

Bolometric Superconducting Optical Nanoscopy (BOSON)

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Superconducting transition-edge sensors are renowned for their extraordinary photon sensitivity and energy resolution, finding applications spanning quantum information, astronomy, and nanophotonics. Here, we report the development of bolometric superconducting optical nanoscopy (BOSON), a novel platform that integrates bolometric detection at the superconducting transition edges with near-field optical techniques. BOSON enables the mapping of photoinduced changes in superconductivity with unprecedented spatial resolution and photon sensitivity. By incorporating BOSON with low-dimensional materials, we achieved polariton imaging at nanowatt excitation levels—at least 4 orders of magnitude lower than the power typically required in prior near-field nanoscopy experiments. Our findings highlight the potential for BOSON to advance scanning-probe-based optical platforms to enable the detection of photons, polaritons, and Cooper pair dynamics at the nanoscale. This paves the way for quantum sensing applications using single-polariton detection and can offer deeper insights into quasiparticle dynamics.

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I. INTRODUCTION

Superconductors (SCs), celebrated for their unique electronic properties and extraordinary sensitivity to external perturbations, have long been integrated into cutting-edge quantum sensing technologies. Superconducting devices that respond to minimal stimuli enable innovations in single-photon detection (SPD) [1–5], bolometry [6–11], and quantum sensing [12,13]. For instance, superconducting bolometers leverage their small superfluid density [7]

and pronounced change in electrical properties near the superconducting critical temperature (T_c) or current (I_c), rendering them highly responsive to minute photoinduced thermal perturbations. More recently, SPDs based on superconductor nanowires rely on the localized suppression of superconductivity upon absorption of a single photon, driving the nanowire over the critical current and contributing to a measurable signal [1]. Among various SC-based techniques, transition-edge sensors (TESs) stand out for their extraordinary sensitivity and low noise. Operating at the brink of the phase transition, TESs function effectively across a broad range of photon energies, independent of polarization [10,13]. Recent advancements in TES-based superconducting detectors and SPDs, such as devices built on niobium nitride (NbN) [14], magnesium diboride (MgB₂) [3], and high- T_c superconductors [2], have expanded the operational temperatures, spectral coverage, and response speeds to new levels, enabling a wide variety

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of choices of SC-based devices for detecting weak light-matter interactions.

Concurrently, scanning probe optical nanoscopy, which uses tip-enhanced near-field light to probe or induce local electromagnetic responses, has emerged as a transformative tool for nanoscale optical imaging, spectroscopy, and nanolight maneuvering. For example, scanning near-field optical microscopy (SNOM) [15,16], photocurrent nanoscopy [17–22], and tip-enhanced nanophoto lithography [23] have enabled many studies of complex material systems. In particular, photocurrent nanoscopy has emerged as a powerful technique for exploring nanoscale optical and photothermal effects [24]. For instance, graphene-based photocurrent nanoscopy has been leveraged to probe local charge puddles [17] and plasmon-polariton propagation in graphene [18,22], which utilizes graphene's exceptional Seebeck coefficient and low heat capacity [25] to detect local heat induced by polaritonic excitations. Because of the reduced electron-specific heat and electron-phonon interaction (phonon cooling), the sensitivity of such systems can be improved at low temperatures. In such applications, exceptional graphene quality and delicate device engineering are often required. The graphene bolometric effect is also explored to function as a terahertz detector [26]. However, due to the weak temperature dependence of resistivity in bulk graphene, bolometric detection is challenging to directly realize in dc transport measurements. These constraints significantly limit the applicability in detecting weak electromagnetic perturbations or resolving subtle light-matter interactions in a wide range of scenarios, where ultrasensitive detection mechanisms are paramount.

Here we introduce bolometric superconducting optical nanoscopy (BOSON) as an ultrasensitive scanning probe

nanoscope that employs superconducting materials as on-chip bolometric detectors for photon and polariton sensing. We demonstrate how photocurrent near-field nanoscopy can be utilized to map local transition edge (TE) in superconducting thin films (e.g., Nb nanobridges), where local T_c can be inferred. In addition, by integrating the Nb nanobridge junction with hexagonal boron nitride (*h*-BN), we achieved hyperbolic phonon-polariton imaging at nanowatt excitation levels—at least 4 orders of magnitude lower than the power typically required in an SNOM and graphene-based near-field photocurrent nanoscopy experiments. We believe these developments significantly enhance our capability to detect extremely weak nanolight signals with exceptional precision and a low-power threshold.

Figure 1(a) illustrates the typical configuration of a BOSON setup, integrating superconductors as photocurrent sensors for detecting tip-induced electromagnetic waves. The detection mechanism hinges on the suppression of supercarrier density by photoexcitation. The suppression drives a near-critical-point superconducting channel resistive, typically monitored at the steepest region of the resistance-temperature or resistance-bias curve known as the transition edge [6,7,11]. The resulting resistive normal region generates a photocurrent or photovoltage signal under current bias, which is detected through the electrodes connected to the system. The photocurrent can be measured under two scenarios. One is the far-field photocurrent (FFPC) measurements, where we measure the photocurrent without the tip for basic sample characterization. The other is the near-field photocurrent (NFPC), where the tip-launched electromagnetic excitation induces a local change of sample properties. As a result, when the sample is raster scanned under the tip, a tip-modulated photocurrent map can be generated. The NFPC enables the mapping of local

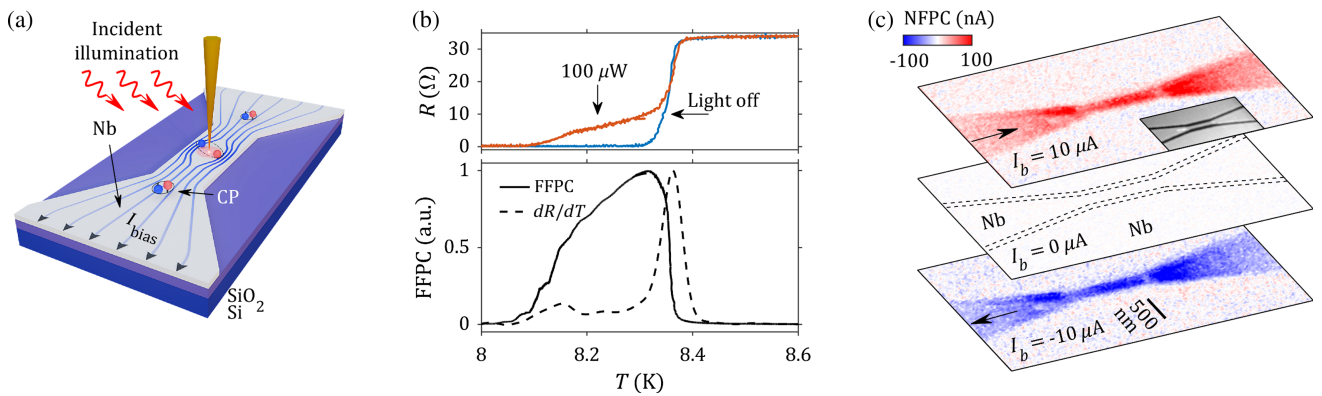


FIG. 1. Experimental setup and measurement concept of BOSON. (a) Schematic of the experimental configuration demonstrating the layered structure of the SC and the near-field photocurrent (PC) characterization. CP: Cooper pair. (b) dc and FFPC characterization of an 8.5- μ m-wide, 50-nm-thick Nb bridge device with an incident beam at 1555 cm^{-1} and 100 μ W. (c) Near-field bolometric photocurrent detection of an Nb nanobridge structure with a 200-nm-wide center bridge near T_c . Top, positively biased; middle, zero bias; bottom, negatively biased. The laser is at 880 cm^{-1} and 50 μ W. The double-dashed line in the middle panel indicates the location for the lithographically defined trench that separates the active region and inactive region of the Nb film. The inset shows the AFM image of the Nb nanobridge structure.

sample properties under the tip apex, whereas the FFPC measures the photoinduced current across the entire sample ensemble. The details of both methods can be found in Supplemental Material [27]. With this setup, we can measure transport properties, FFPC, and NFPC responses without major modifications to the system.

Figure 1(b) shows the temperature dependence of the four-point resistance and FFPC of a 50-nm Nb film. The FFPC is measured with an approximate 10- μ A bias current and a 100- μ W incident illumination (1555 cm^{-1} , 192 meV). The signal is dc filtered, amplified, and subsequently demodulated (the measurement circuit is included in Supplemental Material [27]). All temperatures in this report are calibrated (the calibration method is detailed in Supplemental Material [27]). Two distinct regimes are evident in the resistance measurements under laser illumination: a low-temperature regime where local heating occurs due to laser absorption, and a high-temperature regime corresponding to the global critical temperature (T_c). The FFPC measurements align with the derivative of the resistivity with respect to the temperature dR/dT , suggesting that the photocurrent response is mostly thermally induced within this experimental scheme.

Unlike graphene-based near-field photocurrent measurements, which rely on precise electrostatic gating near the charge-neutral point [17], NFPC in BOSTON experiments operates near the critical current of the working temperature. We utilize a specific type of sample for the NFPC measurements: an Nb thin film (50 nm thick) etched into a nanobridge junction where the current runs through a narrowed bridge at the center of the device. Here, Nb is chosen for its robust and relatively high transition temperature as a conventional SC, and its simplicity of sputtering deposition and reactive ion-etching patterning. The width of the bridge, 200 nm, is intentionally chosen to be comparable to the coherence length of the Cooper pairs in Nb (50–100 nm) [28]. As a result, the bridge has a tiny local heat capacity, a limited superfluid density, and is extremely sensitive to external perturbations near the critical point.

The NFPC maps of the Nb nanobridge structure with a small bias applied in either direction are shown in the top and bottom panels of Fig. 1(c). Without the bias current, no photocurrent signal is observed [middle panel in Fig. 1(c)]. The NFPC signal observed in our setup can, to the first-order approximation, be considered proportional to the derivative of the local voltage drop with respect to the local temperature ($I_{\text{loc}} \Delta R_{\text{loc}} / \Delta T_{\text{loc}}$), where the local temperature change (ΔT_{loc}) is induced by the tip field ($\Delta T \propto |E_{\text{tip}}^2|$). The tip-enhanced field is typically distributed in a range characterized by the tip apex size (20 nm) due to the lightning-rod effect [20,29]. The distribution of local heating is subsequently determined by either quasiparticle diffusion ($L_D = \sqrt{D\tau_{\text{th}}}$) or thermal conduction ($L_T = \sqrt{\kappa\tau_{\text{th}}/C_e}$). Here, D is the diffusion parameter. τ_{th} is the

thermalization timescale mainly limited by electron-phonon-coupling efficiency, κ is the electron thermal conductivity, and C_e is the electron heat capacity. The typical thermal length in the current configuration ranges from submicron to micron scales [7].

Next, we demonstrate the application of BOSTON for areal mapping of transition edges in superconductor devices. We report the NFPC measurements of the same Nb nanobridge structure in Fig. 1(c) with 10- μ W incident power. At the lowest achievable temperature, the NFPC signal is predominately observed when the tip is located near or directly above the bridge, as seen in the 6.70-K panel in Fig. 2(a). As the temperature increases, the signal at the bridge peaks at approximately 7.79 K and decreases beyond 8.01 K. Around 8.25 K, the NFPC signal extends across the entire SC sample, while the bridge region no longer yields the strongest signal. At 8.33 K, the NFPC signal over most of the scanning window begins to diminish and vanishes entirely at 8.48 K. Despite the tiny tip apex size (approximately 20 nm), we notice that the generation of photocurrent signal is not confined to the size of the tip apex or the nanobridge but expands to the bulk of the sample. This is due to the finite diffusion or thermal length of quasiparticles at the micrometer scale. Upon tip-induced absorption, the micron-sized resistive region shuts down the superconducting channel, leading to an observable signal.

Local TE temperature under weak illumination and small bias current can be extracted from temperature-dependent BOSTON images. In Fig. 2(b), we map the spatially resolved TE temperature by locating the temperature where the NFPC signal is maximized. The mapping reveals a variation in TE temperature between the bridge and other regions of the device, with the bridge exhibiting a lower temperature compared to the bulk of the sample. This spatially resolved behavior is consistent with the typical nanobridge resistivity features measured in Fig. 2(c). The bulk Nb region maintains an intrinsic TE temperature at $T_c = 8.5$ K. The bridge region, however, has a lower TE temperature. The variation of TE temperature is due to the difference in local current density and the comparable width of the bridge to the coherent length of Cooper pairs in Nb. Notably, microscopic details of the junction become visible. For instance, two defects [labeled in Fig. 2(a)] appear in NFPC mapping at the top and bottom sections of the nanobridge, exhibiting lower NFPC responses [30]. The same measurement principle can be applied to examine the intrinsic and extrinsic inhomogeneity of other types of superconductors with carefully patterned contacts, such as two-dimensional (2D) SC $\text{FeTe}_{1-x}\text{Se}_x$ (FTS) thin flakes. A detailed discussion of the FTS results is provided in Supplemental Material [27].

Beyond probing local superconductivity, SC junctions can be integrated with low-dimensional van der Waals systems to enable ultrasensitive BOSTON mapping of

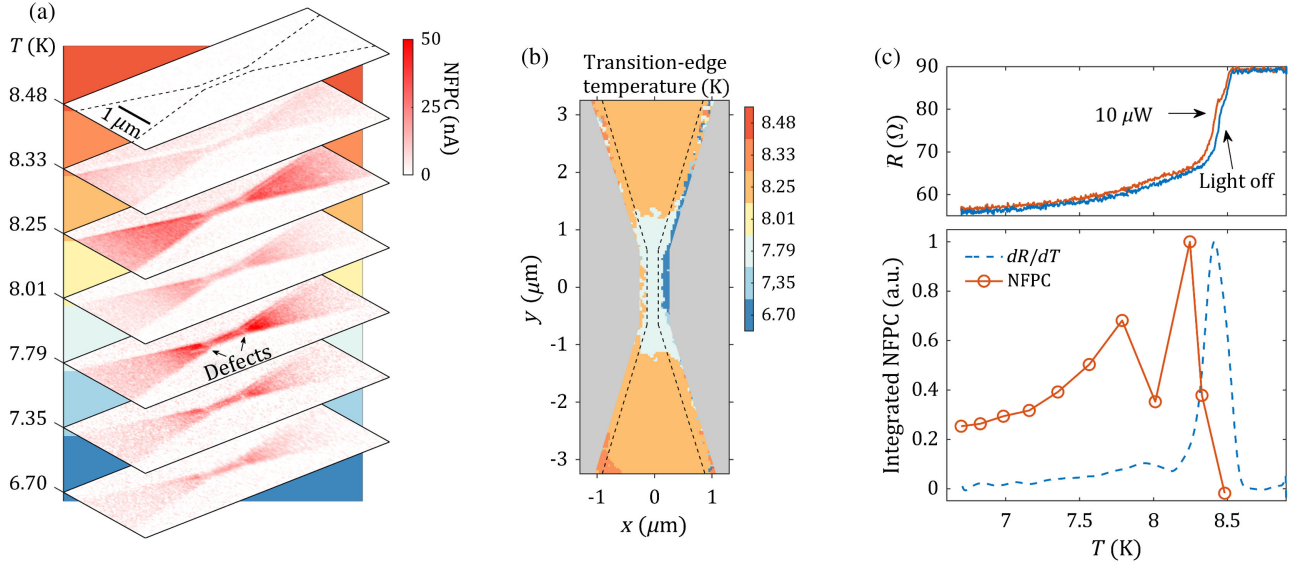


FIG. 2. Temperature-dependent transition-edge mapping using BOSTON. (a) NFPC response of the Nb nanobridge structure, the same as in Fig. 1(c), at various temperatures. The structure is outlined by black dashed lines in the top panel. The incident light is at 880 cm^{-1} with $10\text{-}\mu\text{W}$ power, and the bias current is approximately $10\text{ }\mu\text{A}$. (b) Transition-edge temperature map of the Nb nanobridge extracted from the data in (a). (c) Top panel: temperature-dependent resistivity of the device with light on and off. Bottom panel: the NFPC signal integrated over each map (orange dots) in (a) and compared with the temperature derivative of the resistivity measured by transport (blue dashed curve) side by side.

diverse types of quasiparticles or elementary excitations. As a proof-of-principle demonstration, we showcase real-space mapping of polaritons with unprecedented sensitivity, which can be crucial for quantum information science as the confinement, propagation, and interactions of polaritons have enabled many interesting observations [15,16,31–34] and proposals for applications in correlated quantum systems [35,36].

We leverage the Nb-based nanobridge structures to enhance the detection sensitivity of polaritons in *h*-BN, a 2D van der Waals material renowned for its hyperbolic phonon polaritons [31]. The hyperbolic phonon polariton tracks a unique propagation path in the *h*-BN flake, as shown in Fig. 3(a). The heterostructure was prepared through exfoliation and stacking of an approximately 50-nm-thick *h*-BN flake onto a similar device used in Fig. 2(a), with an Nb bridge of 250 nm width in the center (see Supplemental Material [27]). In this experiment, a quantum-cascade laser (QCL) laser tuned to midinfrared frequencies at 1491.9 cm^{-1} is used to excite polaritons in the *h*-BN layer. Two types of near-field images are simultaneously acquired: the NFPC signal from BOSTON measurements and the tip-scattered signal (S_3) from conventional SNOM for comparison. The basic principles [37] and specific parameters used in our SNOM measurements are detailed in Supplemental Material [27].

Upon optical excitation, polariton waves are excited by both the tip and the sharp edges of the structure. In conventional SNOM imaging of *h*-BN polaritons [31], two types of fringe patterns can be observed at different

locations of an *h*-BN flake. Neighboring metallic boundaries, edge-launched polaritons contribute to a dominating fringe pattern with an intrinsic polariton wavelength $\lambda = \lambda_p$. Near the natural boundary, tip-launched polaritons contribute to both $\lambda = \lambda_p$ and $\lambda = \lambda_p/2$ patterns depending on whether the scattering happens at the boundary or the tip [31]. Both types of polariton patterns can be observed in the SNOM channel as analyzed in Supplemental Material [27]. In contrast, the PC signal detected using BOSTON originates solely from tip-launched polaritons reaching the Nb nanobridge [bottom panel of Fig. 3(a)]. The observed fringe pattern results from the interference between tip-launched polaritons and strongly enhanced local field near the Nb edges. We explain the details of a potential mechanism of polariton sensing using the BOSTON method in Supplemental Material [27]. We confirm that the experimentally extracted and calibrated wavelength of the fringe pattern in the PC channel is $\lambda = 268\text{ nm}$ in the thicker *h*-BN (bottom half flake) and $\lambda = 231\text{ nm}$ in the thinner *h*-BN (top half flake). The wavelengths should linearly depend on the thickness of flakes [31]. The two wavelengths correspond to polariton modes screened by a metal (Nb) substrate with *h*-BN thicknesses of 59 and 51 nm, consistent with our calibrated AFM measurement. As the tip sweeps across the sample, the nanobridge experiences a variation of localized electromagnetic field due to interference, leading to changes in NFPC signal generation. In Figs. 3(b)–3(d), we record the NFPC and SNOM signal under different incident laser power (100 μW , 1 μW , and 50 nW). Experimental data

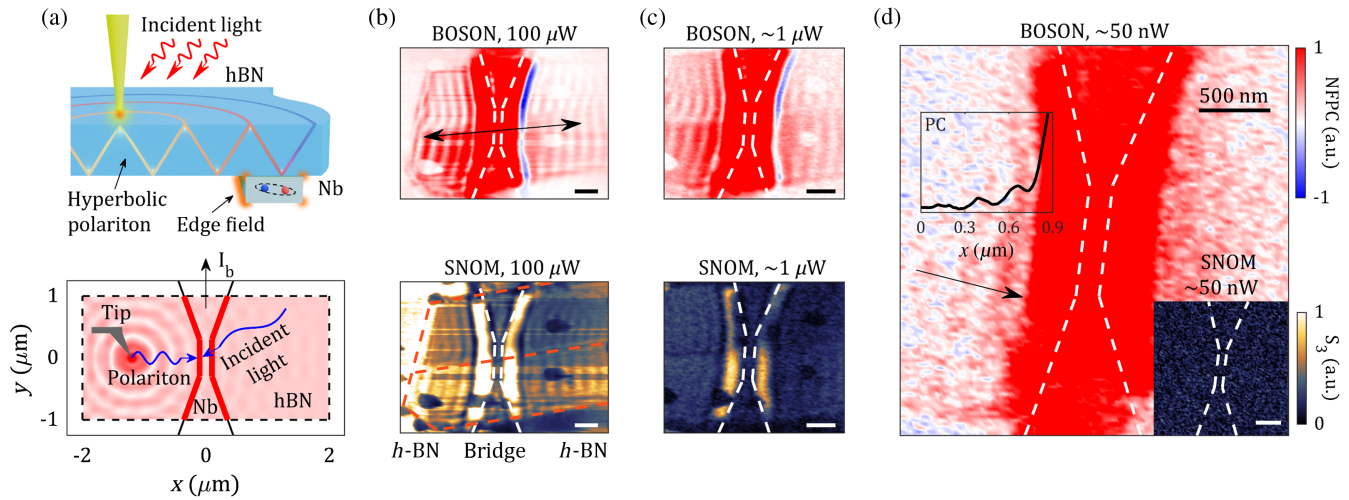


FIG. 3. On-chip nanowatt sensing of polaritons with current-induced transition edges. (a) Top panel: schematic representation of polariton sensing using an on-chip TES. Bottom panel: a potential mechanism of polariton sensing. The tip-launched polaritons interfere with the enhanced local field near the Nb edges. These Nb edges become a strong thermal absorber, making the Nb bridge a sensitive detector to polariton wave fronts. The detailed mechanism and simulation are summarized in Supplemental Material [27]. (b),(c) Identification of hyperbolic phonon polaritons through BOSTON imaging (top) and SNOM imaging (bottom) with 100- μ W and approximately 1- μ W incident power, respectively. BOSTON and SNOM images are recorded simultaneously. The white dashed lines demarcate the Nb nanobridge structure, while the red dashed lines [bottom panels in (b)] outline the *h*-BN flake with a thinner (51 nm) upper region and a thicker (59 nm) lower region. The black arrow marks the location where the bias-sweep signal in the following discussion is collected. Scale bar: 500 nm. (d) BOSTON imaging of hyperbolic phonon polaritons with incident light power as low as approximately 50 nW. The black arrow indicates a linecut revealing the fringe pattern in the top left inset. The bottom right inset shows that SNOM measurements fail to yield meaningful results under the same approximately 50-nW illumination.

confirm robust photocurrent imaging of hyperbolic phonon-polariton fringes even under optical excitation as low as approximately 50 nW, whereas in SNOM measurements, no trace of the signal can be seen with this low incident energy [inset of Fig. 3(d)]. Therefore, these results demonstrate BOSTON's unprecedented sensitivity in probing local elementary excitations or quasiparticles induced by nanoprobles. As a comparison, previous near-field optical methods typically require milliwatt to submilliwatt power levels to generate detectable signals [15–17,19,20,31,38–41].

We note that the resolution of BOSTON measurements for sensing polariton waves is strongly influenced by the geometric design of the bridge structure. The constriction leads to a concentration of supercurrent density within the bridge region. By finely tuning the temperature and bias current, the signal originating from the bridge can be made to dominate the overall PC response. As a result, the spatial resolution perpendicular to the bridge is effectively set by the bridge width (see Supplemental Material [27]). In the current design, a 250-nm-wide bridge is sufficient to resolve the hyperbolic polaritons in *h*-BN. In future optimization, both the width and thickness of the bridge can be reduced to much smaller dimensions (e.g., 10 s of nm), thereby enhancing BOSTON's capability to resolve polaritonic features with higher in-plane momentum and better photon sensitivity.

The optimal working condition for maximized responsivity can be determined by analyzing the temperature- and

current-dependent photocurrent map. This process is illustrated by a series of FFPC measurements with 1- μ W illumination at various working temperatures [Fig. 4(a)]. At 8.58 K, where the nanobridge is slightly above the superconducting transition T_c , only a mild photocurrent is observed when sweeping the bias current. Below T_c (< 8.5 K), no photocurrent is detected at bias currents lower than the critical current $I_c(T)$. However, beyond this critical current, a pronounced and narrow peak is observed, followed by a mild response at larger bias currents. As the operating temperature decreases, the critical current $I_c(T)$ increases, and the peak values roughly follow a linear trend $PC_{\max} = I_c(T)R_N$ [7,11], where R_N is the resistance of the Nb nanobridge in the normal state. At 8.09 K, the photocurrent reaches its highest measurable value achievable in our setup. Below 8.09 K, we observed excess noise in the FFPC signal. The large FFPC at superconductor-normal switching can be understood by estimating the bolometric response to be proportional to $dV/dI|_{I_c} dI_c/dT$. A steep slope in the current-voltage relation leads to a giant bolometric response. At the low-temperature end of the switching, however, the resistance switching under a large current bias becomes abrupt and noncontinuous due to a rapid thermal-runaway effect. As a result, $dR/dI|_{I=I_c}$ diverges and experimentally a large noise emerges. This issue may be resolved with a voltage-biased (hence, with negative feedback) measurement and improvements in low-noise electronics. Combined with a reduction of the

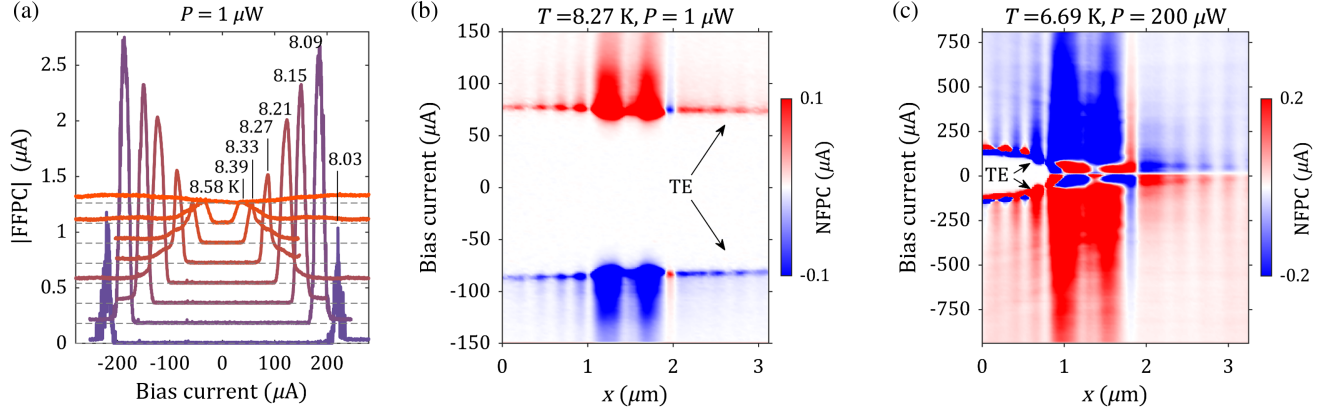


FIG. 4. On-chip detection of far-field radiation and near-field polariton. (a) FFPC of the Nb + *h*-BN junction under 1491.9 cm^{-1} and $1\text{-}\mu\text{W}$ incident power. (b) NFPC linescans at $T = 8.27$ K under varying bias current with weak illumination $P = 1\text{ }\mu\text{W}$. TE: transition edge. (c) NFPC linescans at $T = 6.69$ K with strong illumination $P = 200\text{ }\mu\text{W}$.

Nb thickness, optimization of bridge geometry, and enhancements in material properties, we anticipate that photocurrent sensitivity could be improved by orders of magnitude in future experiments, potentially even enabling the detection of polaritons toward the single-photon level [2,3].

With the knowledge of the $I_c(T)$ under light illumination, we characterize PC sensitivity near the critical bias for detecting the tip-launched polaritons. In Figs. 4(b) and 4(c), we present an NFPC linescan across the junction under varying bias currents, taken along the black arrow indicated in Fig. 3(b). With weak illumination power [Fig. 4(b)], the polariton features, together with other NFPC responses, are absent with a current smaller than $I_c(T)$. Polaritonic fringes emerge with the highest sensitivity precisely at the transition edges for both positive- and negative-bias currents. As the bias current increases beyond the transition edges, the polaritonic fringes gradually diminish in the NFPC signal.

Under high illumination power and lower operating temperatures [Fig. 4(c)], a distinct behavior emerges. The critical bias required to observe polaritons becomes location dependent and exhibits asymmetry depending on whether the tip is positioned on the left or right side of the bridge. This asymmetry may arise from a slight difference in the far-field light illumination received by the nanobridge. At high illumination power, this effect becomes pronounced: On the right side, the combination of far-field illumination and the tip-launched local field drives the nanobridge above the superconducting transition even at minimal bias current. In contrast, the left side requires a larger bias current to reach the transition edge. Additionally, we observed a more complex sign-switching behavior of the photocurrent signal compared to the expected polarity switching following the bias current. This phenomenon is likely attributed to the strong non-linearity of the resistance-temperature relationship $R(T)$ near the TE, leading to additional sign-switching effects.

II. SUMMARY

By integrating superconducting nanobridge structures into SNOM, we have developed BOSTON, a superconducting-based nanoscopy platform capable of resolving superconducting transitions at the nanoscale and probing collective quasiparticle excitations with exceptional sensitivity. This approach leverages the bolometric response in superconductors—a highly sensitive detection mechanism based on perturbations to the superconducting condensate. Compared to existing SNOM and photocurrent nanoscopy techniques, this method achieves significantly enhanced sensitivity and operates at nanowatt power levels, effectively minimizing sample and tip heating. This capability facilitates the exploration of quantum phenomena at extremely low temperatures with reduced noise, establishing BOSTON as a superior tool for ultrasensitive nanoimaging applications, particularly for weak bosonic excitations such as Cooper pairs and polaritons. It also enables the study of low-energy excitations in the THz frequency range, offering new nano-optical functionalities based on existing bolometric techniques.

These advancements enable optical nanoscopy measurements using potentially a wide range of low-fluence light sources such as global and synchrotron-based facilities [41,42]. The capability for reporting local TE temperature can be critical for characterizing superconductor devices such as Nb- or Ta-based capacitors in solid-state qubits, where surface defects, oxidation, and metal-proximity effects are known to impact coherence time [43–45]. Moreover, BOSTON holds the potential to address longstanding challenges in quantum nanophotonics, such as single-polariton detection. Recent breakthroughs in high critical temperature materials such as BiSrCaCuO [2], LaSrCuO [2], and MgB₂ [3] in quantum sensing raise questions about the microscopic photon detection mechanism. The complex electronic band structures and larger superconducting energy gaps in high- T_c materials

challenge traditional methods routinely used for modeling the detection in low- T_c -based sensors. Furthermore, it also remains unclear how irradiation-induced defect formation, a crucial method for high- T_c -based sensors, contributes to the improved performance observed after irradiation.

Building on the BOSON framework, future work will aim to extend the capabilities of superconductor-based nanoscopy, covering a broader frequency range, unveiling local superconductivity dynamics, and potentially achieving single-photon or -polariton imaging nanoscopy (SPIN).

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R. J. and B. Z. contributed equally to this work. R. J., B. Z., and M. K. L. conceived the project and designed the experiments. G. L. C., I. C., D. B., Q. L., K. K. B., D. N. B., X. D., and M. K. L. supervised the project. B. Z., D. K., and X. D. prepared the devices. R. J. and B. Z. performed the experiments with the support of W. Z., Z. Z., H. W., B. C., J. H. P., L. W., Z. D., S. C., and C. D. P. X. C. performed the finite-element simulation. R. J., B. Z., and M. K. L. analyzed experimental data with input from X. D., G. L. C., I. C., D. B., K. K. B., and D. N. B. R. J., B. Z., and M. K. L. cowrote the manuscript with input from all co-authors.

DATA AVAILABILITY

The data that support the findings of this article are openly available [46].

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