

Spatially Resolved Optical Responses of a Superconducting Nanowire Microwave Resonator

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Understanding the optical response of a superconducting microwave resonator is crucial for applications ranging from single-photon detection to quantum transduction between the microwave and optical domains. This topic is gaining significant attention for scaling up quantum computers. However, interactions between the pump light and superconducting resonators often induce unintended resonance frequency shifts and linewidth broadening. In this study, we measure the local optical response of a NbTiN nanowire resonator using a laser-scanning microwave spectroscopy system integrated with a dilution refrigerator. The optical response of the resonator correlates with the resonance modes and position, which we attribute to interactions between two-level systems (TLSs) and laser-induced phonons. These findings establish the TLS-phonon interactions as the dominant mechanism underlying laser-induced resonance variations, providing critical insights for the design and optimization of quantum transducers and superconducting single-photon detectors.

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Superconducting microwave resonators are essential building blocks for modern quantum technologies. Their functions include the measurement of superconducting qubits [1,2], storage of bosonic microwave qubits [3–6], realization of strong coupling to artificial atoms in solid-state systems [7–9], single-photon detection [10,11], and quantum interfacing between microwave and optical photons [12–16]. Among these applications, the interaction between light and superconducting circuits has gained significant attention for scaling up quantum computers via microwave-optical links. However, optical photons can also induce degradation in superconducting devices. Microwave-optical quantum transducers [13,14,17–25] suffer from pump-light leakage during quantum frequency conversion [20,26,27]. Precise understanding of the optical response is crucial for the design and optimization of microwave resonators coexisting with optical ports

including optomechanical systems [13,14,20,27], electro-optical systems [21,26], and optically addressable solid-state defects or atoms [22,23,28] for quantum transduction. Furthermore, high-energy particle strikes (cosmic rays, γ rays) induce long-range correlated errors in superconducting processors because of athermal phonons being propagated [29–35]. Investigating optical responses can reveal the interplay among high-energy particles, superconducting circuits, two-level systems (TLSs), and phonons.

This study investigates the effects of local optical illumination on a superconducting microwave resonator, with a particular focus on illumination-position dependence. This approach applies a custom-built laser-scanning microwave spectroscopy system integrated with a dilution refrigerator. We employ a high-impedance resonator, which is of growing interest in circuit quantum electrodynamics experiments [14,18,20,36,37] including quantum transduction, owing to its high zero-point fluctuation voltages. Furthermore, its high sensitivity to optical power enables experiments at lower optical powers compared to a typical 50- Ω resonator.

We reveal that degradation of the quality factor, Q , and shifts in resonance frequency depend on two factors: the resonator mode and the illumination position. In particular, we find that the local electric field strength interacting with TLSs contributes significantly to the optical response. We estimate that optically induced nonequilibrium phonons

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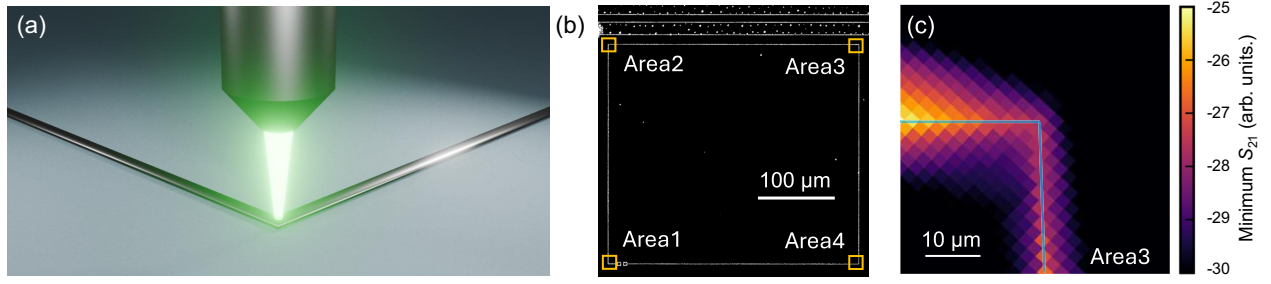


FIG. 1. Spatially resolved optical illumination experiments. (a) Schematic of the optical illumination experiments. (b) Photograph of the resonator. Areas 1–4 correspond to the four corner of the resonator. (c) Two-dimensional (2D) optical response map of the superconducting nanowire. The 2D optical response map of the resonator is constructed by sweeping the laser illumination position using the galvanometer mirror and extracting the minimum S_{21} amplitude at each coordinate. The blue line probably corresponds to the nanowire.

cause changes in TLS populations, resulting in unintended shifts in the resonance spectrum. These findings provide critical insight for the design and operation of quantum transducers and superconducting single-photon detectors, the interaction between TLS and phonons, and the impacts of high-energy particle irradiation on superconducting circuits [38], which are catastrophic to quantum processors [29–35].

Optical illumination experiments [Fig. 1(a)] are performed using a custom-built laser-scanning optical system integrated with a dilution refrigerator at a base temperature of ~ 15 mK. A 515-nm laser beam, focused on the sample surface using an objective lens, is scanned via a two-axis galvanometer mirror. The modulation of the transmitted microwave signal by the laser irradiation is measured using a vector network analyzer. Thus, the structure of the superconducting half-wavelength resonator—fabricated from a 10-nm-thick, 150-nm-wide NbTiN nanowire—is imaged [Fig. 1(b)]. The focused laser locally alters the resonance spectrum, allowing visualization of the nanowire, as shown in Fig. 1(c).

To investigate the dependence on the resonance mode and illumination position, we measure the optical responses of $1/Q$ and $\Delta f_r/f_r$ across 16 combinations of four resonance modes (first, second, third, and fifth) and four illumination positions (corners of Areas 1–4) [Figs. 2(a) and 2(b)]. Here, we exclude the fourth mode due to its shallow resonance dip (see Supplemental Material [39] for details of the resonance spectrum). Additionally, the experiments are performed in the high-microwave power regime in which TLS losses saturate. As shown in Fig. 2(b), the changes in $1/Q$ and $\Delta f_r/f_r$ with optical power vary with the resonance mode and illumination position. $1/Q$ increases linearly with optical power for all modes and positions with different slopes, γ , where γ is defined by $1/Q = \gamma P_{\text{opt}} + 1/Q_0$, where P_{opt} is the laser power. The optical responses in $\Delta f_r/f_r$ differ both in magnitude and sign. Notably, three patterns are observed: low-frequency shift (redshift), high-frequency shift (blueshift), and no significant change. Phenomenologically, $\Delta f_r/f_r$ can be

fitted by $\Delta f_r/f_r = \delta_1 P_{\text{opt}} - \delta_2 [1 - \exp(-\delta_3 P_{\text{opt}})]$, where the first term represents the linear frequency shift and the second term represents the saturating lower frequency shift. We focus on the linear term below and discuss possible reasons for nonlinear behavior in Supplementary Material.

A dominant factor contributing to changes in $1/Q$ and $\Delta f_r/f_r$ is quasiparticles in the superconductor generated by the laser photons. The observed increase in $1/Q$ is possibly due to a rise in the quasiparticle density, n_{qp} ($\Delta(1/Q) \propto n_{\text{qp}} \propto P_{\text{opt}}$ [38]). The frequency shift caused by quasiparticle generation can be approximated as $\Delta f_r/f_r \simeq -\Delta n_{\text{qp}}/(2n_s)$ (see Supplementary Material). Thus, f_r shifts linearly toward lower frequencies with quasiparticle generation. However, the observed upward shifts in $\Delta f_r/f_r$ cannot be explained solely by the linear downward shift expected from quasiparticle generation, suggesting that additional mechanisms contribute.

Remarkably, the comparison between the blueshifts and redshifts indicates that the degree of blueshift correlates with a larger slope in $1/Q$ [Fig. 2(b)]. Additionally, the direction of frequency shifts correlates with the spatial distribution of current density in the nanowire for each resonance mode, as shown by the two-dimensional color-map inset in Fig. 2(b). When the illumination occurs in regions of low current density, a blueshift is observed, whereas a redshift occurs in regions with high current density. Although this trend does not hold for certain higher frequency modes, such as the third and fifth modes at Area 4, most cases are consistent with this assumption.

To analyze quantitatively the observed spatial correlation between the shifts in $[\Delta(1/Q), \Delta f_r/f_r]$ and the current density, the slopes of $\Delta(1/Q)$ (γ) and $\Delta f_r/f_r$ (δ_1) are plotted as a function of $|V_{\text{local}}|$ in Fig. 3. Here, the relative amplitude of the local potential, $|V_{\text{local}}|$, is defined as $|V_{\text{local}}| = |\cos(\sin^{-1} J(x, y))|$, where $J(x, y)$ is the normalized current-density distribution obtained from electromagnetic field simulations. Figure 3 shows that a higher local potential, which quantifies the local electric-field strength, results in larger slopes of $\Delta(1/Q)$ and $\Delta f_r/f_r$.

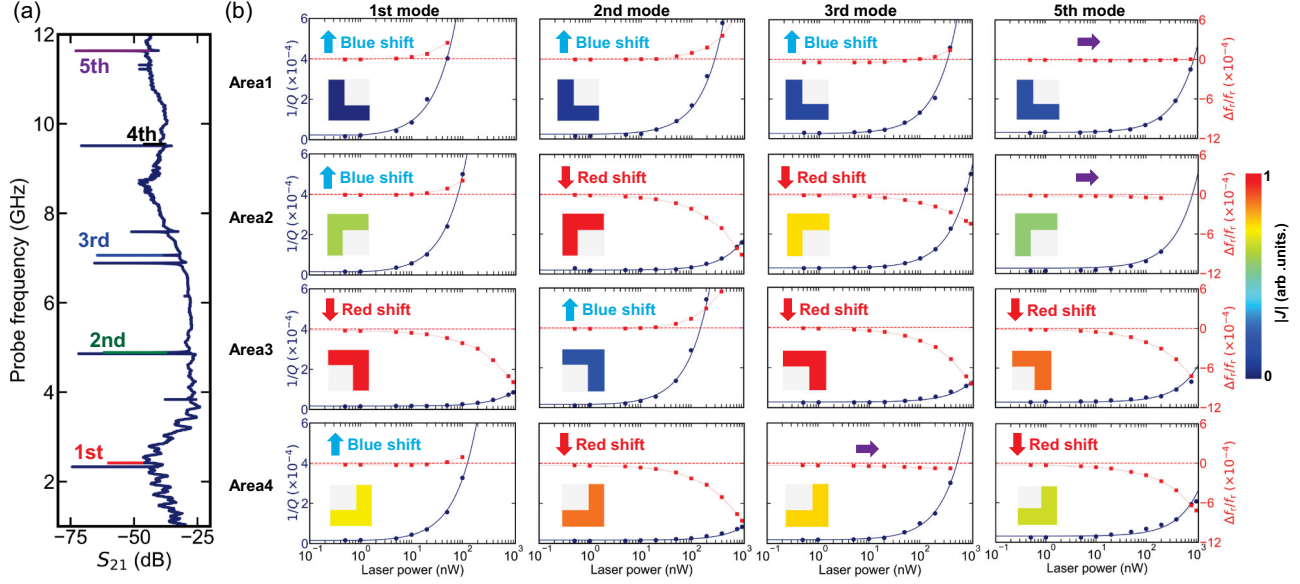


FIG. 2. Optical response of the resonator across four modes and four positions. (a) S_{21} spectrum of the resonator. The five resonance modes are labeled as the first through fifth modes. Additional resonance modes originate from other resonators located on the same chip. (b) Changes in $1/Q$ and $\Delta f_r/f_r$ under laser illumination are plotted for different modes and positions. Q denotes the internal quality factor. Fitting curves for $1/Q$ and $\Delta f_r/f_r$ are also shown. The horizontal red dashed line indicates the resonance frequency measured without optical illumination. Three response types based on frequency shifts are: low-frequency shift (redshift), high-frequency shift (blueshift), and subtle shift (purple). Simulated current-density distributions for each position and mode are shown in the inset. The color is normalized by the maximum current density for each mode. The corners are enlarged to highlight the current density in each mode. To prevent current crowding at the corners, the current density is averaged, excluding the corners.

Additionally, both γ and δ_1 exhibit quadratic dependence on V_{local} . This indicates that both $\Delta(1/Q)$ and $\Delta f_r/f_r$ are dominated by a mechanism other than quasiparticle generation, whose effects scale with the square of the resonator magnetic field (current density) [56].

To explain the observed behaviors not accounted for by quasiparticle generation, we consider a microscopic model based on TLSs, which originate from defects, impurities, and other mechanisms [57] at the metal and substrate surfaces. As TLS-induced loss depends on the local electric field [58], it is natural to consider the contribution of TLSs. Laser irradiation induces the following TLS-related processes [Fig. 4(a)]. First, 515-nm photons incident on the superconductor generate quasiparticles, leading to the degradation of Q and a decrease in $\Delta f_r/f_r$. Simultaneously, photons absorbed at the silicon surface generate nonequilibrium high-energy phonons via the recombination of excited electron-hole pairs. The recombination of quasiparticles in the superconductor also excites nonequilibrium phonons. Subsequently, these nonequilibrium phonons destroy Cooper pairs and alter the state of TLSs via phonon absorption and emission processes. The nonequilibrium population imbalance of TLSs induces complex frequency shifts via the transverse and longitudinal coupling between the resonator and TLSs.

We quantitatively model the aforementioned process to reproduce the slopes of $\Delta(1/Q)$ and $\Delta f_r/f_r$ as follows. We assume that (1) the nonequilibrium phonon diffusion

length scales as ξP_{opt} thus the number of TLSs in the phonon-propagated volume scales as $\hbar \omega_{\text{max}} \rho_{\text{TLS}} A \xi P_{\text{opt}}$, where ρ_{TLS} is the TLS density of states per volume ($\text{J}^{-1} \text{m}^{-3}$), A is the cross sectional area around the nanowire for consideration, and ω_{max} is the cutoff frequency for TLSs; (2) the state of TLSs inside $|x| < \xi P_{\text{opt}}/2$ can be described as nonequilibrium parameters $\tilde{S}(\equiv \langle \hat{\sigma}_z \rangle, -1 \leq \langle \hat{\sigma}_z \rangle \leq 0)$ and $d\tilde{S}(\equiv d\langle \hat{\sigma}_z \rangle/d\omega)$, where x is the distance from the laser spot; and (3) at high microwave driving powers, the contributions from TLSs originally resonant with the resonator without laser irradiation can be ignored. Then, considering the transverse ($\perp$) and longitudinal ($\parallel$) coupling between a TLS and a resonator and performing integration over related TLSs, the slopes of $\Delta(1/Q)$ and $(\Delta f_r/f_r)$ are expressed as

$$\frac{d\Delta(1/Q)}{dP_{\text{opt}}} = 2CK_{\parallel}\omega_r\tilde{g}^2, \quad (1)$$

$$\frac{d\Delta f_r/f_r}{dP_{\text{opt}}} = C(K_{\perp} - \tilde{\Gamma}_1 K_{\parallel})\tilde{g}^2, \quad (2)$$

where $C = \hbar \rho_{\text{TLS}} A \xi / \omega_r$, $K_{\parallel} = \tilde{\Gamma}_1 \omega_{\text{max}} d\tilde{S} / (\tilde{\Gamma}_1^2 + \omega_r^2)$ is derived considering the longitudinal coupling, $K_{\perp} = (1 + \tilde{S}) \ln(\Delta'_{\text{max}}/\Delta'_{\text{min}})$ is the coefficient for the transverse coupling, $\tilde{g}$ is the single-photon coupling between a resonator and TLSs averaged over related TLSs, $\tilde{\Gamma}_1$ is the averaged

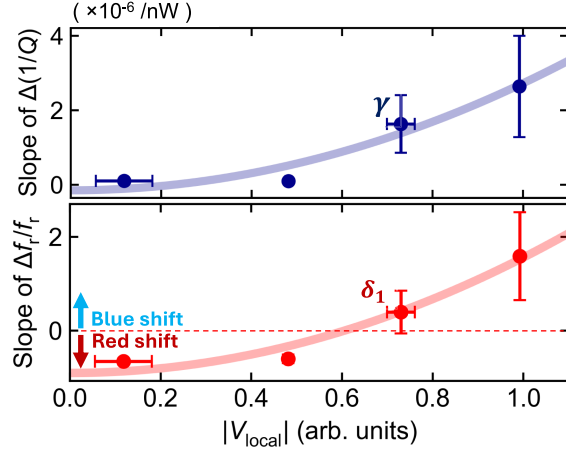


FIG. 3. Relationship between local electric potential and changes in the resonance properties. Top: slope of $\Delta(1/Q)$ ($=\gamma$), and Bottom: slope of $\Delta f_r/f_r$ ($=\delta_1$) as a function of the local potential, $|V_{\text{local}}|$, in each mode and area. The average is calculated over data points with similar $|V_{\text{local}}|$ values. The vertical and horizontal error bars correspond to the standard deviation of these data points. The fitting curves are the quadratic function ignoring the weight from the standard deviation.

relaxation time of TLSs, and $\Delta'_{\text{max}} = \omega_{\text{max}}$ ($\Delta'_{\text{min}} = \omega_r$) is the cutoff detuning used for the frequency-shift calculation (see Supplementary Material for details of the equations including derivations).

Figures 4(b) and 4(c) plot $d\Delta(1/Q)/dP_{\text{opt}}$ and $d(\Delta f_r/f_r)/dP_{\text{opt}}$ as functions of $\tilde{g}$ and ξ for fixed parameters, $\tilde{S} = 0$ (complete mixed state), $2\pi d\tilde{S} = 1/400 \text{ MHz}^{-1}$, $\rho_{\text{TLS}} = 1 \times 10^{45} \text{ J}^{-1} \text{ m}^{-3}$ [59–62], $A = tw$ (TLS layer thickness $t = 2 \text{ nm}$; effective width for consideration $w = 500 \text{ nm}$), $\omega_r/2\pi = 7 \text{ GHz}$, $\tilde{\Gamma}_1/2\pi = 16 \text{ MHz}$, $\Delta'_{\text{max}}/2\pi \simeq \omega_{\text{max}}/2\pi = 1000 \text{ GHz}$, and $\Delta'_{\text{min}} = \omega_r$. The model can reproduce the experimentally observed quadratic dependence of $d\Delta(1/Q)/dP_{\text{opt}}$ and $d(\Delta f_r/f_r)/dP_{\text{opt}}$ on $|V_{\text{local}}|$ because $\tilde{g} \propto |V_{\text{local}}|$. For the chosen parameters with $\tilde{g}/2\pi \sim 2\text{--}8 \text{ MHz}$ and $\xi = 20\text{--}250 \text{ m/W}$, we obtain values close to the observed slopes for both $\Delta(1/Q)$ and $\Delta f_r/f_r$, $\sim 1 \times 10^{-6}/\text{nW}$ and $\sim 0.5 \times 10^{-6}/\text{nW}$ for $f_r = 7.2 \text{ GHz}$ at the voltage antinode. Regarding parameter validity, a g of several MHz is observed in the high- L_k resonator [63]. A value of ξ of 20–250 m/W indicates that the effective phonon diffusion length is $\pm 10\text{--}125 \mu\text{m}$ at $1 \mu\text{W}$ laser power. The effective phonon diffusion length of $\mathcal{O}(10) \mu\text{m}/\mu\text{W}$ can explain that the spatial resolution of our system is limited to $\sim 10 \mu\text{m}$ (see Supplementary Material). If $\xi \sim \mathcal{O}(1000)$, the spatial dependent response would be averaged out since the length of one side of the square-shaped resonator is $\sim 400 \mu\text{m}$. A Monte Carlo simulation that assumes random TLS positional and frequency distributions also reproduces similar slopes [dots with error bars in Figs. 4(b) and 4(c)] (see Supplementary Material for the detailed theoretical model).

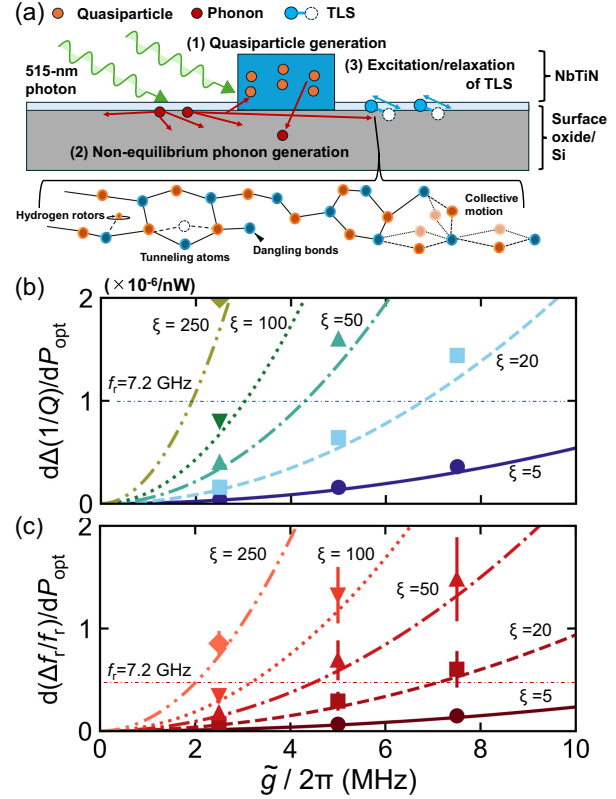


FIG. 4. Schematic of the laser-induced effects and theoretical calculation based on the TLS model. (a) Laser illumination induces (1) quasiparticle generation in the superconductor, (2) nonequilibrium phonon generation, and (3) excitation/relaxation of TLSs via phonon absorption/emission. Some TLS formation mechanisms in the amorphous material are shown [57]. (b) $d\Delta(1/Q)/dP_{\text{opt}}$ and (c) $d(\Delta f_r/f_r)/dP_{\text{opt}}$ as a function of $\tilde{g}$ for different ξ . The lines are calculated using the analytical formula, while the dots with error bars are obtained from Monte Carlo simulations. The error bars correspond to the standard deviation over 100 trials. In each figure, the horizontal dotted line indicates the experimentally measured value at the voltage antinode of the third mode (7.2 GHz).

Furthermore, we must consider (1) the frequency dependence of $d\Delta(1/Q)/dP_{\text{opt}}$ and $d(\Delta f_r/f_r)/dP_{\text{opt}}$, (2) the spatial-mode distribution, and (3) the inhomogeneous TLS distribution, to understand the observed behaviors remaining unexplained: smaller $d\Delta(1/Q)/dP_{\text{opt}}$ and $d(\Delta f_r/f_r)/dP_{\text{opt}}$ at higher modes, the deviation from the global trend at Area 4, and large standard deviation in Fig. 3. Based on Eqs. (1), (2) and $\tilde{g}^2 \propto \omega_r$, $d\Delta(1/Q)/dP_{\text{opt}} \propto 1/\omega_r$ and $d(\Delta f_r/f_r)/dP_{\text{opt}} \propto \text{const.}$ as a function of the resonance frequency. In addition, at higher modes with rapid spatial variation, the local response can be averaged out. For instance, since the distance between nodes and antinodes for the fifth mode is $\sim 150 \mu\text{m}$, the spatial variation in V_{local} is smoothed out assuming a large $\xi > 100 \mu\text{m}/\mu\text{W}$. These explain that the higher the resonance mode, the smaller the $d\Delta(1/Q)/dP_{\text{opt}}$ and $d(\Delta f_r/f_r)/dP_{\text{opt}}$ (observation of the

subtle shift instead of the blueshift). Additionally, as the TLS position and frequency distributions are random, the resonator response exhibits a large standard deviation that depends on the number and frequencies of nearby TLSs. This effect is remarkable for $\Delta f_r/f_r$ in Monte Carlo simulations. Thus, the deviation from the global trend in the third and fifth modes at Area 4 can be explained by considering that the number of relevant TLSs is larger at frequencies between these modes. These factors, (1), (2), and (3), cause the variation in optical responses that are dependent on resonant modes and positions in addition to $|V_{\text{local}}|$, resulting in the large standard deviation in Fig. 3, which shows averaged values only focusing on $|V_{\text{local}}|$.

Finally, we note the influence of equilibrium temperature shifts as discussed in Refs. [64,65]. Throughout the discussion above, we ignore the temperature-dependent shift of TLS permittivity because the experimentally estimated temperature-induced shifts are too small to account for the laser-induced shifts in resonance properties (see Supplementary Material for details). The point is that laser-induced high-energy nonequilibrium phonons excite high-energy TLSs ($\hbar\omega_{\text{TLS}} > \hbar\omega_r, k_B T$) that are never excited under equilibrium conditions. This is why the blueshift and large degradation in Q are only observed in optical-illumination experiments, not for temperature dependence measurements.

In conclusion, we have measured the spatial and mode-dependent optical response of the superconducting nanowire microwave resonator. This method, based on laser-scanning microscopy, enables precise control of the irradiation position. We have demonstrated that the local optical response strongly depends on the local electric potential of the resonator, which can be explained by interactions between TLSs and nonequilibrium phonons. These insights provide guidance for the design and operation of devices that couple microwave and optical fields, including quantum transducers and superconducting detectors. Moreover, the developed local optical-illumination technique can be applied to superconducting qubits, enabling the investigation of their critical behavior in quantum computing chips dominated by the interplay of high-energy particle irradiation, nonequilibrium phonons, TLSs, and the coherence of superconducting circuits.

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Kurokawa designed the experiments and wrote the manuscript. K. T. and H. T. fabricated the sample. H. Kosaka supervised the project.

The authors declare no competing interests.

Data availability—The data that support the findings of this article are openly available [66], embargo periods may apply.

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