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An ultrahigh finesse Fabry-Perot superconducting resonator as a photon box for cavity-QED experiments

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We have built a microwave Fabry-Perot resonator made of diamond-machined copper mirrors coated with superconducting niobium. Its damping time ($T_c = 130$ ms at 51 GHz and 0.8 K) corresponds to a finesse of 4.6×10^9 , the highest ever reached for a Fabry-Perot in any frequency range. We have tested this resonator by sending across it two circular Rydberg atoms, the first emitting a photon and the second absorbing it after a delay of 1/10 s. This long storage time photon box opens novel perspectives for quantum information. It can be used to perform sequences of hundreds of gate operations on individual atomic qubits. A set-up with one or two photon boxes can store mesoscopic fields made of hundreds of photons for decoherence and non-locality studies.

PACS numbers: 42.50.Pq, 03.67.-a, 84.40.-x, 85.25.-j

Since Bohr-Einstein's photon box thought experiment [1], storing a photon for a long time has been a dream of physicists. Cavity quantum electrodynamics (CQED) in the microwave domain comes closest to the realization of this goal. Photons are trapped in a superconducting cavity and probed by atoms crossing the field mode one at a time. Experiments with circular Rydberg atoms and Fabry-Perot resonators have led to fundamental tests of quantum theory and various demonstrations of quantum information procedures [2]. The open geometry of the cavity is essential to allow a perturbation-free propagation of long-lived atomic coherences through the field mode. With this cavity structure, however, the field energy damping time T_c is very sensitive to geometrical mirror defects. In previous experiments, T_c was limited to 1 ms, a value which precluded the realization of complex sequences of quantum operations. We report here the realization of a Fabry-Perot resonator at $\omega/2\pi = 51$ GHz, with a cavity damping time of 130 ms, measured both with classical and single-photon fields. The cavity quality factor Q is 4.2×10^{10} and its finesse 4.6×10^9 , to our knowledge the highest ever achieved in any frequency domain for this geometry.

This important step opens the way to a new generation of CQED experiments. Quantum logic operations involve the coupling of atoms with single photons used as qubits stored in the cavity. The gate operation time is $2\pi/\Omega_0$ where Ω_0 is the vacuum Rabi frequency corresponding to the resonant exchange of a single quantum between atom and field ($\Omega_0/2\pi = 50$ kHz for the 51.099 GHz

transition between the circular states e and g with principal quantum numbers 51 and 50). The number of sequential operations before decoherence drops the fidelity below 90% is $\approx \eta/10$ with $\eta = \Omega_0 T_c/2\pi$ ($\eta = 6700$ with $T_c = 130$ ms). Hundreds of operations can now be realized, as opposed to only a few in previous experiments [3]. For instance, a control-NOT gate between a control photon qubit and a target atom amounts to a quantum non-demolition (QND) measurement of the photon [4]. The same photon can now be probed by hundreds of atoms, revealing the quantum jumps of the field [5]. QND measurements of larger photon numbers become possible [6].

Long cavity damping times are also essential for fundamental decoherence studies. A Rydberg atom interacting with a coherent field containing on average \bar{n} photons generates a superposition of coherent components with different phases whose characteristic decoherence time is $\approx T_c/\bar{n}$. It must be longer than the state preparation time, $2\pi\sqrt{\bar{n}}/\Omega_0$ in the optimal case of a resonant atom-field interaction [7]. The upper limit of \bar{n} is thus $\eta^{2/3} = 350$ with $T_c = 130$ ms. Quantitative decoherence studies deep into the mesoscopic regime are within reach. With two such cavities, entangled field states involving many photons in two spatially separated modes can be generated, leading to new non-locality tests [8].

Our previous superconducting Fabry-Perot cavities, made of bulk niobium, had three main limitations. (i) Their surface quality was far from ideal, being affected by local roughness due to grain boundaries and by deviations from a sphere produced by deformations during polishing. (ii) Small 0.2 mm diameter irises at the centers of the mirrors, used for microwave coupling, resulted in deformation of the surface. (iii) The cavity sustained two nearly degenerate Gaussian modes with linear or-

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thogonal polarizations. The frequency splitting between them, due to mirror imperfections, was only a few times $\Omega_0/2\pi$, making it difficult to realize a situation in which a two-level atom is coupled to a single field mode.

The new design solves these problems. (i) The mirrors are made of a copper substrate diamond-machined to nanometer accuracy and are covered with a Niobium layer by cathode sputtering. (ii) The coupling irises are suppressed, the field being injected in the cavity by residual scattering on the mirrors. (iii) The mirror surfaces are toroidal, lifting the degeneracy of the two orthogonal modes by an amount much larger than $\Omega_0/2\pi$.

A picture of the cavity with the top mirror removed is shown in Fig. 1. The mirrors have a diameter $D_0 = 50$ mm (radii of curvature 39.4 and 40.6 mm in two orthogonal planes). The distance between the mirror apices is $L = 27.57$ mm. The two TEM_{900} modes near 51.099 GHz have orthogonal linear polarizations and are separated by 1.2 MHz. The mirrors are electrically insulated. A static electric field parallel to the cavity axis is applied between them to preserve the circular states and to tune the atomic transition via the Stark effect [2]. The 1 cm spacing between mirror edges is partly closed by two cylindrical guard rings improving the static electric field homogeneity inside the cavity. The atomic beam enters and exits the cavity through two large ports ($1 \text{ cm} \times 2 \text{ cm}$) so that they never come close to metallic surfaces, preserving them from patch effect stray fields. This ensures a good transmission of atomic coherences through the cavity. Four piezoelectric actuators are employed to translate one of the mirrors and to tune the cavity (within ± 5 MHz) with kHz accuracy.

We realized two mirror sets, M_1 and M_2 . The copper substrate is first machined to a gross spherical shape. The mirrors are then submitted to two temperature cycles to release stresses. They are first heated in a vacuum chamber to 400°C and cooled down to liquid N_2

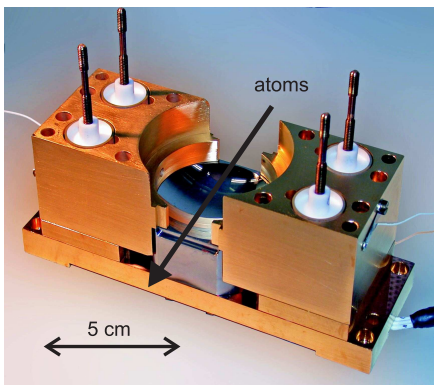


FIG. 1: Photograph of the cavity assembly with the top mirror removed. The atomic beam path is visualized by the arrow. The four posts are used to mount the upper mirror. Piezoelectric actuators, used for fine tuning of the cavity length, are housed inside the gold-coated copper blocks and centered by the white teflon cylinders surrounding the posts.

temperature. The final diamond machining is then performed (Kugler company). The local surface roughness is 10 nm r.m.s. and the surface has a peak-to-valley deviation of < 300 nm from the ideal toroidal shape. To avoid deformation of the mirrors in the final assembly, their thickness is 30 mm. Their back surface and that of the matching holders are polished to $1 \mu\text{m}$ accuracy.

The mirror surface is covered with a $12 \mu\text{m}$ layer of Nb. We use a coating facility at CEA, Saclay, designed to realize r.f. cavities for particle accelerators [9]. The Nb layer is deposited by d.c. cathode sputtering in a magnetron discharge [10]. We first clean the substrate with ultra-pure filtered alcohol in an ultrasonic bath and dry it with filtered Ar. The sputtering chamber is evacuated to 10^{-8} mbar and then filled with 10^{-1} mbar of Ar. We set the mirror potential to -1000 V for 20 s, creating an Ar plasma which blows away remaining dust particles. The chamber is evacuated again and we start the sputtering process. A 1 kW magnetron creates a dense Ar plasma in the vicinity of a cylindrical Nb cathode (Ar flux: $3 \text{ cm}^3/\text{min}$, residual pressure: 10^{-3} mbar). Initially, the Nb cathode is far away from the mirror. When its impure surface layer is removed, we move the Nb cathode in front of the mirror. The evaporated atoms are deposited at a rate of $0.1 \mu\text{m}/\text{min}$ on the mirror surface which heats up to $300 - 400^\circ\text{C}$ during this process. Before being mounted in the Rydberg atom set-up, the mirrors are rinsed in an alcohol ultrasonic bath and dried with Ar.

In order to characterize the modes of the cavity C , microwave is coupled in via weak diffraction loss channels. This coupling is large enough to inject a mesoscopic field in C , but it is not sufficiently large to directly detect the slow decay of the leaking field. We monitor instead the cavity ring-down with an atomic probe. The reproducibility of the mirror mounting results in an uncertainty of the cavity frequencies of ± 10 MHz. Finding the cavity resonances requires a broadband atomic detector. The narrow transition between the circular states e and g with its moderate Stark shift is not appropriate. We use instead a sample of ^{85}Rb atoms in the $52D_{5/2}$ level. At the beginning of a measurement sequence, we inject a microwave pulse by a waveguide ending in the guard rings around the mirrors. Most of the microwave power is not coupled into the mode and propagates in the apparatus where it decays in less than $1 \mu\text{s}$. After a time interval t , we send the atomic probe in C . It is produced by a two-step laser excitation scheme involving a diode laser at 420.30 nm ($5S_{1/2} \rightarrow 6P_{3/2}$) and a second diode laser at 1014.67 nm ($6P_{3/2} \rightarrow 52D_{5/2}$). The cavity field induces transitions from $52D_{5/2}$ to other Rydberg levels. The absorption is made broadband by the Stark effect in a 13.4 V/cm electric field applied in C . The cavity-field induced atomic transitions are monitored by a state-selective field-ionization detector.

We have first used the atomic absorption probe to identify the modes in C . By sweeping the microwave source and recording the atomic absorption, we precisely de-

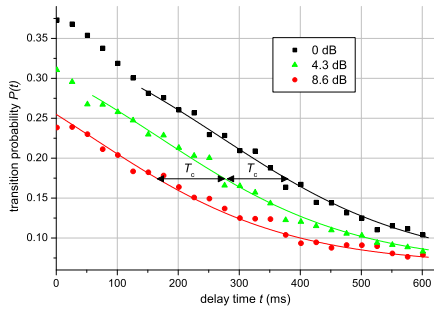


FIG. 2: Measurement of the decay time T_c of cavity M_1 at $T = 0.8$ K (lower frequency mode). We show the transition probability $P(t)$ as a function of the delay t between microwave injection and the atomic probe crossing the cavity. The points (circles, triangles and squares) correspond to three initial field energies E_0 , eE_0 and e^2E_0 , respectively. The fits (solid lines) result from a simple absorption model including saturation. They are equidistantly shifted in time with respect to one another by T_c , measured to be 112 ± 4 ms. Each point is the average of 1600 atomic detections.

terminated the cavity mode resonances. For M_1 and M_2 we find two modes close to 51.1 GHz separated by the expected 1.2 MHz frequency splitting. We have also mapped the transverse profile of the mode. Using pulsed velocity-selected atomic samples, we know the atomic position at any time. Switching the Stark field in C on and off, we set the atoms in resonance during a short time window, at well defined positions in C . The absorption reveals the intensity profile of the mode along the atomic beam axis, a Gaussian with a $w_0 \simeq 6$ mm waist.

We then measure the modes quality factors. We record the transition probability $P(t)$ as a function of time delay t . Typical data, obtained with the mirror set M_1 (lower frequency mode) at 0.8 K is shown in Fig. 2 for three different initial field energies, E_0 , eE_0 and e^2E_0 (e is the base of natural logarithms), corresponding to microwave source attenuations of 8.6, 4.3 and 0 dB respectively. Due to the exponential decrease of E versus time, $E(t) = E_0 e^{-t/T_c}$, an arbitrary energy $E < E_0$ is reached at times t_0 , $t_0 + T_c$ and $t_0 + 2T_c$ for these three attenuations. Since $P(t)$ depends only upon E the corresponding $P(t)$ curves are thus shifted in time by T_c with respect to each other. From the data in Fig. 2 we obtain $T_c = 112 \pm 4$ ms. For the upper frequency mode of M_1 , $T_c = 87 \pm 10$ ms. For M_2 we find, at 0.8 K, $T_c = 74 \pm 6$ ms and $T_c = 130 \pm 4$ ms for the lower and higher frequency modes respectively. These four modes have all an extremely long energy storage time. The best corresponds to a quality factor $Q = \omega T_c = 4.2 \times 10^{10}$ and to a finesse $Q/9 = 4.6 \times 10^9$.

Knowing precisely the cavity transition frequency, we have tuned it in resonance with the $e - g$ transition. As a first test of the set-up's quantum information capability, we have used the upper frequency mode of M_2 to transfer an excitation between two atoms separated in time

by a long delay. A first atom prepared in e enters the empty cavity, performs a π Rabi pulse and exits in g , leaving a photon in C [11]. A second atom is sent in g at a later time t and absorbs the photon in the reverse process. Fig. 3 shows the probability $P_e(t)$ for detecting the probe atom in e as a function of t . The fitted decay time is 145 ± 16 ms, in agreement with the measurement performed with a classical field. This experiment demonstrates an information transfer between two atoms relying on a single-photon memory with a storage time larger than $1/10$ s.

Using the measurement with classical fields, we have also made a study of T_c as a function of the mirror temperature T for the lower frequency mode of M_1 (see Fig. 4). For $T > 1.4$ K, we observe an exponential increase of T_c versus $1/T$, while for $T < 1.4$ K, T_c saturates. The exponential behavior is explained by BCS theory. The quality factor Q can be expressed as the ratio G/R_e of two resistances characterizing the geometry (G) and the losses (R_e) of the cavity [12] ($G = 2800 \Omega$ in our case). The effective resistance $R_e = R_{\text{BCS}} + R_0 + R$ has three contributions: the resistance R_{BCS} given by BCS theory, the residual resistance R_0 of the metal at $T = 0$ K due to defects, impurities and magnetic vortices, and an additional contribution R measuring the diffraction losses. The BCS resistance is $R_{\text{BCS}} = (A/T) \exp(-\Delta_0/k_B T)$, where Δ_0 is the superconducting gap and A an intrinsic parameter of the superconductor. For $T > 1.6$ K, R_{BCS} is the dominant contribution to R_e , while it is negligible for $T < 1.4$ K. The line in Fig. 4 is a fit of the data with the formula $T_c = G/\omega(R_{\text{BCS}} + R_0 + R)$, from which we infer $\Delta_0/k_B = 20.2 \pm 0.3$ K. This value, confirmed by measurements on other mirror sets, differs slightly from the value $1.854 T_{\text{Nb}}$ found in Ref. [14] at 22 GHz with bulk Nb ($T_{\text{Nb}} = 9.2$ K is the Nb superconducting critical temperature).

The saturating value of T_c below 1.4 K yields the ef-

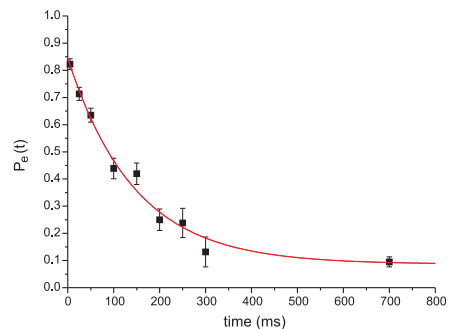


FIG. 3: Transfer of excitation between two atoms mediated by the cavity (mirror set M_2 , upper frequency mode). A photon deposited by a first atom at $t = 0$ is absorbed at time t by a second atom initially in g . We show the probability $P_e(t)$ that this atom exits the cavity in e . Each point is an average of 40 to 400 realizations (error bars are static). The exponential fit (red line) yields a photon decay time of 145 ± 14 ms. The asymptotic value $P_e = 0.09 \pm 0.02$ for large times is due to thermal photon background ($n_{\text{th}} = 0.05$) and atomic detection errors.

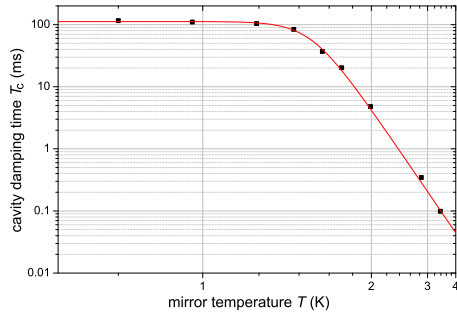


FIG. 4: Cavity damping time T_c vs mirror temperature T (mirror set M_1 , lower frequency mode). The horizontal scale is reciprocal and the vertical one logarithmic. The dots are experimental and the solid line is a fit (see text for details) providing a gap value $\Delta_0/k_B = 20.2$ K. Below 1.4 K, the lifetime saturates at 112 ms.

fective residual resistance $R_0 + R = 75$ n Ω for M_1 (lower mode) and 68 n Ω for M_2 (upper mode). The diffraction losses term R , due to the finite size of the mirrors and to surface roughness, can be estimated. The mirror diameter D_0 limits the quality factor to $Q_{\text{diff}} \approx (\omega L/c) \exp(D_0^2/2w^2) = 2.7 \times 10^{11}$ ($w = 1.23w_0$ is the mode waist at the mirror surface). The surface roughness is characterized by the r.m.s. deviation, h_{rms} , of the surface with respect to the ideal shape. The corresponding quality factor, calculated by evaluating the “total integrated scattering” (TIS) [13], is $Q_{\text{surf}} = cL/4\omega h_{\text{rms}}^2$. From the measured mirror substrate roughness, $h_{\text{rms}} \simeq 10$ nm, we obtain $Q_{\text{surf}} = 6.4 \times 10^{10}$. Combining the estimated losses yields $Q' = (Q_{\text{diff}}^{-1} + Q_{\text{surf}}^{-1})^{-1} = 5.2 \times 10^{10}$. This value, close to the measured ones ($Q = 4.2 \times 10^{10}$

in the best case), indicates that diffraction losses have an important contribution at low T . The small difference between Q' and Q might be caused by a slight increase of h_{rms} after the Nb coating or by a contribution of the surface resistance R_0 .

It is also instructive to compare the Q factor of our open resonators with that of closed cylindrical cavities at 22 GHz used in Rydberg atom micromaser studies [14, 15]. In these experiments, a quality factor $Q = 4.0 \times 10^{10}$ at 0.3 K was obtained [16]. The residual resistance was $R_0 + R = G/Q = 28$ n Ω ($G = 1089$ Ω), a value comparable to the one reported here. The difference could be due to the frequency dependence of R_0 , to variations in the Nb purity, or to diffraction losses in our open geometry. It is remarkable that our cavity reaches the same Q as the best closed one in the same frequency domain. At much lower frequencies, around 1 GHz, Q factors up to 10^{12} have been obtained [17]. This frequency domain is however much less convenient for cavity QED experiments. Keeping the cavity field in the vacuum state would require temperatures in the 10 mK range.

We have reported the realization of an ultra-high- Q photon box for quantum information and decoherence studies of mesoscopic superpositions. This cavity, with its open geometry, is ideally suited for the propagation of atomic coherence through the field mode, atomic interferometry and quantum information.

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