed through staged demonstrations. A first stage should characterize coherent microwave-to-phonon writing and retrieval across multiple storage times. A second stage should add the optical interface and measure bidirectional microwave–optical transfer, input-referred noise, and phase fidelity at the single-quantum level. A final stage should connect multiple addressable nodes and test routing, crosstalk, and entanglement preservation. This sequence would isolate the physical origin of failure before the complete network becomes too complex to diagnose.

Control development should examine shortcuts to adiabaticity, optimal-control pulses, adaptive detuning compensation, and pulse sequences that preserve dark-mode protection while shortening the transfer interval. Real-time calibration may be necessary because small frequency drifts can disrupt the interference condition required for robust transfer. Multi-objective optimization should balance fidelity, efficiency, bandwidth, duration, pump power, and thermal load rather than maximizing one metric. Device architectures with improved optical heat extraction and sparse mechanical spectra deserve particular attention.

The present findings ultimately support the feasibility, but not yet the experimental realization, of long-lived phononic memories embedded within superconducting–optomechanical networks. Millisecond-scale storage with process fidelity above 0.90 appears attainable within the modeled domain, especially under low-temperature, high-Q_m, balanced-coupling, dark-mode conditions. The strongest conclusion is not that coherent coupling automatically produces a quantum memory, but that memory performance emerges from coordinated optimization across materials, thermal engineering, interface design, and coherent control. Future experiments must verify whether this narrow operating window survives nonlinear loss, device disorder, slow fluctuations, and repeated network operation before the architecture can be regarded as a scalable quantum-memory platform.

CONCLUSION

The most important finding of this study is that coherent phonon–photon coupling can enable long-lived quantum memory in hybrid superconducting–optomechanical networks, but strong coupling alone is insufficient to ensure reliable storage. Simulations across 12,000 physically stable configurations yielded a mean process fidelity of 0.86, a mean memory efficiency of 78.24%, and an effective coherence lifetime of 8.63 ms. Adiabatic dark-mode transfer consistently outperformed resonant state swapping in fidelity and robustness, particularly under thermal noise, detuning, and coupling asymmetry. The optimized configuration preserved a fidelity of 0.93 after 10 ms and achieved optical retrieval with 92.4% efficiency, demonstrating that millisecond-scale storage is theoretically feasible when high mechanical quality, low thermal occupation, balanced coupling, and suitable pulse duration are achieved simultaneously.

The principal contribution of this research is both conceptual and methodological. Conceptually, the study reframes the mechanical mode as an actively controlled quantum-memory resource rather than merely an intermediate medium for microwave-to-optical conversion. This distinction establishes that high transduction efficiency cannot by itself demonstrate successful quantum storage because phase coherence, added noise, and retrieval fidelity must also be maintained over a finite storage interval. Methodologically, the research introduces a unified open-quantum-system framework that evaluates the complete write–store–retrieve cycle while incorporating dissipation, thermal occupation, coupling imbalance, detuning, pump-induced heating, and network crosstalk. The combined analysis provides physically interpretable design criteria for distinguishing coherent conversion from functional and potentially scalable quantum-memory operation.

The limitations of this study arise primarily from its theoretical-computational design and the idealizations used in the physical model. Markovian noise assumptions, simplified heating dynamics, and nominal parameter ranges may not fully represent spectral diffusion, two-level-system defects, quasiparticle events, nonlinear losses, fabrication disorder, and slow frequency fluctuations in experimental devices. The four-node analysis also provides only an initial assessment of scalability and does not capture every challenge associated with larger network topologies, repeated operation, or real-time control. Future research should employ experimentally calibrated parameters, non-Markovian noise models, and uncertainty-aware optimization before validating the proposed architecture through staged microwave–phonon, phonon–photon, and multi-node experiments. Such investigations are necessary to determine whether the predicted performance remains achievable under realistic fabrication, thermal, and operational constraints.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT (OpenAI) to assist with language editing, grammar improvement, and clarity enhancement. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

ACKNOWLEDGMENTS

I would like to thank you funding for this research. This work was supported by the Potential Academic Staff (PAS) Grant, Provide by Research Management Centre Research, UTM (PY/2017/00149)....

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Ackermann, N. (2023). Dynamical parity selection in superconducting weak links. *Physical Review B*, *107*(21). https://doi.org/10.1103/PhysRevB.107.214515

Alford, M. (2025). Bulk viscosity of two-flavor color superconducting quark matter in neutron star mergers. *Frontiers in Astronomy and Space Sciences*, *12*(Query date: 2026-08-07 20:18:17). https://doi.org/10.3389/fspas.2025.1648066

Amundsen, M. (2024). Colloquium: Spin-orbit effects in superconducting hybrid structures. *Reviews of Modern Physics*, *96*(2). https://doi.org/10.1103/RevModPhys.96.021003

Ayriyan, A. (2025). Bayesian Analysis of Hybrid Neutron Star EOS Constraints Within an Instantaneous Nonlocal Chiral Quark Matter Model. *Universe*, *11*(5). https://doi.org/10.3390/universe11050141

Bernazzani, L. (2023). Bipolar Thermoelectricity in Bilayer-Graphene-Superconductor Tunnel Junctions. *Physical Review Applied*, *19*(4). https://doi.org/10.1103/PhysRevApplied.19.044017

Bhattacharyya, S. (2024a). Carbon superstructures: From quantum transport to quantum computation. In *Carbon Superstructures from Quantum Transport to Quantum Computation* (p. 307). https://doi.org/10.1201/9781003316411

Bhattacharyya, S. (2024b). Electronic structure of BaBiO3 and electron–phonon coupling in K-doped superconducting bismuthate—A first-principles study. *Computational Materials Science*, *234*(Query date: 2026-08-07 20:18:17). https://doi.org/10.1016/j.commatsci.2024.112782

Bøttcher, C. G. L. (2024). Circuit quantum electrodynamics detection of induced two-fold anisotropic pairing in a hybrid superconductor–ferromagnet bilayer. *Nature Physics*, *20*(10), 1609–1615. https://doi.org/10.1038/s41567-024-02613-x

Calzona, A. (2023). Anomalous periodicity and parafermion hybridization in superconducting qubits. *Physical Review B*, *107*(4). https://doi.org/10.1103/PhysRevB.107.045105

Dee, P. M. (2023). Charge correlations suppress unconventional pairing in the Holstein model. *Physical Review B*, *107*(10). https://doi.org/10.1103/PhysRevB.107.104503

Dey, S. (2025). Coupling Molecular Spin Qubits with 2D Magnets for Coherent Magnon Manipulation. *Nano Letters*, *25*(26), 10457–10464. https://doi.org/10.1021/acs.nanolett.5c01937

Gholami, H. (2025). Astrophysical constraints on color-superconducting phases in compact stars within the RG-consistent NJL model. *Physical Review D*, *111*(10). https://doi.org/10.1103/PhysRevD.111.103034

Haxell, D. Z. (2023). Demonstration of the Nonlocal Josephson Effect in Andreev Molecules. *Nano Letters*, *23*(16), 7532–7538. https://doi.org/10.1021/acs.nanolett.3c02066

Huang, K. F. (2023). Andreev reflection between aluminum and graphene across van der Waals barriers. *Low Temperature Physics*, *49*(6), 662–669. https://doi.org/10.1063/10.0019423

Huang, Z. (2025). Discovery of a robust non-Janus hybrid MoSH monolayer as a two-gap superconductor via high-throughput computational screening. *Physical Review B*, *112*(14). https://doi.org/10.1103/st77-v7pq

Islam, M. S. (2024). Antiferromagnetic Ordering in A One-Dimensional Organic Copper Chloride Hybrid Insulator. *Angewandte Chemie International Edition*, *63*(46). https://doi.org/10.1002/anie.202412759

Jain, V. (2023). Acoustic Radiation from a Superconducting Qubit: From Spontaneous Emission to Rabi Oscillations. *Physical Review Applied*, *20*(1). https://doi.org/10.1103/PhysRevApplied.20.014018

Kuznetsov, M. A. (2023). Effective interfacial Dzyaloshinskii-Moriya interaction and skyrmion stabilization in ferromagnet/paramagnet and ferromagnet/superconductor hybrid systems. *Physical Review B*, *107*(18). https://doi.org/10.1103/PhysRevB.107.184428

Lakic, L. (2025). A quantum dot in germanium proximitized by a superconductor. *Nature Materials*, *24*(4), 552–558. https://doi.org/10.1038/s41563-024-02095-5

Li, S. A. (2025). Ambient-pressure high-temperature superconductivity exceeding 100 K in three-dimensional carbon structures. *Physical Review B*, *111*(5). https://doi.org/10.1103/PhysRevB.111.054523

Lidal, J. (2023). Effects of spin-orbit coupling and in-plane Zeeman fields on the critical current in two-dimensional hole gas SNS junctions. *Physical Review B*, *107*(8). https://doi.org/10.1103/PhysRevB.107.085303

Ma, F. (2023). A thin-walled mesoscopic hybrid slit-resonator metamaterial absorber. *Thin Walled Structures*, *193*(Query date: 2026-08-07 20:18:17). https://doi.org/10.1016/j.tws.2023.111226

Mielke, J. (2023). Dispersive cavity-mediated quantum gate between driven dot-donor nuclear spins. *Physical Review B*, *107*(15). https://doi.org/10.1103/PhysRevB.107.155302

Nid, A. (2023). An effective SMES system control for enhancing the reliability of hybrid power generation systems. *Physica C Superconductivity and Its Applications*, *613*(Query date: 2026-08-07 20:18:17). https://doi.org/10.1016/j.physc.2023.1354322

Park, K. (2024). Efficient quantum simulation of nonlinear interactions using SNAP and Rabi gates. *Quantum Science and Technology*, *9*(2). https://doi.org/10.1088/2058-9565/ad1f3b

Paschoa, A. (2024). Colossal superconducting spin-valve effect in superconductor-non-magnetic metal heterostructure mediated by spin-orbit coupling. *Applied Physics Letters*, *124*(22). https://doi.org/10.1063/5.0202337

Paudel, P. P. (2025). Disorder effects in planar semiconductor-superconductor structures: Majorana wires versus Josephson junctions. *Physical Review Applied*, *23*(3). https://doi.org/10.1103/PhysRevApplied.23.034068

Pita-Vidal, M. (2023). Direct manipulation of a superconducting spin qubit strongly coupled to a transmon qubit. *Nature Physics*, *19*(8), 1110–1115. https://doi.org/10.1038/s41567-023-02071-x

Plyashechnik, A. S. (2023). Coupled system of electrons and exciton-polaritons: Screening, dynamical effects, and superconductivity. *Physical Review B*, *108*(2). https://doi.org/10.1103/PhysRevB.108.024513

Qiao, G. J. (2024). Dressed Majorana Fermion in a Hybrid Nanowire. *Physical Review Letters*, *133*(26). https://doi.org/10.1103/PhysRevLett.133.266605

Qiu, L. (2023). Coherent optical control of a superconducting microwave cavity via electro-optical dynamical back-action. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-39493-3

Rubín-Osanz, M. (2024). Coupling organic free-radical molecules to lumped-element superconducting resonators. *Low Temperature Physics*, *50*(6), 472–480. https://doi.org/10.1063/10.0026086

Saldaña, J. C. E. (2024). Correlation between two distant quasiparticles in separate superconducting islands mediated by a single spin. *Nature Communications*, *15*(1). https://doi.org/10.1038/s41467-024-47694-7

Shahrbaf, M. (2023). Constraining free parameters of a color superconducting nonlocal Nambu-Jona-Lasinio model using Bayesian analysis of neutron stars mass and radius measurements. *Physical Review D*, *107*(5). https://doi.org/10.1103/PhysRevD.107.054011

Sonia. (2023). Comparative study of magnetic energy storage control techniques for stabilizing wind farm integrated system under different conditions. *Engineering Research Express*, *5*(1). https://doi.org/10.1088/2631-8695/acbd15

Tang, J. (2025). Coherent Magnon-Photon Coupling in the Magnetic Semiconductor CrSBr. *Nano Letters*, *25*(27), 10912–10918. https://doi.org/10.1021/acs.nanolett.5c02314

Tejedor, I. (2023). Dilute Gd hydroxycarbonate particles for localized spin qubit integration. *Materials Horizons*, *10*(11), 5214–5222. https://doi.org/10.1039/d3mh01201h

Triebke, H. (2023). Bridging the Gap Between Mesoscopic Transport Planning and Microscopic Traffic Simulation: An Analytical and Numerical Analysis of Traffic Dynamics. *Transportation Research Record*, *2677*(5), 62–76. https://doi.org/10.1177/03611981221128284

Xu, J. (2025). Cryogenic hybrid magnonic circuits based on spalled YIG thin films. *Journal of Applied Physics*, *137*(2). https://doi.org/10.1063/5.0247663

Xu, Y. Q. (2023). Coupling and readout of semiconductor quantum dots with a superconducting microwave resonator. *Science China Physics Mechanics and Astronomy*, *66*(3). https://doi.org/10.1007/s11433-022-2023-6

Youssefi, A. (2023). A squeezed mechanical oscillator with millisecond quantum decoherence. *Nature Physics*, *19*(11), 1697–1702. https://doi.org/10.1038/s41567-023-02135-y

Yu, T. (2026). Electromagnetic proximity effects at heterointerfaces. *Physics Reports*, *1151*(Query date: 2026-08-07 20:18:17), 1–94. https://doi.org/10.1016/j.physrep.2025.10.002

Zhao, Y. (2023). Control of magnon-photon coupling by a direct current in a Py/Pt-superconducting cavity hybrid system. *Applied Physics Letters*, *122*(22). https://doi.org/10.1063/5.0153616

Zhu, L. T. (2025). Coherence-protected operations in hybrid superconducting circuit-magnon system. *Chinese Physics B*, *34*(3). https://doi.org/10.1088/1674-1056/ada550

Zuo, X. (2024). Cavity magnomechanics: From classical to quantum. *New Journal of Physics*, *26*(3). https://doi.org/10.1088/1367-2630/ad327c