

Stability, Degeneracy, and Scalability of a 600-Site Cavity Array Microscope

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Optical cavities are a foundational technology for controlling light-matter interactions. While interfacing a single cavity to either an atom or ensemble has become a standard tool, the advent of single-atom control in large atomic arrays has spurred interest in a new frontier of “many-cavity QED,” featuring many independent resonators capable of separately addressing individual quantum emitters. In this fast-evolving landscape, the *cavity array microscope* was recently introduced—employing free space intracavity optics to engineer a two-dimensional array of tightly spaced cavity TEM₀₀ modes with wavelength-scale waists, ideally suited for interfacing with atom arrays. Here, we realize the next generation of this architecture, achieving hundreds of degenerate cavity modes with improved, uniform finesse, and explore the technical features of the system which will enable further scalability. In particular, we study imperfections, including optical aberrations, field of view constraints, array nondegeneracies, and losses from optical elements. We identify the sensitivity to these various factors and exposit the control knobs and techniques necessary to align and operate the system in a stable manner. Ultimately, we lay out a pathway toward operation with tens of thousands of independent cavities while maintaining compatibility with existing atom arrays, paving the way to myriad applications including highly parallelized remote entanglement generation, fast and nondestructive midcircuit readout, and the implementation of hybrid atom-photon Hamiltonians.

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I. INTRODUCTION

Cavity quantum electrodynamics (QED) is the study and control of light-matter interactions when photons are trapped in a high- Q resonator [1]. The cavity-enhanced density of states allows for pristine isolation of single or multiple photon modes, which has been enabling in fields ranging from bioimaging and spectroscopy [2–4] to detection of gravitational waves [5] and quantum metrology [6–8]. To advance these varied areas, cavity engineering has expanded continuously with the development of ultrahigh-finesse optics [9,10], nanophotonic [11] and fiber [12] interfaces, introduction of intracavity lenses [13–15], nonlinear optics [16], and integration with high-NA imaging systems [17]. Despite these evolutions, an elusive challenge

is that an optical cavity typically acts as a very high-performance “single pixel,” lacking spatial resolution across its mode when probing a set of emitters.

To address this limitation, a new optical cavity design was recently debuted, the *cavity array microscope* (CAM) [18]. This architecture employs intracavity lenses to create a two-dimensional array of many independent, small-waist, tightly spaced TEM₀₀ cavity modes, effectively realizing a new regime of many-cavity QED. The CAM can be applied in any context in which a “many-pixel” cavity interface is desirable and is especially useful when interfacing optical cavities with large arrays of individually trapped atoms [19–24], where the parallelized atom-cavity interface can improve the rate of transducing quantum information between atoms and photons as part of, for example, a distributed quantum computer [25] or enable studies of new light-matter coupled Hamiltonians [26–28]. This was the context for the first CAM demonstration [18], where an array of single atoms was simultaneously interfaced with 43 independent cavities. This first generation exhibited several limitations: Bulky optics were required approximately 1 mm away from atoms, limiting optical access and hosting surface charges; the number of accessible cavities

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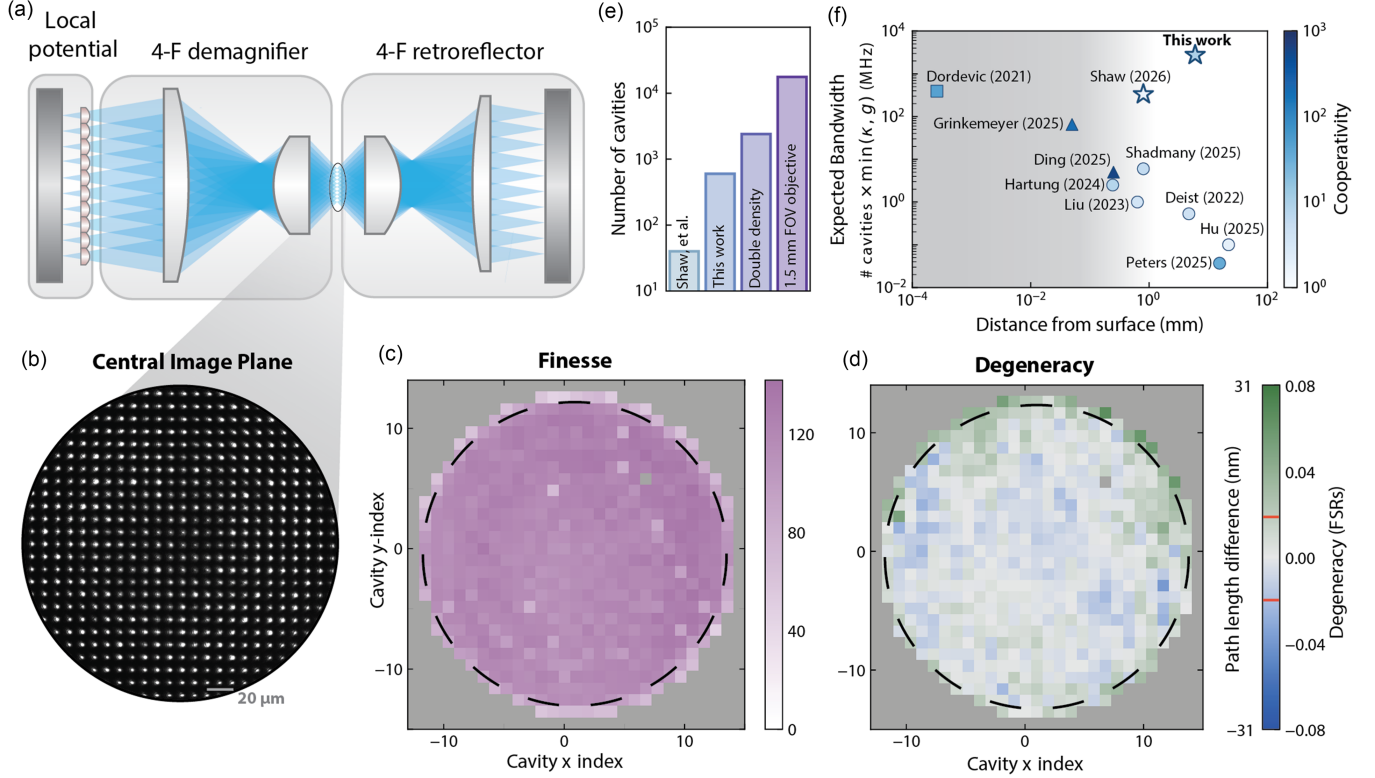


FIG. 1. Summary of results. (a) The CAM is an optical imaging system that generates a 2D array of independent, simultaneously resonant optical cavities with wavelength-scale mode waists and mode spacings. (b) Cavity transmission for hundreds of simultaneously driven individual cavity modes. (c),(d) We demonstrate a cavity array microscope with > 600 cavities and an array-averaged finesse of 114(17). When the outcoupling is optimized for collection efficiency (Supplemental Material [29], Sec. E), 537 cavities are degenerate to within the cavity linewidth, indicated by red lines on the color bar. The dashed black circle indicates the field of view of the intracavity optics, beyond which field curvature inhibits stability (Sec. III). The degeneracy of the CAM is interferometrically sensitive to nanometer-scale variations in optical path lengths between cavities due to misalignments, aberrations, stresses, and surface irregularity of various optics. (e) The number of achievable cavities can be increased through simple modifications to the intracavity optics. By doubling the density of the MLA and leveraging a wider field of view microscope objective, the CAM could support tens of thousands of cavities at high cooperativity. (f) We compare the CAM to other state-of-the-art, neutral atom array-compatible resonator geometries on the axes of bandwidth (fastest possible readout and entanglement speed), distance of atoms from dielectric surfaces, and cooperativity. Gray shading is a guide to the eye for distances at which surface charges are potentially deleterious to Rydberg excitation [30]. Stars, cavity array microscopes [18]; squares, nanophotonic cavities [24]; triangles, fiber and micromirror cavities [9,20]; circles: macromirror cavities [15,19,21–23].

was constrained; each cavity mode averaged over two “pixels”; and cavity finesse was low due to several nonideal optical components.

In this work, we present a substantial evolution of the CAM design that overcomes these challenges, creating a scalable, high-performance cavity array interface with over 600 sites [Figs. 1(a) and 1(b)]. We anticipate that this improved architecture will establish the cavity array microscope as a versatile tool for a broad range of fields, from quantum computing and metrology to biological and chemical sensing (Supplemental Material [29], Sec. K). The key performance metrics for the system are its finesse (which at fixed waist determines the cavity cooperativity [1]), the field of view (which determines the number of cavities), and the mutual degeneracy between cavities (which determines whether they can be simultaneously

probed and read out). In this new realization, each of these metrics are improved by an order of magnitude. Besides these direct quantitative improvements, we uncover the sources of error and aberration which limit each performance metric and elucidate clear pathways to eliminate them.

Specifically, we obtain an average finesse of 114(17) across 603 cavities [Fig. 1(c)], limited by coating losses and surface roughness of various optics. Paired with our nominal waist of 1.15 μm , this corresponds to an array-averaged single-atom peak cooperativity $C > 10$. The field of view of the CAM is 140 μm (radius), determined by the numerical aperture (NA) required to achieve the expected waist and limited primarily by field curvature produced by the intracavity aspheric lens. Lastly, we achieve 537 cavities mutually degenerate within the readout-optimized

cavity linewidth, wherein the transmission of the out-coupling mirror is increased, at the expense of cooperativity, to maximize the total efficiency of photons collected and outcoupled through the cavity [Fig. 1(d) and Supplemental Material [29], Sec. E]. The residual non-degeneracy is due to surface irregularity and stress on optics that results in nanometer-scale optical path length variations, which we identify through novel optical characterization techniques enabled by the CAM. With straightforward optics replacements, we project that the CAM can be scaled to tens of thousands of cavities [Fig. 1(e)]—on par with the largest neutral atom arrays [31–33].

Perhaps the biggest strength of our cavity design is its inherent scalability—both in the raw number of sites as well as in our novel scheme for tuning all cavities to degeneracy through control over just a few degrees of freedom. Because of this high degree of parallelization, we envision the cavity array microscope as an ideal platform for quantum networking. We compare the projected performance of our system in terms of information bandwidth (defined as the number of cavities multiplied by the minimum of the cavity linewidth and cavity coupling, which limit the atom-photon entanglement rate) against other recent optical cavity designs [Fig. 1(f)], predicting a state-of-the-art bandwidth while maintaining high cooperativity and keeping atoms far from dielectric surfaces. This latter point is important, as the short lengths, and, thus, small atom-surface separation of typical highly performant cavities, increase susceptibility to surface charges and, thus, decoherence of Rydberg atom operations [30]. In contrast, our long working distance aspheric lenses realize a large 5.7-mm atom-surface separation. Thus, we expect the cavity array microscope to provide a viable path toward gigahertz-scale entangling rates, with the full capabilities of neutral atom quantum processors.

In the following sections, we detail the capabilities and limitations of the cavity array microscope: In Sec. II, we describe the experimental setup, paraxial cavity array stability, and design considerations; in Sec. III, we combine data with numerics to understand the impact of field curvature on the cavity field of view; in Sec. IV, we catalog the sources of loss that impact the cavity finesse; finally, in Sec. V, we identify sources of nondegeneracy, assess sensitivity to misalignment, and project achievable performance.

II. CAVITY ARRAY DESIGN

Because the CAM is constructed with multiple intra-cavity optics, it offers a highly configurable design space that can be customized to suit a multitude of applications, with flexible control of resonator length, cavity mode spacing, and mode waist. In this realization, we employ a combination of off-the-shelf and custom optics to construct a CAM optimized to interface with a 2D neutral atom array in its central image plane. Here, we detail both

TABLE I. Typical parameters of the cavity array microscope. Values in parentheses denote the standard deviation of array-averaged quantities. The mode waist is extracted from paraxial $ABCD$ -matrix calculations. Direct measurements of comparable λ -scale waists in related resonator geometries have been shown to agree with paraxial $ABCD$ -matrix predictions within experimental uncertainty [15,18].

Mean parameter	Value	Unit
FSR	143.8	MHz
g —for ^{87}Rb cycling transition	$2\pi \times 4.4$	MHz
κ —array averaged	$2\pi \times 1.26$	MHz
Finesse—max	145	
Finesse—array averaged	114(17)	
Waist—central focal plane	1.15	μm
Pitch—central focal plane	10	μm
Length	1.0424	m
Achieved no. cavities	603	
Geometric cooperativity—array averaged	10.2	
Projected collection efficiency (Supplemental Material [29], Sec. E)	53	%

the experimental parameters of this CAM as well as the heuristics for customizing it to a generic set of design constraints. See Table I for a summary of cavity parameters.

A. Experimental setup

The CAM has three primary components: (i) the micro-lens array (MLA), which acts as an array of optical potential wells, each defining a local ray axis that returns to itself under a round trip through the cavity, and about which a family of paraxial TEM cavity modes can be expanded [34], (ii) a primary demagnifying telescope that images the plane of the MLA into the central image plane where we plan to couple to an array of single atoms, and (iii) a secondary retroreflecting telescope that reimages the central image plane back to itself, thus avoiding the need for a mirror in the plane where the atoms will ultimately reside [Fig. 1(a)]. For an ideal set of lenses, this setup creates an array of cavities with identical mode waists and transverse mode spectra, where the waists are spatially separated yet tightly spaced in the central image plane [Fig. 1(b)].

The principal design criteria for the CAM are the size and spacing of the mode waists. The spacing between mode waists is intuitively the demagnified MLA pitch, while the waist size is set by an effective “short” cavity consisting of the MLA and subsequent end mirror [Fig. 3(a)]. The waist size, thus, depends upon the MLA focal length f_{MLA} , the demagnification M of the primary telescope, and the MLA–end mirror distance Δd_{Mirror} . When the distance between the mirror and MLA is exactly $\Delta d_{\text{Mirror}} = f_{\text{MLA}}/2$, the

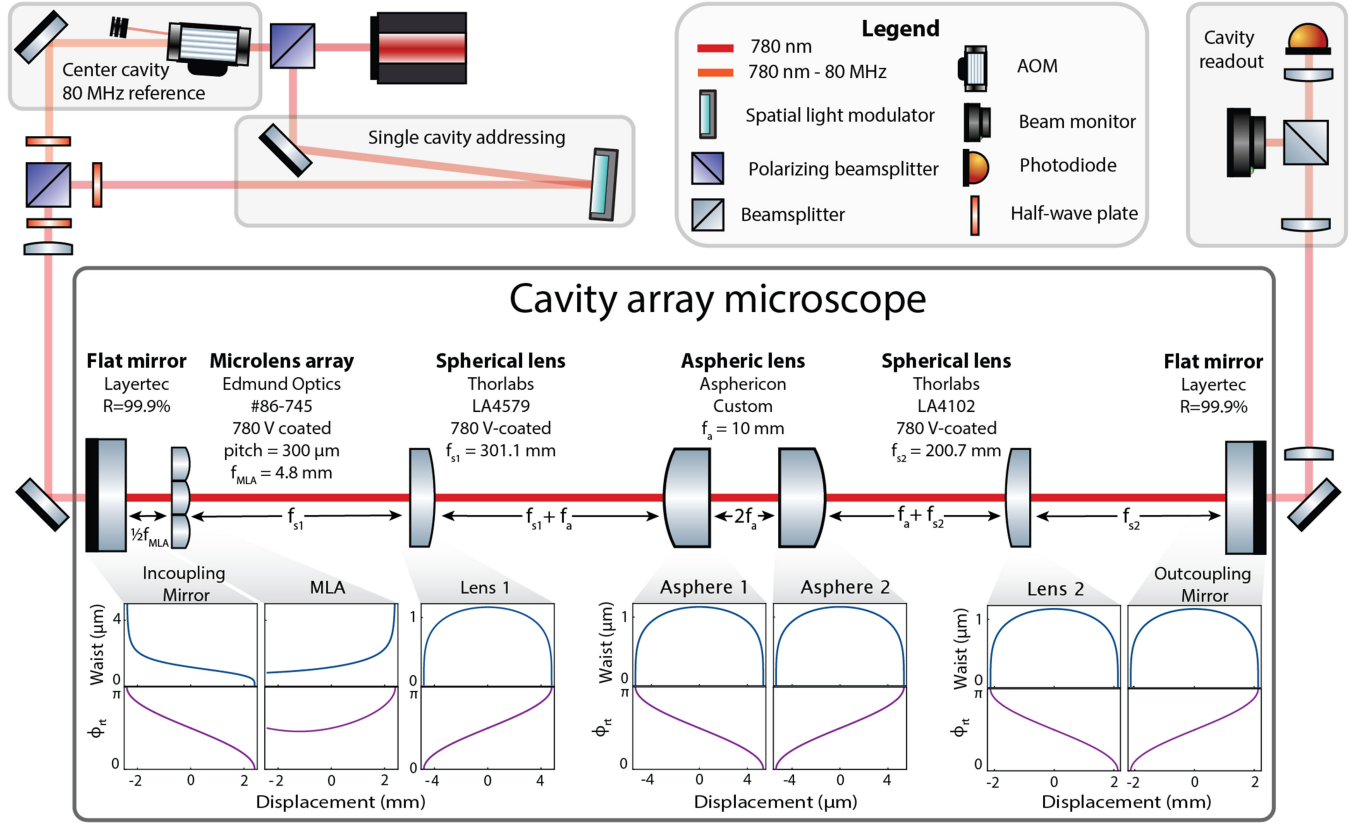


FIG. 2. Experimental setup. Our experimental realization of the CAM contains both off-the-shelf and custom optical elements. An SLM is used to couple serially into each cavity in the array. The central cavity can be separately driven using light detuned by 80 MHz relative to the SLM path, enabling characterization of the relative degeneracy of different cavities to less than the cavity linewidth. All cavities are read out using a shared avalanche photodiode. Lower: paraxial stability diagrams for the central cavity, plotting the smallest waist and round-trip Gouy phase (ϕ_{rt}) as a function of displacements of each optic from its optimal telescopic position (indicated in the cavity schematic). The stability of all cavities in the array can be approximated by a paraxial model of the central “on-axis” cavity. The aspheric lens is the most sensitive optic, with its stability region spanning only 11 μm of longitudinal displacement.

mode waist in the central image plane can be written analytically as

$$w_0 = \frac{1}{M} \sqrt{\frac{\lambda \times f_{\text{MLA}}}{\pi}} \quad (1)$$

(derivation detailed in the following subsection). We can understand this expression as the intrinsic waist set by the chosen focal length of the MLA, with an additional demagnification factor.

For our CAM, we use an MLA with a 4.8-mm focal length and 300- μm pitch, which sets an intrinsic waist of $\sqrt{\lambda \times f_{\text{MLA}}/\pi} = 35 \mu\text{m}$. We choose this short MLA focal length in order to reduce the required telescope magnification. Next, we use a 30 $\times$ demagnifying primary telescope to shrink the mode waist to 1.15 μm and the mode spacing to 10 μm . For this telescope, we employ a 300-mm focal length spherical lens paired with a 10-mm focal length high-NA aspheric lens [35] with a relatively large, 5.7-mm working distance. Finally, we complete the cavity with a 20 $\times$ retroreflecting secondary telescope composed of the

same high-NA aspheric lens and a 200-mm spherical lens (Fig. 2). While the magnification of the primary telescope is chosen in conjunction with f_{MLA} to set the cavity mode waist, the secondary telescope is unconstrained—without a microlens array on that side, the paraxial round-trip $ABCD$ matrix of the secondary telescope is just the identity and consequently has no impact on the mode waist of the central image plane. At 20 $\times$, the magnified side of the telescope is relatively low NA, which allows us to use low-loss spherical optics without significant impacts from spherical aberration (Supplemental Material [29], Sec. B).

To better understand the sensitivity of the mode waist to misalignment of various optics, we create a paraxial model describing the central cavity of the CAM. Using this model, we compute the mode waist and Gouy phase with respect to longitudinal displacements of each optic from its ideal telescopic position (Fig. 2, lower) and find that the waist is either quadratically insensitive to perturbations (for most optics) or minimally sensitive to perturbations over millimeter length scales (for the incoupling mirror and the MLA). These calculations also reveal a narrow stability

region for the aspheric lens—nearly 3 orders of magnitude smaller than that of any other optic. This means that the CAM's constituent cavities are particularly sensitive to micrometer-scale drifts in the asphere axial positions, as well as optical aberrations that cause micrometer-scale distortions to the asphere's focal plane (Sec. III). In practice, we find negligible axial drifts over week-long timescales (Supplemental Material [29], Sec. H).

In order to measure the performance of the CAM, we sequentially excite the cavities using a spatial light modulator (SLM) and read out the resulting spectra with a shared avalanche photodiode. For finesse measurements, the cavities are excited using a narrow (< 1 kHz) linewidth, 780-nm laser, while a piezo sweeps the incoupling mirror through multiple cavity free spectral ranges (FSRs). Because the motion of the piezo interferes with the measurement of the CAM degeneracy, the degeneracy measurements are instead performed with a laser whose frequency is swept across many cavity FSRs. For the degeneracy measurements, we also add a beam permanently coupled into the central cavity that is shifted by 80 MHz relative to the SLM beam, serving as a static frequency reference (further details in Sec. V).

B. Design heuristics

In Eq. (1) of the previous section, we showed that the mode waist of the CAM is set by f_{MLA} and M , as long as $\Delta d_{\text{Mirror}} = f_{\text{MLA}}/2$. In this section, we derive Eq. (1) and generalize our understanding to different values of Δd_{Mirror} by systematically reducing the CAM's physics to that of a simple two-mirror cavity. Finally, we explain how Δd_{Mirror} can be tuned in conjunction with the asphere position to select a maximum mode waist for the CAM.

To derive Eq. (1), we begin with the constraints enforced by the CAM's $4f$ telescopes; the primary demagnifying telescope sets a linear relationship for both the mode sizes and mode spacings between the plane of the MLA and central image plane: $w_0 = w_{\text{MLA}}/M$, where w_{MLA} is the mode size at the MLA, w_0 is the mode waist, and M is the telescope magnification. Importantly, $4f$ telescopes are imaging systems which return rays exactly onto themselves after a double pass: The action of a round trip through the two $4f$ telescopes is equal to an identity matrix in the $ABCD$ -matrix formulation [36]. As such, we can create a model of the CAM that removes the $4f$ telescopes and replaces them with a “virtual” end mirror right behind the MLA without changing the (paraxial) behavior of the light rays. The combination of virtual end mirror and MLA acts identically to a micromirror array with mirror radii of curvature $R = f_{\text{MLA}}$, allowing us to effectively reduce the CAM to an array of half-planar two-mirror cavities each consisting of the planar incoupling mirror and an $R = f_{\text{MLA}}$ curved mirror [Fig. 3(a)].

The stability diagram of half-planar cavities is simple—depending only on the mirror spacing and radius of

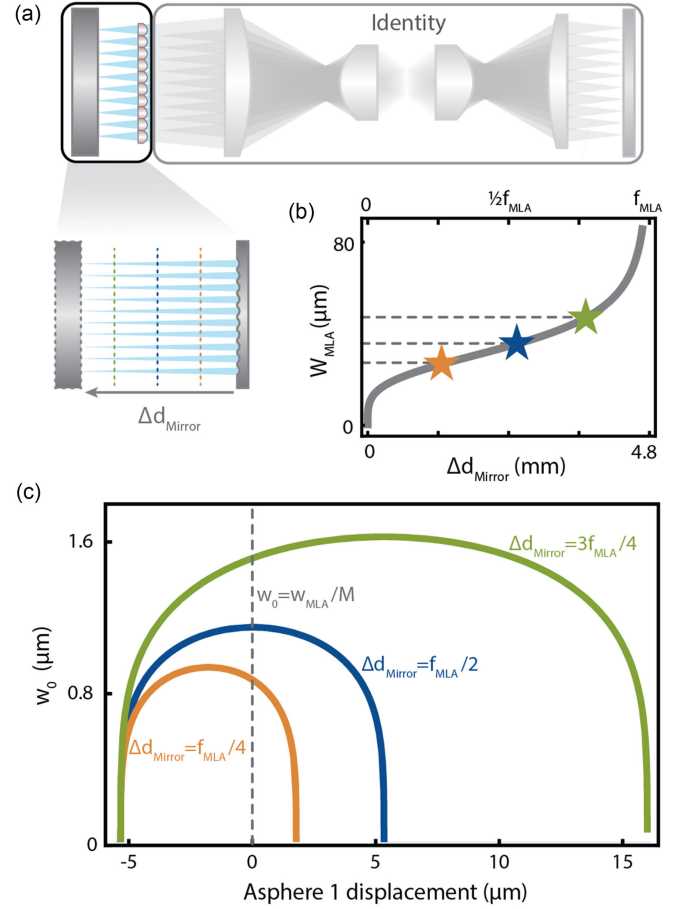


FIG. 3. Cavity mode waist. (a) The two $4f$ telescopes of the CAM have the action of the identity on an incoming ray (in the $ABCD$ -matrix formalism), which means that the CAM can be reduced to an effective two-mirror cavity consisting of the planar end mirror and a curved micromirror array. (b) In this effective cavity picture, the mode size at the micromirror array (and MLA) increases monotonically as Δd_{Mirror} is swept from zero to f_{MLA} . (c) Asphere stability diagrams at three values of Δd_{Mirror} , illustrating that Δd_{Mirror} fixes the maximum size of the cavity mode waist (as the asphere separation is varied). At zero asphere defocus (dashed line), the mode waist is exactly equal to w_{MLA}/M .

curvature [36]. For a spacing of $\Delta d_{\text{Mirror}} = f_{\text{MLA}}/2$, the mode waist on the planar mirror is $[f_{\text{MLA}} \times \lambda / (2\pi)]^{1/2}$, and the mode waist on the curved mirror is $w_{\text{MLA}} = (f_{\text{MLA}} \times \lambda / \pi)^{1/2}$. Combining this expression with the telescope demagnification condition yields Eq. (1).

Now we consider what happens when Δd_{Mirror} is adjusted. In the picture of the effective half-planar cavity, when Δd_{Mirror} is close to zero, the mode waist on both mirrors is infinitesimally small. As Δd_{Mirror} is increased, the mode size on the curved mirror grows monotonically, approaching infinity at $L = f_{\text{MLA}}$ [Fig. 3(b)]. Because the $4f$ telescope simply demagnifies the MLA plane, the CAM mode waist in the image plane obeys the same trend with $w_0 = w_{\text{MLA}}/M$.

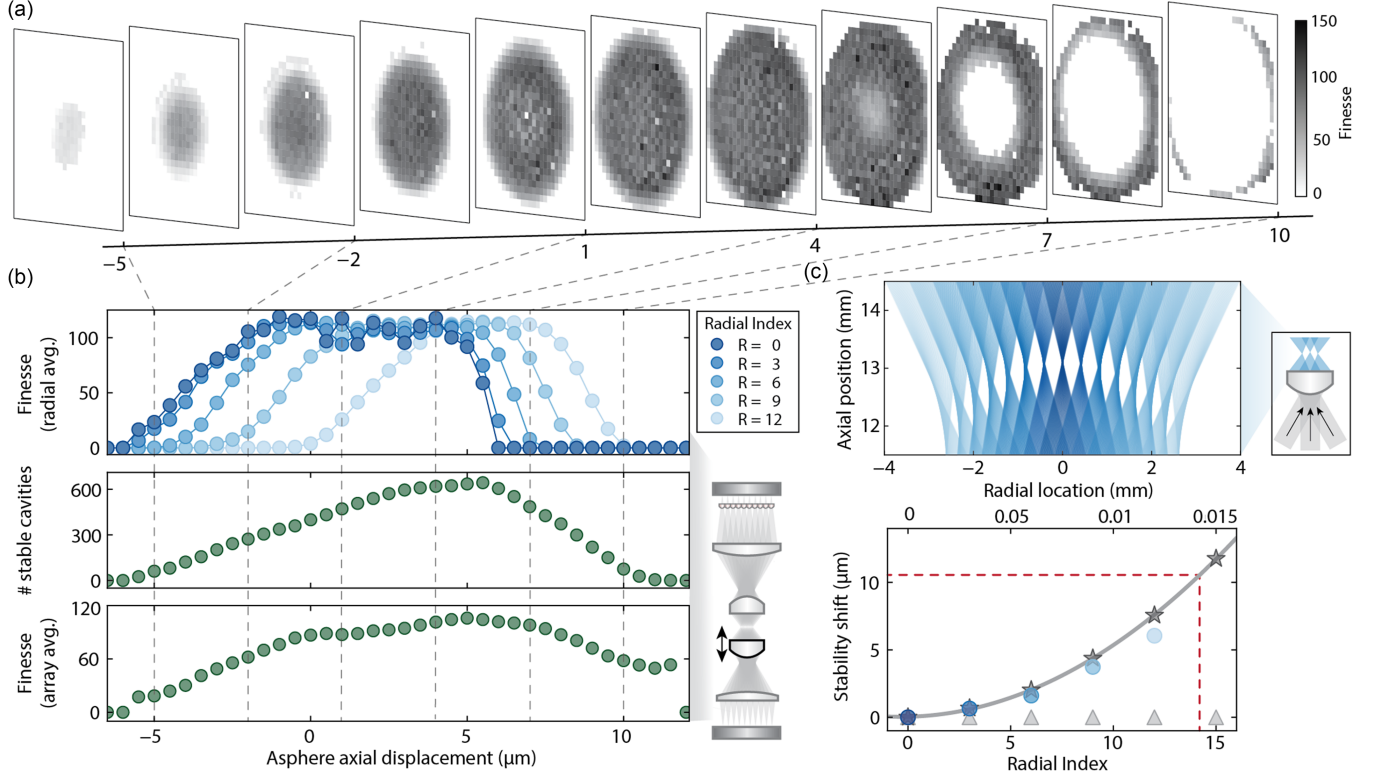


FIG. 4. Field of view. (a),(b) Both (a) the field of view—plotted as an array of cavity finesses—and (b, top) the stability of cavities at a given radial displacement from the central cavity are sensitive to micron-scale longitudinal displacements of the two aspheres. Radially averaged finesse measurements are used as a proxy for assessing the corresponding stability regions, with lines connecting points to guide to the eye. We work at a displacement that simultaneously maximizes both the number of stable cavities (b, middle) and the array-averaged finesse (b, bottom); with further optics development, we anticipate substantial gains in the achievable field of view. (c) The field curvature of the asphere (top) produces a radially dependent, quadratic focal shift which translates the asphere stability regions as a function of radial cavity index, limiting the field of view. Inset: we visualize this curvature by ray tracing tilted plane waves through a single pass of the aspheric lens. Bottom: experimental (circles) and numerically calculated (stars; see Supplemental Material [29], Sec. A) stability diagram shifts align with the expected focal shift from the asphere field curvature (multiplied by 4 for the number of asphere passes per cavity round trip), while numerical calculations using ideal lenses (triangles) exhibit no shift. We attribute the small discrepancy between the experimental data and the numerics to quadratic misalignment aberrations, such as defocus, which add to or subtract from the intrinsic field curvature. Red lines indicate the radial index and stability shift corresponding to the maximum field of view.

Up to this point, we have maintained the telescope in a perfect $4f$ configuration while changing Δd_{Mirror} ; however, it is crucial to understand how displacements of the aspheric lens factor in, since the asphere stability diagram is sensitive over micrometer length scales. In Fig. 3(c), we choose three different values of Δd_{Mirror} and plot the CAM waist with respect to displacements of the aspheric lens. These aspheric lens displacements slightly defocus the $4f$ telescope. At zero defocus, the waist is equal to $w_0 = w_{\text{MLA}}/M$, as expected. However, for $\Delta d_{\text{Mirror}} > f_{\text{MLA}}/2$ ($\Delta d_{\text{Mirror}} < f_{\text{MLA}}/2$), the maximum waist is shifted to a point where the telescope has a slight positive (negative) defocus. It is, thus, possible to choose Δd_{Mirror} to achieve larger (or smaller) cavity mode waists and then longitudinally displace the aspheric lens to a position where this new waist is maximally stable.

It is important to be able to infer this maximum waist when aligning the CAM. Within the paraxial

approximation, the width of the asphere stability diagrams (for longitudinal displacements) is equal to twice the Rayleigh range of the maximum waist. In the lab, this provides a valuable diagnostic tool for quickly inferring the mode waist and corresponding value of Δd_{Mirror} and tuning them to the desired value (Supplemental Material [29], Sec. L).

III. CAVITY FIELD OF VIEW

One of the primary figures of merit for the CAM is its intrinsic field of view (FOV), which we define as the diameter in the central image plane over which simultaneously stable, near-diffraction-limited cavity modes are formed. The number of achievable cavities is related to the field of view as $N_{\text{cavities}} \approx \pi(d_{\text{FOV}}/2d_0)^2$, where d_0 is the spacing of the mode waists in the central image plane.

In this realization, the intrinsic FOV (d_{FOV}) is limited to 280 μm (corresponding to approximately 615 cavities) by the field curvature of the aspheric lens, discussed below, while the total observable set of cavities is physically limited to a diameter of 300 μm due to a ring piezo on the incoupling mirror. We expect that the intrinsic field of view can be greatly expanded by using wide field of view, high-NA microscope objectives in place of the aspheric lenses [33].

In the previous section, we characterized the stability of the central cavity with respect to perturbations of the CAM's most sensitive optic—the aspheric lens. Here, we use this method to experimentally and numerically extract stability regions for all cavities in the CAM. In Fig. 4(a), we plot the CAM field of view for a set of aspheric lens longitudinal displacements over a range of 18 μm . Strikingly, we observe that the central cavities become stable first, followed by those at larger radial indices. After a displacement of 11 μm —equal to the expected width of the stability region—the central cavities become unstable, leaving a ringlike structure that gets thinner as the innermost cavities become unstable. Radially averaged slices of these data explicitly show these shifted stability regions [Fig. 4(b), top]. To determine the ideal operating point of the CAM, we plot the number of stable cavities and array-averaged finesse [Fig. 4(b), middle and bottom], finding that the array-averaged finesse and number of cavities are maximized at similar aspheric lens displacements, corresponding to the point right before the central and outermost stability regions become nonoverlapping.

In order to quantitatively understand the source of the radially dependent stability shifts, we performed a set of numerical ray-traced simulations of the CAM [Fig. 4(c), bottom]. For a CAM composed of ideal lenses, no stability shift is observed (triangles); in contrast, simulations incorporating realistic aspheres (stars) exhibit a stability shift consistent with the experimentally measured stability shifts (circles), with residual deviations attributable to additional first-order aberrations, such as defocus, which arise from alignment imperfections rather than from intrinsic properties of the system. Other aberrations, including astigmatism and spherical aberration, are found in our numerics to have a negligible impact (Supplemental Material [29], Secs. C and B).

The stability shifts uncovered by these numerics are attributable to the field curvature of the aspheric lenses, illustrated in the top in Fig. 4(c). The numerically calculated stability shifts quantitatively follow the single-pass ray-traced field curvature of the asphere, multiplied by the number of passes through the aspheric lens per round trip [Fig. 4(c), bottom, solid gray line]. Within the CAM, multiple round trips through the optics constrain all cavity waists to lie in a flat central image plane, and, thus, the asphere field curvature instead manifests as shifts to

individual cavity stability regions which ultimately limit the CAM field of view.

In order to expand the CAM field of view and avoid the deleterious effects of field curvature, the aspheres could be replaced with high-NA, wide field of view microscope objectives. Such objectives would have a few unique design constraints: (i) The single-pass loss should be kept below 1% to ensure high cavity array finesse; and (ii) beyond maintaining a flat focal plane, the objective must ensure equal absolute path lengths to all field points, as is required for the degeneracy condition (Sec. V). High-NA objectives in typical atom array experiments are already designed to provide diffraction-limited performance with submicron field curvature across their specified field of view. With minimal additional design, we anticipate that a 1.5-mm field of view objective at 10- μm spacing could realize over 17 000 simultaneously resonant cavities, with uniform mode waists, provided that the loss condition can be met [33].

IV. CAVITY FINESSE

Finesse is one of the primary figures of merit of the CAM, determining, for a fixed waist, the cavity cooperativity and, thus, the light collection efficiency [1]. In this section, we take a detailed look at the observed and expected cavity losses and their cavity-to-cavity variation.

Because of the CAM's constituent intracavity optics, there are a multitude of potential sources of loss that can degrade the finesse, including scattering from surface roughness, specular reflection and absorption from antireflective (AR) coatings, clipping on lens apertures, and dust. Here, we catalog losses from each optic, finding that AR coating and scattering losses dominate, and then detail strategies for mitigating these sources and others.

In Table II, we summarize the measured and predicted losses for each intracavity optic as well as across the array. The experimentally measured average round-trip loss per cavity is 5.3%, corresponding to the array-averaged finesse of 114. However, there are individual cavities with poor performance, which we attribute to dust, local imperfections on the MLA and mirrors, and radially dependent clipping loss (most prominent for cavities operated near the edge of their stability region). In order to disambiguate the intrinsic losses (due to AR coatings and surface roughness) from the extrinsic losses (due to dust and clipping), we identify the cavity with the highest finesse (145) and use its corresponding loss (4.2%) as a baseline for comparison against expected coating and scattering losses.

We compute the intrinsic loss using two methods: first, from a combination of the manufacturer-provided AR coating curves and calculated scattering loss due to surface roughness; second, from a direct measurement of the loss of each intracavity optic by placing it inside of a simple two-mirror “characterization” cavity of known finesse. We combine these losses to obtain an elementwise total

TABLE II. Cavity loss budget. Single-pass loss from each individual optic is listed, alongside the number of passes for one cavity round trip. The “measured” loss of each intracavity optic was determined by placing it between two highly reflective end mirrors and measuring the resulting finesse at low NA. The loss from the end mirrors was provided by the manufacturer. The “expected” loss was calculated from the manufacturer-provided AR coating reflectivity and from scattering losses. Scattering loss was calculated via the normal-incidence total integrated scatter in transmission [37]: $TIS \approx \{[(2\pi\sigma)/\lambda](n-1)\}^2$ with $\lambda = 780$ nm, where σ is the rms surface irregularity given by the manufacturer. The surface roughness from all spherical optics is subnanometer and, thus, negligible. Total elementwise losses are calculated as $1 - \prod_i (1 - l_i)^p$, where l_i is the component loss and p is the number of passes.

Optic	Measured loss (%)	Expected loss (%)	Passes
Incoupling mirror	0.1	0.1	1
Microlens array	0.1	0	2
Spherical lens 1	0.07	0	2
Aspheric lens 1	0.8	0.42	2
Aspheric lens 2	0.8	0.42	2
Spherical lens 2	0.07	0	2
Outcoupling mirror	0.1	0.1	1
Total (elementwise)	3.8	1.9	
Total (from peak finesse)	4.2		
Total (from array-averaged finesse)	5.3		

measured loss of 3.8% (Table II). We find that the elementwise loss is consistent with the measured peak finesse, differing by a small amount (0.4%) which could be accounted for by minimal dust accumulation on the intracavity lenses or imperfect alignment of the full composite system.

The predominant source of loss in the CAM comes from the intracavity aspheric lenses, which each have 0.8% measured single-pass loss and, thus, account for more than three-quarters of the total intracavity loss. About half of this loss can be explained from the manufacturer-provided AR coating reflectivity and surface roughness (Table II). We suspect that the remaining 0.4% loss comes from nonidealities in the AR coating, as the aspheric lenses are highly curved, which makes it difficult to both deposit a coating with uniform thickness and ensure stable performance across all angles of incidence.

In addition to the aspheric lenses, a small amount of loss is added by the other intracavity optics—the two spherical lenses and the MLA. These spherical optics have negligible scattering loss due to their exceptionally low surface roughness. Each of these optics are coated with a high-quality antireflective V coating centered at 780 nm. In theory, these coatings have zero reflectance at their design

wavelength; however, in practice, we measure 0.07% single-pass loss for the spherical lenses and 0.1% loss for the MLA.

Degradation from dust is also a major concern. For cavity optics in the multiple image planes of the CAM, such as the end mirrors and MLA, dust and imperfections result in isolated cavities with low finesse. For cavity optics in and near Fourier planes, including the aspheric and spherical lenses, dust impacts all cavities to a similar degree because the cavity modes at the lenses are large and overlapping. To minimize loss from dust, we find that a positive pressure, HEPA-filtered enclosure is sufficient to avoid noticeable degradation over months-long time periods. Without HEPA-filtered air, we observe the array-averaged loss of the CAM increase by several percent in just a couple weeks. Fortunately, the optics can be cleaned and restored to their initial performance with standard cleaning techniques [38].

A final source of loss in the CAM is clipping on the apertures of the intracavity optics. In the design of the CAM, we take precautions to minimize total clipping losses to $< 0.1\%$, a small amount compared to the total 5.3% array-averaged loss. The primary source of clipping loss is the high-NA asphere. Keeping the total clipping loss to a sub-0.1% level requires choosing a mode waist such that the $1/e^2$ mode diameter at the lens is no larger than half of the lens diameter. For our $NA = 0.55$ asphere, a mode waist around $1 \mu\text{m}$ is an optimum below which clipping losses begin to significantly degrade the finesse. Poor alignment of the CAM can also contribute to additional clipping loss and can be mitigated through careful alignment according to the procedure detailed in Supplemental Material [29], Sec. L.

There are several ways in which careful selection of the intracavity optics could further reduce the amount of intrinsic loss. For the aspheric lens, a high-index glass could be used to reduce its curvature, making it possible to coat the asphere with a more performant AR coating—though such glasses often have high absorption. For applications that can tolerate larger mode waists, the aspheric lenses could even be replaced by spherical lenses which can have losses below 0.1%. For applications requiring small mode waists and large fields of view, we believe that an intracavity high-NA microscope objective consisting of V-coated or nanotextured optics could achieve sub-1% loss, similar to that of our asphere. Finally, losses due to the MLA could be eliminated entirely through a slight modification of the CAM geometry: replacing the incoupling mirror and microlens array with a micromirror array [9]. With these further improvements in optic design and AR coatings, we expect that total losses could be reduced to approximately 1.5%, corresponding to array-averaged finessses over 400 and a $3.5\times$ improvement in cooperativity.

V. CAVITY DEGENERACY

Besides the number of cavities and their finesses, the third figure of merit for the CAM is the array degeneracy, or the degree to which all cavities can be made simultaneously resonant. The cavity frequency is controlled by the round-trip optical path length of each cavity's local axis and Gouy phase. In particular, the shift in resonance frequency between a cavity with indices (i, j) and the central one depends on both the change in one-way optical path length $\Delta L(i, j)$, as well as on the difference in round-trip Gouy phase $\Delta\phi_{\pi}(i, j)$:

$$\Delta\nu = \nu_{\text{FSR}} \left(\frac{1}{\pi} \Delta\phi_{\pi} - \frac{2\Delta L}{\lambda} \right). \quad (2)$$

Experimentally, this is measured as the fractional detuning, $\Delta_m(i, j) = \Delta\nu/\nu_{\text{FSR}}$.

One of the principal benefits of the CAM architecture is that simultaneous resonance can be achieved purely by proper positioning of the intracavity optics, without explicit requirements for local cavity control. For a CAM with ideal optical components, this condition is met when all lenses are perfectly centered transversely along the same optical axis and when the aspheric and spherical lenses are positioned longitudinally in a perfect telescope configuration. This is the case because, in the paraxial approximation, a $4f$ imaging system not only images points to points, but also plane waves to plane waves, thereby ensuring that all path lengths through the system are equal.

In practice, various nonidealities break this condition. Misalignments of the various cavity optics can change the relative optical path lengths in predictable ways. For instance, if one of the end mirrors is tilted, or if one of the spherical lenses is transversely offset from the optical axis, then a linear detuning gradient will be applied across the array. Similarly, aberrations in optics arising from surface irregularity or mounting stress can lead to differences in path length [Fig. 5(a)]. Finally, the Gouy phase variation across the array is a substantial fraction of π resulting in an additional radially dependent frequency shift (Supplemental Material [29], Sec. D).

We interrogate the cavity degeneracy with a fixed excitation beam coupled into the central cavity and a variable excitation beam controlled with an SLM [Figs. 2 and 5(b)]. The fixed excitation beam is detuned from the SLM beam by 80 MHz (approximately half the FSR), and the relative powers are tuned such that the two drives are unambiguously distinguishable on simultaneous photodiode measurements of the cavity transmission [Fig. 5(b)]. From this photodiode signal, we can extract the relative cavity detuning, and by addressing different cavities across the array with the SLM we can measure the detuning across the entire array modulo the cavity FSR. Intentionally misaligning an optic (e.g., tilting an end mirror) or using a known-astigmatic end mirror produces detuning maps reflecting the expected aberration [Figs. 5(c) and 5(d)]. Crucially, we are able to decompose

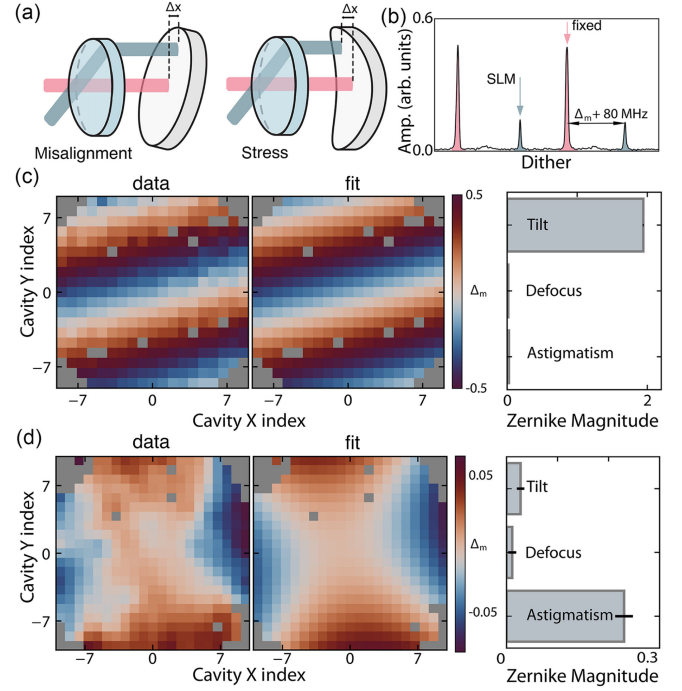


FIG. 5. Degeneracy characterization. (a) The degeneracy of the CAM is sensitive to perturbations that change the relative round-trip optical path length of the individual cavities in the array. Such perturbations can, for instance, arise from misalignments of various intracavity optics or from imperfections of their surfaces, such as stress or form error of the end mirrors. (b) To characterize these effects, we measure the fractional detuning Δ_m of each cavity (blue) relative to the central cavity (red). (c) Transverse misalignment of the spherical lens produces a linear gradient of detunings across the array, while (d) a mechanically stressed end mirror produces astigmatism across the array. We distinguish these effects by decomposing the map of detunings into a sum of Zernike polynomials (with one-site Gaussian smoothing applied on the data), allowing quantitative evaluation of aberrations, order by order. Error bars denote the bootstrapped standard error of the fitted Zernike coefficients.

these detuning maps into a sum of low-order Zernike polynomials, thereby quantitatively identifying the degree to which different aberrations affect the array degeneracy [Figs. 5(c) and 5(d), right].

Ultimately, by carefully controlling optic alignments and aberrations, we are able to realize hundreds of simultaneously degenerate cavities, detuned by less than the optimal outcoupling linewidth [Fig. 1(d)]. In the following, we describe in detail the techniques and heuristics we employ to perform this optimization, the sensitivity to misalignments, and the means by which we can use the CAM to identify aberrations in its own optics at the nanometer scale.

A. Misalignments of the cavity imaging system

Achieving degeneracy across hundreds of cavities requires precise positioning of the optics in the CAM's

$4f$ telescopes. As illustrated in Fig. 6(a), transverse and longitudinal misalignments of the CAM's spherical lens induce linear (tilt) and quadratic (defocus) nondegeneracies. Other degrees of freedom, such as end mirror tip and tilt, affect the degeneracy in a similar manner—in fact, we observe that all misalignment-induced nondegeneracy is predominantly linear and quadratic. This means that, after careful prealignment of all optics (Supplemental Material [29], Sec. L), small residual nondegeneracies can be compensated entirely with the spherical lens position, regardless of the culpable optic.

This compensation is also important for correcting the fractional detuning induced by differential Gouy phases across the array. The Gouy phase varies radially through a significant fraction of π due to the fact that we increase the size of our array by maximizing the set of cavities with intersecting stability regions. The resulting spread of Gouy phases is approximately quadratic with radial index and can, therefore, be corrected via millimeter-scale longitudinal adjustments of the spherical lenses (Supplemental Material [29], Sec. D). We note, however, that the possible negative effects of an overreliance on this compensation are not fully explored. In the following, we hone in on the misalignment-induced nondegeneracies—deriving their analytical form, assessing their positional tolerance, and elucidating the surprising impact of the MLA on the degeneracy landscape.

Misalignment-induced nondegeneracies arise due to small optical path length differences across the CAM. In order to better understand these, we derive a paraxial model of fractional detuning Δ_m (assuming zero differential Gouy phase), as a function of both transverse ($\delta_{\mathbf{r}} = \delta_x \hat{\mathbf{x}} + \delta_y \hat{\mathbf{y}}$) and longitudinal (δ_z) displacements of the demagnifying, $f = 300$ mm, spherical lens from its ideal telescope position. We compute Δ_m for a generalized off-axis cavity indexed by (i, j) , located at a transverse position $\mathbf{r} = p_{\text{MLA}}(i\hat{\mathbf{x}} + j\hat{\mathbf{y}})$ in the image plane of the spherical lens, where p_{MLA} is the MLA pitch. This yields

$$\Delta_m(\delta_{\mathbf{r}}, \delta_z, \mathbf{r}) = \frac{1}{\lambda f} \left(\frac{\delta_z \|\mathbf{r}\|^2}{f} - 2\delta_{\mathbf{r}} \cdot \mathbf{r} \right) \quad (3)$$

for a spherical lens of focal length f . Equation (3) is consistent with our observation that longitudinal misalignments (δ_z) of the spherical lens result in quadratic nondegeneracies across the array, while transverse misalignments produce linear nondegeneracies [Fig. 6(a)]. Moreover, the dependence on $\mathbf{r}$ indicates that cavities located further from the central optical axis are increasingly sensitive to misalignment. These results define a set of alignment tolerances specifying the maximum allowable lens displacement (δ_x , δ_y , and δ_z) before a given cavity becomes detuned from the central cavity by one linewidth. We obtain closed-form expressions for the

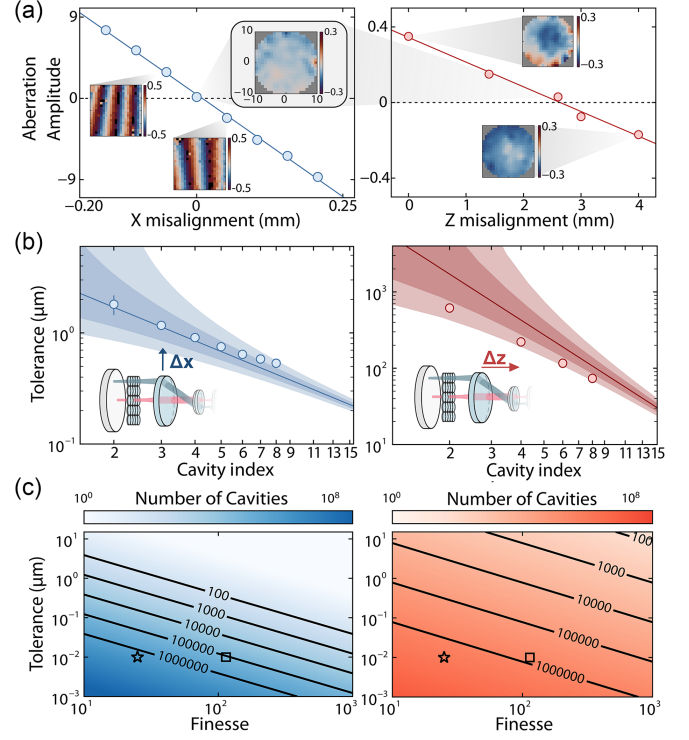


FIG. 6. Positioning of the intracavity optics. (a) Achieving a degenerate CAM requires precise alignment of intracavity optics. Transverse (left) or longitudinal (right) misalignments of the $f = 300$ mm spherical lens produce linear (i.e., “tilt”) or quadratic (i.e., “defocus”) variations, respectively, in the round-trip optical path length across the array, observed as variations in site frequencies. We fit each detuning map using Zernike polynomials, plotting the dominant Zernike coefficient as a function of lens displacement and operating where the coefficient crosses zero for all axes. For visual clarity, the inset detuning maps are displayed with one-site Gaussian smoothing. (b) Positional tolerance (microns of spherical lens transverse and longitudinal displacement required to shift the relative cavity detuning by one linewidth) as a function of cavity x index (i , with $j = 0$). The solid line indicates the theoretical model developed in Eq. (4) with the shaded region indicating the range of deviation that would occur if the chosen center cavity differed from the central optical axis by ± 1 (dark red and blue, respectively) or ± 2 (light red and blue, respectively) cavity sites. Error bars on individual data points denote propagated uncertainties from the fitted slope of detuning versus lens displacement. (c) The number of cavities that can be made simultaneously resonant depends on the tolerance with which the spherical lens can be positioned and the cavity finesse. At our array-averaged finesse of 114, and with the 10-nm precision of our translation stage (Thorlabs MAX381), this corresponds to over $> 10^5$ cavities (square). For the readout-optimized linewidth (Supplemental Material [29], Sec. E), this corresponds to $> 10^6$ cavities (star).

spherical lens positional tolerance per fractional linewidth by separately considering each term in Eq. (3), solving for $\delta_{x,y,z}$ and normalizing by the array-averaged finesse, $F = 114$:

$$(\delta_x, \delta_y, \delta_z) = \frac{\lambda f}{F} \left(\frac{1}{2p_{\text{MLA}} \times i}, \frac{1}{2p_{\text{MLA}} \times j}, \frac{f}{\|\mathbf{r}\|^2} \right). \quad (4)$$

In Fig. 6(b), we experimentally measure this tolerance as a function of cavity x index (i , with $j = 0$) for both transverse and longitudinal displacements of the spherical lens. The dashed line indicates the theoretical tolerance predicted by Eq. (4), while the shaded region denotes the associated uncertainty arising from a potential offset between the chosen central cavity and optical axis of up to ± 1 cavity site. Additionally, the low sensitivity of the degeneracy to z displacements means that the coupling between axes can result in a lower measured tolerance than theoretically predicted (Supplemental Material [29], Sec. G).

These tolerance plots provide insights into the conditions required to operate at degeneracy, showing that, in order to stabilize this 600-cavity CAM to degeneracy, the spherical lens transverse position must be controlled to within 300 nm, while the longitudinal position needs to be controlled only to within 10 μm . Such levels of precision are readily achievable using closed loop feedback with precision three-axis piezo stages (e.g., Thorlabs MAX381, which we employ here).

We also investigate the theoretical limit for the number of cavities that can be simultaneously stabilized at degeneracy when limited only by the positional accuracy of our translation stage. As illustrated in Fig. 6(c), this fundamental limit is over 10^5 cavities (and $> 10^6$ cavities at the ideal outcoupling linewidth), implying that other factors—most notably the CAM field of view—will constrain the achievable number of cavities count well before degeneracy stabilization becomes a limiting factor.

Having determined the required tolerance for the spherical lens positioning, we now identify and characterize the degeneracy condition in further detail. Naively, Eq. (3) suggests that there is a unique degeneracy point where $\Delta_m(0, 0, \mathbf{r}) = 0$ for all cavity positions $\mathbf{r}$. However, due to the periodicity of each cavity's longitudinal mode spectrum, we can distinguish only fractional detunings $\Delta_m(\delta_{\mathbf{r}}, \delta_z, \mathbf{r}) \bmod 1$. This leads to an array of seemingly identical degeneracy points at different displacements of the spherical lens, with the spacing determined by the MLA pitch, lens focal length, and probe wavelength. We experimentally observe this extended grid of degenerate configurations in Fig. 7(a), where each subpanel shows the detuning map for a given transverse displacement (δ_x, δ_y) of the spherical lens (with the longitudinal displacement fixed near $\delta_z = 0$).

To understand the extended grid of degenerate points, we revisit the treatment of the cavities' longitudinal modes. For a set of cavities with identical optical path lengths, the longitudinal spectra across the cavities will be degenerate. However, if the one-way optical path length varies linearly with an integer multiple of $\lambda/2$ between each cavity, they

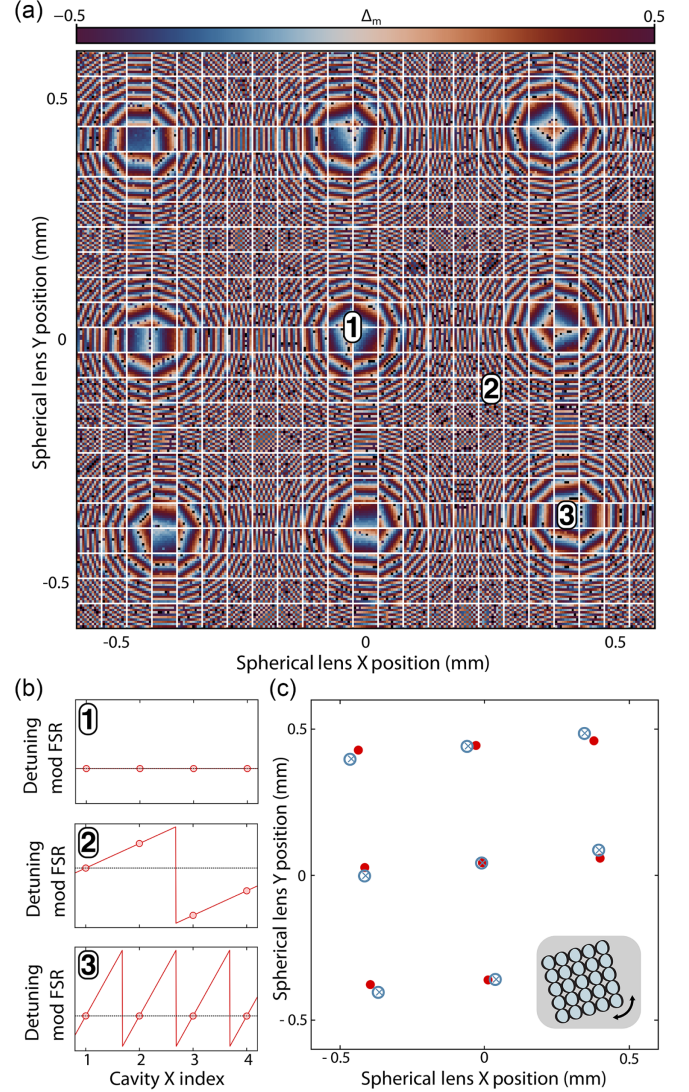


FIG. 7. Aliasing of the degenerate condition. (a) We measure detuning maps for multiple choices of spherical lens displacement along both transverse axes (x , y), revealing a varied landscape: at many lens positions, the array appears degenerate, leading to ambiguity as to what the correct alignment is. (b) We interpret these effects as arising from aliasing due to the finite spacing of the MLA which samples the underlying displacement-induced linear phase gradient, depicted with cartoon plots of detuning mod FSR. (c) To identify the nonaliased alignment, we rotate the MLA and plot the locations of the fitted degeneracy points from (a), both with (blue) and without (red) a four-degree rotation; for the rotated data, we compare the measured degeneracy points (blue crosses) and a rotated prediction (blue open circles) based off the original points in red, finding good agreement. We identify the “true” degeneracy point as the center of rotation about which other “fake” degeneracy points rotate.

will also be degenerate. Thus, the extended grid of degenerate points reflects conditions wherein the magnitude of the linear detuning error induced by the transverse displacement of the spherical lens causes multiples of $\lambda/2$

optical path length variation between adjacent cavities in a grid established by the regular spacing of the MLA [Fig. 7(b)].

To set a reproducible alignment target and mitigate the effect of potential off-axis aberrations, we seek to park the spherical lens at the “true” degenerate point where $\Delta_m(0,0,\mathbf{r}) = 0$ and the central axes of all optics are coaligned. We identify this true degeneracy point by rotating the MLA, thereby changing the spherical lens transverse positions at which the periodic condition above is met. After fitting the positions of the degenerate points for both the rotated and unrotated cases, we see that all of the degenerate points rotate according to the MLA angle about a center point coinciding with the true degeneracy location [Fig. 7(c)]. We park the spherical lens at this location, leaving further investigations of the negative impacts associated with using the other degeneracy points for future studies.

B. Resolving nanometer-scale aberrations

In addition to the bulk adjustments necessary to approach the degeneracy point, residual nondegeneracies arise from imperfections, including stress on optics and surface irregularities which introduce variations in the optical path length between cavities. The CAM is most sensitive to displacements and surface errors of optics located in or near image planes of the circulating light, i.e., where the independent cavity modes are spatially separated, as this causes differential—rather than common-mode—changes in path length.

We study this for the case of a known-aberrated planar mirror for which glue-induced mounting stress leads to tens of nanometers of curvature of the mirror surface. Measuring the map of detunings as described above allows the CAM to directly characterize this surface curvature as residual nondegeneracy once the effects of the bulk misalignments from Fig. 6 have been removed by tuning to degeneracy. After swapping the unstressed planar end mirror for the stressed sample, we measure the detuning map at three rotational orientations of the stressed mirror and extract the resulting rotation of the astigmatism from the fitted Zernike polynomials [as in Fig. 5(d)], finding good agreement between the two (Fig. 8).

We can apply this procedure to analyze general variations in surface profile and aberrations, so long as the aberrated optics are located in or near an image plane of the cavity array (so as to have an impact on the optical path length) and as long as the magnitude of the induced error is larger than the limits on resolution. At an average finesse of $F = 114$, the linewidth of the resonator sets a path length resolution of $[\lambda/(2F)] = 3.4$ nm (smaller than the observed approximately 40-nm peak-to-peak variation of the aberrated mirror) with further limits imposed by residual nondegeneracies from other optics.

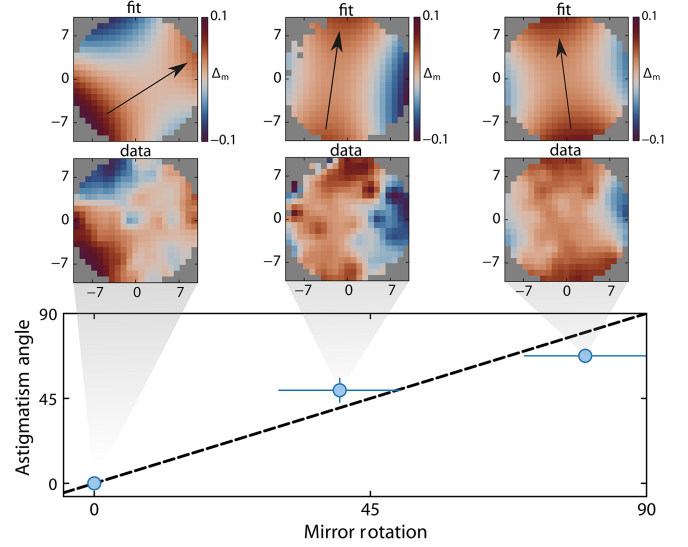


FIG. 8. Measuring cavity degeneracy allows us to evaluate the intrinsic aberrations of specific optics. For instance, we insert a known astigmatic mirror as the end mirror of the cavity and then measure the angle of the fitted astigmatism as the mirror is rotated in place, observing a close correlation. Horizontal error bars denote the uncertainty in the measured mirror rotation angle; vertical error bars denote the standard error propagated from the bootstrapped Zernike astigmatism coefficient.

VI. OUTLOOK

The CAM is a powerful new technology for controlling light-matter interaction across an array of optical cavities. In this paper, we have identified the fundamental mechanisms governing its scalability and demonstrated the largest, most performant CAM to date, with roughly 600 cavities operating with intrinsic finesse greater than 100 and mutual degeneracy within the outcoupling optimized linewidth. Combined with a similarly sized neutral atom quantum processor node, we expect that this architecture will enable record quantum networking bandwidth while minimally disturbing computing operations. A critical component of this work is our quantitative analysis of imperfections in the CAM. Through insights gained in these studies, we anticipate a straightforward path toward tens of thousands of mutually degenerate cavities with intrinsic finesse approaching one thousand and correspondingly improved networking performance [25] (Supplemental Material [29], Secs. I and J).

Besides networking, the CAM will also dramatically improve readout rates of neutral atom quantum processors, approaching about 10- μ s readout with our projected 53% collection efficiency (Fig. 9 and Supplemental Material [29], Sec. E). By inducing diffractive coupling between cavities, we expect to realize coherent coupling of photons between neighboring cavity sites, enabling studies of hitherto unexplored light-matter Hamiltonians [26–28].

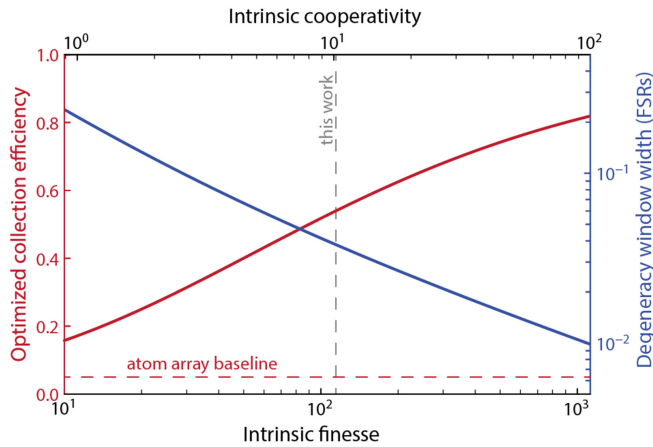


FIG. 9. Projected cavity performance. Total optimized light collection probability (solid red line) for current CAM parameters—see Supplemental Material [29], Sec. E; our projected performance is already an order of magnitude greater than the approximately 5% expected for standard atom arrays (dashed red line), with further room to develop as the intrinsic cavity finesse is improved. Notably, even as the finesse grows, the acceptable window of cavity nondegeneracy [i.e., red bars in the color bar in Fig. 1(d)] decreases only mildly (solid blue line).

Further enhanced connectivity could be enabled by introducing programmable optics (like deformable mirrors) into the system, enabling fast, parallelized, nonlocal atom-atom interaction within a single array. If, instead of collecting photons from the atoms, the CAM is instead used to transduce environmental photons *onto* the atom array, it could realize a natural constituent of a quantum-computing-enhanced optical imaging system [39].

We emphasize that, while we have designed this current iteration of the CAM around compatibility with neutral atom quantum processors, the fundamental apparatus is versatile and may enable gains across a variety of disciplines, e.g., biological or chemical sensing [2,3]. Ultimately, the CAM is the culmination of a long, active, and fruitful history of cavity engineering; through studying, characterizing, and optimizing the factors which affect its performance (as we have done here), we anticipate a similarly fruitful new frontier of many-cavity QED awaits.

ACKNOWLEDGMENTS

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D. S., D. I. S., and J. S. hold a patent on the resonator geometry demonstrated in this work. J. S. is a consultant for, and on the advisory board of, Atom Computing.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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