

Optically accessible high-finesse millimeter-wave resonator for cavity quantum electrodynamics with atom arrays

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Cavity quantum electrodynamics (QED) is a powerful tool in quantum science, enabling preparation of nonclassical states of light and scalable entanglement of many atoms coupled to a single field mode. While the most coherent atom-photon interactions have been achieved using superconducting millimeter-wave cavities coupled to Rydberg atoms, these platforms so far lack the optical access required for trapping and addressing individual atomic qubits. We present a millimeter-wave Fabry-Pérot cavity with finesse $5.8(1) \times 10^7$ at a temperature of 1 K providing generous transverse optical access (numerical aperture 0.56). Conflicting goals of strong atom-photon coupling and optical access motivate a near-confocal geometry. Close to confocality, however, postparaxial corrections to the cavity spectrum introduce unexpected degeneracies between transverse modes, leading to excess cavity loss. Modeling these corrections allows for tuning the cavity geometry to evade this loss, producing a high finesse that will enable cavity QED experiments with trapped atoms deep in the strong coupling regime.

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Coherent exchange of quantum information between photons and matter qubits is a key capability in quantum science, with applications ranging from quantum sensing and networking to computation and simulation. Achieving coherent light-matter interactions requires placing the emitters in a cavity or waveguide that enhances their interaction with an electromagnetic mode. One may then use the emitters to engineer nonclassical states of light [1,2], or use the cavity field to mediate nonlocal interactions [3–6] and entanglement [7–14] between emitters. In ensembles of trapped atoms, the collective coupling to a single field mode has allowed for engineering squeezed [7–10] and non-Gaussian [11,12] collective spin states. Combining strong atom-light coupling with local control in tweezer-based atom arrays [13–17] has further enabled pairwise entanglement of atomic qubits [13,14] and nondestructive readout for error correction [15–17].

The coherence of atom-light interactions is quantified by the cooperativity $\eta = 4g^2/\kappa\Gamma$, which compares the

vacuum Rabi frequency g to the resonator and emitter decay rates κ and Γ . Achieving coherent photon-mediated interactions between two atoms requires operating deep in the strong coupling regime $\eta \gg 1$. Error rates in two-qubit gates based on cavity-mediated interactions, for example, scale as $\eta^{-1/2}$ [18,19]. In the optical domain, the highest single-atom cooperativities achieved to date are of order $\eta \sim 10^2$ [20], posing a limit to deterministically generating high-fidelity entanglement. Thus, the preparation of entangled states in optical cavities has required using either atomic ensembles with collectively enhanced coupling to light [7–12] or conditional or heralded techniques [13–15,21].

Significantly higher cooperativities are possible in millimeter-wave cavities, which couple to transitions between Rydberg states. In particular, frequencies from 50 to 100 GHz are low enough to couple to long-lived transitions, yet sufficiently high to suppress thermal population of cavity modes. In this regime, a finesse $F \gtrsim 10^9$ has been achieved [22] thanks to the availability of superconducting mirrors and to millimeter-scale wavelengths, long when compared to mirror surface roughness. The resulting cooperativity $\eta = 5 \times 10^8$ enabled pioneering observations of photon-mediated interactions between atoms transiting a cavity [23] and preparation of nonclassical states of the cavity field [24] via quantum nondemolition measurements [25]. Microwave and millimeter-wave

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frequencies are also naturally suited for interfacing atomic and solid-state qubits [26], motivating demonstrations of coherent coupling between atoms and coplanar waveguide resonators [27–29]. Simultaneously coupling millimeter-wave and optical cavities to an atomic ensemble has furthermore enabled efficient quantum frequency conversion [30,31]. However, incorporating single-atom trapping and addressing into such systems remains an outstanding challenge.

We report on the design and characterization of a superconducting millimeter-wave Fabry-Pérot resonator for use in future atom-array cavity quantum electrodynamics (QED) experiments. Motivated by the competing requirements of high cooperativity and optical access, we adopt a near-confocal geometry (Fig. 1). In this regime, we find that an understanding of postparaxial effects is crucial to avoiding excess loss due to accidental mode hybridization. Guided by a model of these effects, we tune the cavity length to achieve a finesse $F = 5.8(1) \times 10^7$, limited primarily by magnetic flux trapping. The measured finesse corresponds to a cooperativity $\eta = 2.7 \times 10^6$ for long-lived circular Rydberg states. By establishing the compatibility of a high-cooperativity millimeter-wave cavity with optical access for atomic tweezer arrays, our work paves the way to harnessing strong atom-photon interactions for nonlocal quantum gates, scalable entanglement, and many-body quantum simulation.

The twin goals of optical access and high cooperativity place conflicting requirements on the geometry of a Fabry-Pérot cavity. This tension is best understood by rewriting the cooperativity in terms of geometric parameters. For an atom at an antinode at cavity center, the cooperativity on a cycling transition of wavelength λ is

$$\eta_0 = \frac{6}{\pi^3} \frac{F\lambda^2}{w_0^2} = \frac{6}{\pi^2} \frac{F\lambda}{z_R}, \quad (1)$$

where F is the finesse, w_0 the mode waist, and $z_R = \pi w_0^2/\lambda$ the Rayleigh range [32,33]. The first expression compares the atomic cross-section with the cross-sectional area of the cavity mode (λ^2/w_0^2), augmented by the average number F/π of round-trips made by photons in the cavity. Equivalently, the cooperativity can be written in terms of the solid angle λ/z_R subtended by the cavity mode in the far field which, together with the enhancement factor F/π , determines the probability that an emitted photon is scattered into the cavity mode. Thus, the cooperativity improves as the mode grows more divergent. A more divergent mode, however, requires cavity mirrors subtending a larger solid angle to maintain a high finesse, limiting the solid angle that remains open for optical access [Fig. 1(a)].

To balance the tradeoff between cooperativity and optical access, we consider the imaging aperture available over the entire design space of cavity length L and mode size [Fig. 1(c)], parametrizing the latter by the Rayleigh range

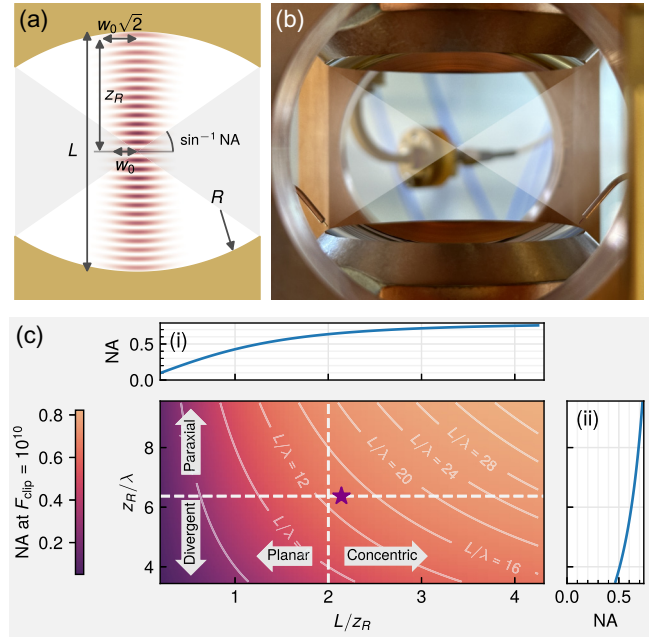


FIG. 1. Cavity design for combining strong coupling with optical access. (a) Schematic of Fabry-Pérot cavity of length L and mirror radius of curvature R . Red shading shows Gaussian TEM_{00} mode of waist w_0 and Rayleigh range z_R . (b) The cavity and coaxial probes. Overlaid cones show numerical aperture (NA) available for imaging from the open sides of the cavity. (c) Dependence of NA on dimensionless parameters L/z_R , describing the cavity geometry, and z_R/λ , characterizing the mode divergence. Contour lines give cavity length normalized to mode wavelength. Color shows NA when mirrors are sized to permit a finesse $F_{\text{clip}} = 10^{10}$ for a Gaussian TEM_{00} mode. The star marks the chosen cavity geometry, while dashed lines indicate the cross sections shown in the subplots: (i) constant z_R/λ ; (ii) confocality, $L = 2z_R$.

z_R . For each combination (L, z_R) , we choose the mirror size such that clipping of the Gaussian mode limits the cavity to a fixed finesse $F_{\text{clip}} = 10^{10}$. We plot the remaining transverse numerical aperture (NA) in Fig. 1(c) as a function of dimensionless parameters L/z_R and z_R/λ . The ratio L/z_R specifies the cavity geometry and is solely determined by mirror spacing and curvature, with $L/z_R \rightarrow 0, \infty$ in the planar and concentric limits, respectively. The normalized Rayleigh range z_R/λ is inversely proportional to the mode divergence and thus also to the cooperativity at fixed finesse.

Figure 1(c) shows that the transverse aperture available for imaging improves with increasing cavity length L/z_R and with increasing Rayleigh range z_R/λ , but also shows points of diminishing returns along both axes. As optical access grows only marginally beyond confocality ($L/z_R = 2$), we opt for a near-confocal geometry, which additionally provides robustness to misalignment [34]. Here, choosing $z_R/\lambda \approx 6$ provides sufficient optical access ($\text{NA} \approx 0.5$) for tweezer trapping and imaging, whereas

further increasing z_R/λ (i.e., decreasing mode divergence) provides little gain in NA while directly reducing cooperativity. The resulting cavity design, depicted in Fig. 1(b), is marked by the star in Fig. 1(c).

The cavity consists of two concave toroidal metal mirrors of diameter $D = 48$ mm and curvature radii $R_{x,y} = 42.0$ and 43.5 mm, with their principal axes aligned. These mirrors consist of diamond-machined oxygen-free copper substrates with a $2\text{-}\mu\text{m}$ film of superconducting niobium [33,35,36]. We considered three cavity lengths $L_{0,1,2} = 43.75, 45.44$, and 47.15 mm; at L_2 , the cavity leaves a numerical aperture $\text{NA} = 0.56$ for optical access. $L_{0,1,2}$ are all slightly longer than confocal to avoid degeneracy between transverse modes. We quantify the deviation from confocality with the parameter $\bar{g} = 1 - L/\bar{R}$ comparing cavity length to the harmonic mean mirror curvature radius $\bar{R}$. From cavity spectra in the three geometries, we determine $\bar{g}_{0,1,2} = (-0.029, -0.068, -0.109)$, corresponding to $\bar{R} = 42.53$ mm.

We probe the cavity in a closed-cycle dilution refrigerator, at temperatures T from 0.4 to 4 K, using the two coaxial probes shown in Fig. 1(b). The probes are oriented at 45° from the principal axes of the toroidal mirrors, permitting coupling to both polarization modes [33]. When one probe is driven at millimeter-wave frequencies, cavity modes appear in the resulting transmission (S_{21}) spectrum as narrow resonance features whose widths give mode finesse and whose amplitudes quantify the coupling to the probes. We mount the probes on cryogenic translation stages to

adjust this coupling *in situ* for tuning to a regime where the finesse is limited by intrinsic cavity losses and not by loss through the probes.

In the geometry closest to confocality, with $\bar{g}_0 = -0.029$, we observed excess cavity losses attributable to mode hybridization. The TEM_{00} mode frequencies [Fig. 2(a)] reveal an avoided crossing in which, over successive free spectral ranges, the frequency of a higher-order transverse mode crosses through the TEM_{00} frequency. This avoided crossing coincides with a dip in TEM_{00} mode finesse [Fig. 2(b), measured at 4 K]. Together, these data suggest that admixture of the transversely larger higher-order mode into the TEM_{00} mode increases clipping loss at the mirrors. Measurements of probe coupling [Fig. 2(c)] support this explanation: modes with a larger fraction of the higher-order mode couple more strongly to the probes, which in these measurements were located just outside the edge of the mirrors, 25 mm from the cavity axis. We quantify probe coupling by the geometric mean $\sqrt{\kappa_1\kappa_2}$ of the loss rates of cavity energy through the two probes, computed from the linewidth and amplitude of the S_{21} response [33].

The intrusion of this higher-order mode is unexpected in the paraxial theory of Gaussian beams. Around the $\text{TEM}_{26,0,0}$ mode at 90.818 GHz, for instance, paraxial theory predicts the spectrum shown in Fig. 2(d), with $\text{TEM}_{26,0,0}$ separated by 25 MHz from the closest higher-order transverse mode—far in excess of the 1-MHz coupling to higher-order modes indicated by the spectral

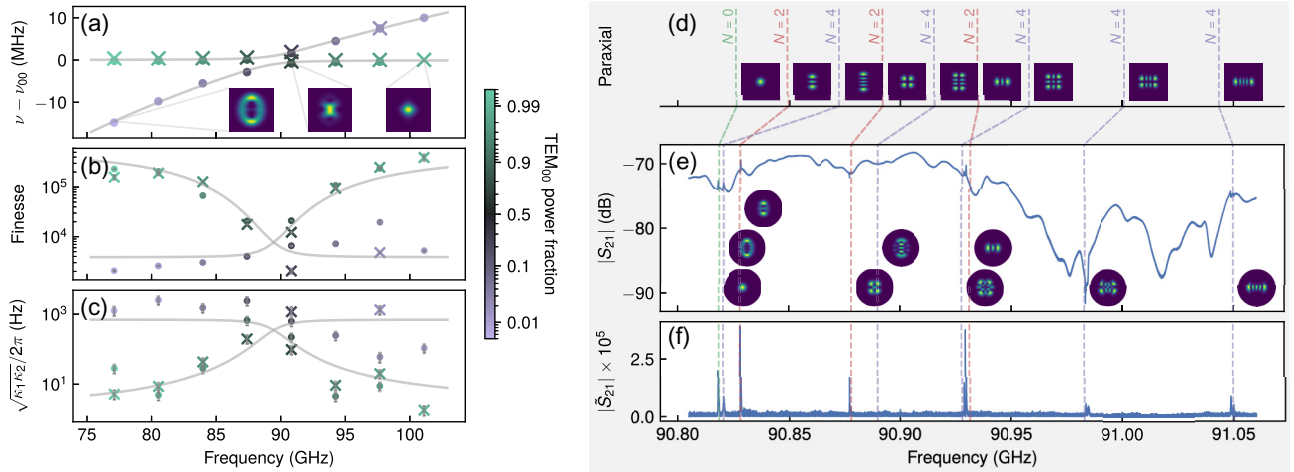


FIG. 2. Cavity spectroscopy of mode hybridization in the $\bar{g}_0$ -geometry, measured at $T = 4$ K. (a)–(c) Spectroscopy of an avoided crossing between the TEM_{00} mode series and a series of fourth-order modes. (a) Mode frequencies ν relative to TEM_{00} mode frequencies ν_{00} absent coupling to fourth-order mode, (b) finesse, and (c) probe coupling $\sqrt{\kappa_1\kappa_2}$, plotted versus absolute mode frequency. Points and crosses respectively indicate x - and y -polarized modes. Solid gray curves are guides to the eye. Insets in (a) show reconstructed transverse intensity profiles for three indicated modes [33]. (d) Paraxial prediction for the cavity spectrum around $\text{TEM}_{26,0,0}$, with colored dashed lines marking modes of various transverse orders N , illustrated by transverse intensity profiles. (e) Measured cavity S_{21} spectrum, with postparaxial predictions of mode frequencies indicated by dashed lines [37] and reconstructed transverse intensity distributions in accompanying insets. (f) Applying a high-pass filter to the raw data in (e) reveals more clearly the narrow cavity modes, with amplitudes dependent on coupling to the probes.

gap in Fig. 2(a). However, the cavity operates in a *quasi-optical* regime, where the wavelength is comparable to characteristic mode dimensions ($z_R/\lambda \lesssim 10$). The resulting highly divergent modes are advantageous to cavity QED [Eq. (1)], but necessitate accounting for postparaxial corrections: higher-order terms in the expansion parameter $1/kw_0 = \sqrt{\lambda/4\pi z_R}$, where $k = 2\pi/\lambda$ [38].

The consequences of working with such divergent modes have previously been explored, primarily in optical microcavities. Mode mixing there has been found to cause excess losses [39,40], though it may also suppress diffractive loss in certain cavity geometries [41]. Postparaxial frequency shifts, too, have been observed at optical [42,43] and microwave frequencies [44,45], and an operator approach has been developed to compute them analytically [37].

Applying the operator approach of Ref. [37] to our cavity, we identify the higher-order mode appearing in Fig. 2(a), showing that postparaxial effects can explain the surprising mode degeneracies in near-confocal geometries. The theory predicts mode frequencies as a function of four geometric parameters—cavity length L , mirror curvature radii $R_{x,y}$, and a coefficient describing the fourth-order curvature of the mirrors—which we fit to observed spectra [33]. Figures 2(e)–2(f) plot the S_{21} cavity spectrum around $\text{TEM}_{26,0,0}$ with model predictions of mode frequencies and mode field patterns, implicating an errant fourth-order mode in the finesse dip observed in Fig. 2(b). Indeed, the postparaxial frequency corrections are comparable to the transverse mode spacings predicted by paraxial theory, shifting higher-order modes in the $\bar{g}_0$ -geometry much closer to the TEM_{00} modes.

To avoid mode mixing, we lengthened the cavity to a geometry further from confocality, with $\bar{g}_1 = -0.068$. Here, the higher-order transverse modes are pushed to spacings of order 100 MHz, much greater than the 1-MHz coupling strength observed in the $\bar{g}_0$ -geometry, so the TEM_{00} modes should be purer and consequently better localized along the cavity axis. Figure 3(a) compares probe coupling $\sqrt{\kappa_1\kappa_2}$ as a function of probe position for two analogous TEM_{00} modes in the $\bar{g}_0$ - and $\bar{g}_1$ -geometries. As the probes are retracted in the $\bar{g}_1$ -geometry, this coupling drops steeply to levels far below those observed in the $\bar{g}_0$ -geometry. The measured couplings, directly proportional to the local mode field intensity at the probes, agree with the simulated intensity profiles plotted in Fig. 3(b) [33,46,47], confirming the improved mode localization in the $\bar{g}_1$ -geometry.

We confirm that the reduction in mode mixing away from confocality translates into improved finesse by performing cavity ringdown spectroscopy in the $\bar{g}_1$ -geometry and in an even longer cavity with $\bar{g}_2 = -0.109$. The ringdown measurement avoids broadening of the cavity line due to subnanometer oscillations of the cavity length driven by residual vibrations in the cryostat [33].

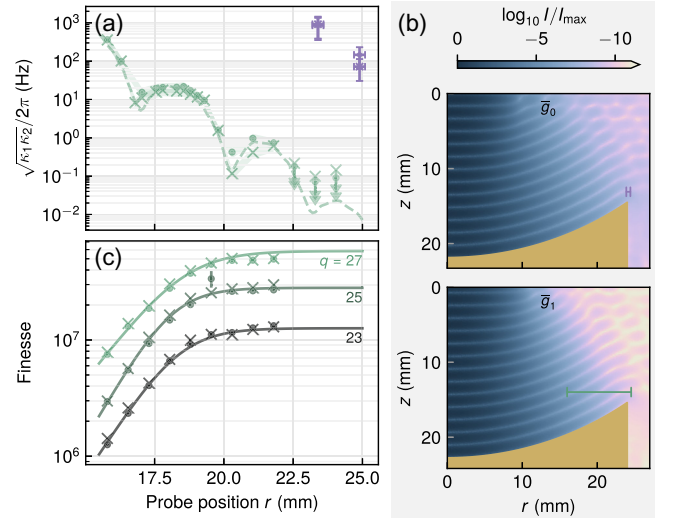


FIG. 3. Improved localization of cavity modes away from confocality. (a) Probe coupling $\sqrt{\kappa_1\kappa_2}$ versus distance r of probe tips from cavity axis for (purple) $\text{TEM}_{26,0,0}$ at 90.818 GHz in the $\bar{g}_0$ -geometry and for (green) $\text{TEM}_{27,0,0}$ at 90.655 GHz in the $\bar{g}_1$ -geometry. Points and crosses show x - and y -mode polarization, respectively. Bands and error bars indicate 1σ measurement uncertainty, while arrows denote upper bounds for mode response amplitudes below the detection limit. The dashed line gives simulation estimates in the $\bar{g}_1$ -geometry, obtained from (b) finite-element simulations of the modes in (a), where we approximate the cavity as cylindrically symmetric for computational efficiency [33]. We plot electric field intensity versus cylindrical coordinates (r, z) , normalized to peak intensity. Colored lines indicate range of positions over which probe coupling is plotted in (a). (c) Finesse of $\text{TEM}_{q,0,0}$ modes in the $\bar{g}_1$ -geometry at 0.4 K (from dark to light, $q = 23, 25, 27$) as probes are retracted. Curves are guides to the eye.

We further operate at a lower temperature $T = 0.4$ K to avoid being limited by temperature-dependent cavity loss. Figure 3(c) shows the finesse of three TEM_{00} modes in the $\bar{g}_1$ -geometry as a function of probe position. The finesse initially increases as the probes are retracted, consistent with their decreased coupling to the cavity, before plateauing to unloaded finesse $F \gtrsim 10^7$, two orders of magnitude higher than achieved in the $\bar{g}_0$ -geometry.

Figure 4(a) summarizes the improved finesse as a function of mode frequency in the $\bar{g}_1$ -geometry (red markers) and the longer $\bar{g}_2$ -geometry (blue markers). For both cavity lengths, the finesse of the TEM_{00} modes increases with increasing frequency ν before plateauing to a common value $F_{\text{max}} = 5.8(1) \times 10^7$ for $\nu \gtrsim 90$ GHz. We attribute the lower finesse at low frequencies to residual mode mixing, which is more significant for the more confocal ($\bar{g}_1$) geometry. The plateau to the same finesse F_{max} for both geometries at high frequency indicates that mode mixing is no longer a dominant limitation in this regime. Rather, the remaining losses at high frequency are well explained by magnetic flux trapping and a smaller contribution from the surface roughness of the mirrors.

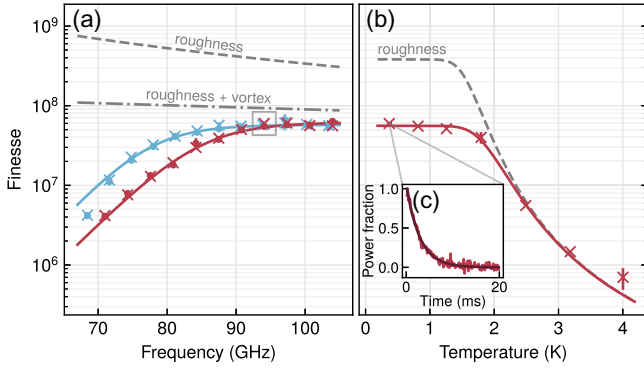


FIG. 4. Cavity performance. (a) Finesse of TEM_{00} cavity modes at 0.4 K in the $\bar{g}_1$ - (red) and $\bar{g}_2$ - (blue) geometries compared to limits set by mirror roughness and magnetic flux trapping. (Points, crosses: x - and y -polarized modes, respectively.) Solid lines are guides to the eye. For the $\text{TEM}_{28,0,0,y}$ mode of the $\bar{g}_1$ -geometry at 94.073 GHz (red cross, boxed), we show (b) finesse versus cavity temperature. The solid line fits the temperature dependence as a combination of superconductor ac resistance and a constant residual loss [33]; the dashed line shows the same fit with the lower residual loss set by the roughness limit in (a). (c) Ringdown data behind the measurement at 0.4 K; the fitted exponential decay rate $\kappa = 2\pi \times 55.1(1.5)$ Hz yields finesse $F = 5.99(16) \times 10^7$.

Both residual mode mixing and magnetic flux trapping can be mitigated in future experiments to reach even higher finesse. Further detuning the cavity away from confocality should improve the purity of the TEM_{00} modes, and hence their transverse localization, to reduce the diffractive losses we observe at low frequencies. Additionally, mirror profiles may be numerically optimized to suppress mode mixing using the finite-element simulations shown in Fig. 3(b), which provide fast, reliable estimates of even very low mode losses [33,46,47]. At high frequencies, the dominant source of loss is flux trapping due to an ambient magnetic field with component $B_{\perp} = 0.22$ G normal to the mirrors, as shown in Fig. 4(a) (dot-dashed curve). Suppressing the magnetic field during cavity cooldown to $B_{\perp} \lesssim 10$ mG would yield high-frequency cavity performance limited only by the mirror surface roughness (dashed curve). The measured roughness $h_{\text{rms}} = 23$ nm sets a finesse limit $F_{\text{surf}} = \pi/4k^2h_{\text{rms}}^2 \gtrsim 3 \times 10^8$.

Crucial for achieving high finesse is operating below the superconducting transition temperature $T_c = 9.2$ K of the niobium mirror coatings. Even in this regime, BCS theory predicts a residual temperature-dependent ac resistance. To understand the implications for the required operating temperature, we measured the finesse in the $\bar{g}_1$ -geometry for temperatures T from 0.4 to 4 K, as shown in Fig. 4(b) for the $\text{TEM}_{28,0,0,y}$ mode. We observe a finesse consistent with BCS resistance, roughly following a Boltzmann scaling $R_{\text{BCS}}(T) \sim e^{-\Delta/k_B T}$ governed by the superconducting gap $\Delta/k_B = 17.67$ K, until reaching the limiting value F_{max} at low temperature. Encouragingly, the cavity can operate at

temperatures up to 1.3 K without impacting cavity performance, even if the finesse were limited only by surface roughness. This flexibility is important for cryogenic atom array experiments, where heat loads due to scattered trapping light may limit the achievable temperature.

The cavity is poised to benefit from ongoing advances in developing cryogenic atom arrays [48–50] and controlling circular Rydberg states. Circular Rydberg atoms, recently prepared in tweezer arrays [51,52], offer long radiative lifetimes at low temperature and maximal cooperativity, as their only dipole-allowed radiative transition is the millimeter-wave transition that couples to the cavity. Coupling the 92-GHz transition between circular Rydberg states $|41C\rangle \leftrightarrow |42C\rangle$ to a linearly polarized cavity mode yields a cooperativity $\eta = \eta_0/2 = 2.7 \times 10^6$. The corresponding parameters $(g, \kappa, \Gamma) = 2\pi \times (22 \times 10^3, 55, 13)$ Hz permit nonlocal entangling gates [18,19,53,54] with fidelity above 98% [33].

The prospect for deterministic millimeter-wave-mediated entanglement in atom arrays opens myriad opportunities in quantum information processing, from manipulating nonlocally encoded information in topologically ordered states [55] to investigating low-overhead quantum error correcting codes that rely on nonlocal connectivity [56–58]. The cavity also offers a route to scalably generating nonclassical states of atoms or photons as metrological resources for Heisenberg-limited phase estimation [59,60]. Further, the interplay of cavity-mediated nonlocal interactions with local dipolar interactions opens rich possibilities in quantum many-body physics, from inducing maximally chaotic dynamics [61] to stabilizing quantum spin liquids [62].

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Data Availability. The data that support the findings of this article are openly available [63].

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