A single ion as a nanoscopic probe of an optical field

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In near-field imaging, resolution beyond the diffraction limit of optical microscopy is obtained by scanning the sampling region with a probe of subwavelength size[1]. In recent experiments, single molecules were used as nanoscopic probes to attain a resolution of a few tens of nanometres[2,3]. Positional control of the molecular probe was typically achieved by embedding it in a crystal attached to a substrate on a translation stage. However, the presence of the host crystal inevitably led to a disturbance of the light field that was to be measured. Here we report a near-field probe with atomic-scale resolution—a single calcium ion in a radio-frequency trap—that causes minimal perturbation of the optical field. We measure the three-dimensional spatial structure of an optical field with a spatial resolution as high as 60 nm (determined by the residual thermal motion of the trapped ion), and scan the modes of a low-loss optical cavity over a range of up to 100 μm. The precise positioning we achieve implies a deterministic control of the coupling between ion and field. At the same time, the field and the internal states of the ion are not affected by the trapping potential. Our set-up is therefore an ideal system for performing cavity quantum electrodynamics[4,5] experiments with a single particle.

One of the principal goals in optical imaging is to improve spatial resolution. Observations of the optical far field are limited by diffraction, and structures smaller than the wavelength of the radiation cannot therefore be resolved. This limitation has been overcome with the method of near-field imaging[1], in which a probe is brought close to the field to be measured. The resolution is then determined by the size of the probe. Initial experiments were performed using optical fibres with sharply pointed tips, but better resolution was obtained by employing single molecules[2]. The intensity distribution of the optical near field is mapped by detecting the fluorescent light emitted by the molecule as a function of its position. Using this technique, a resolution below 100 nm can be achieved[6–9]. An inherent drawback of this method is the need for a host-crystal matrix or a substrate to accommodate and immobilize the single molecule. This causes absorption, diffraction, scattering and dephasing of the optical field under investigation in the vicinity of the probe molecule.

With the technique that we present here, the detrimental effects of the host crystal are avoided by using a single ion in a radio-frequency (r.f.) trap as a near-field probe. In many ways, a trapped ion is the perfect nanoscopic detector of the radiation field. Because of the absence of a medium from the interaction region, the optical field is not affected by the probe. The resolution may be adjusted by varying the strength of the confining r.f. field, and is then limited only by the size of the wavefunction of the ion in its motional ground state. In addition to the high spatial resolution, the spectral resolution of a single ion may be an additional advantage, as some of the narrowest spectral lines investigated so far have been measured with trapped ions.

In our experiment, a single $^{40}Ca^{+}$ ion is employed as a probe of the field. It is sensitive to radiation close to the resonance line $4^2S_{1/2}$–$4^2P_{1/2}$ at a wavelength of $\lambda = 397$ nm. The fluorescent light emitted by the ion is collected with a lens (numerical aperture 0.17) and detected with a photomultiplier tube (overall detection efficiency $\eta \approx 10^{-4}$). The observed fluorescence rate R is proportional to the local intensity of the optical field at the position r of the ion, that is, $R \propto I(r)$, provided that there is no saturation of the atomic transition. By scanning the position of the ion in the field and detecting the fluorescence rate at each point, a high-resolution map of the optical intensity distribution is obtained. It should be noted that a single ion can also probe the amplitude distribution $E(r)$ of the light field and hence measure its phase. Heterodyne detection of the fluorescent light must be used for such measurements, with the exciting laser as a local oscillator[10,11].

To demonstrate our method of single-ion mode mapping, we have investigated the eigenmodes of a Fabry–Perot resonator (Fig. 1). The transverse mode pattern is described by Hermite–Gauss functions with a beam waist $w_0 \approx 24$ μm, while in the direction of the cavity axis a standing wave builds up. In the

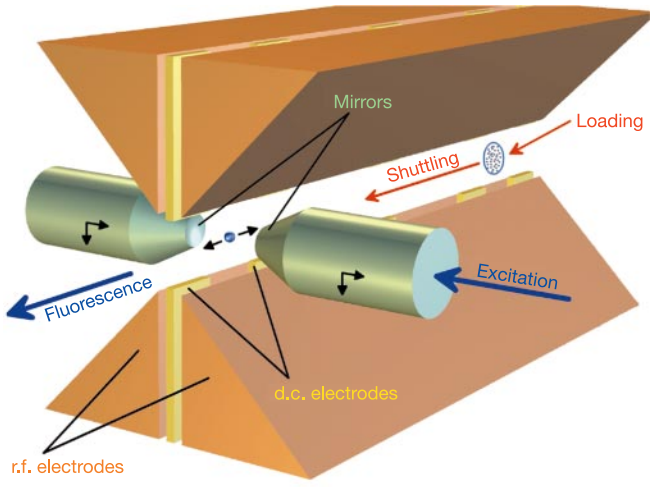

Figure 1 Experimental arrangement of trap electrodes and cavity. The ion is loaded at the rear end of the trap, and subsequently shuttled to the cavity region. Two mirrors with a radius of curvature of 10 mm and 6 mm apart form the cavity. Fluorescence is observed from the side of the cavity. For scans in the direction of the trap axis, the ion is moved with d.c. electrodes. In all other directions, the cavity is translated relative to the ion's position, as indicated by arrows.

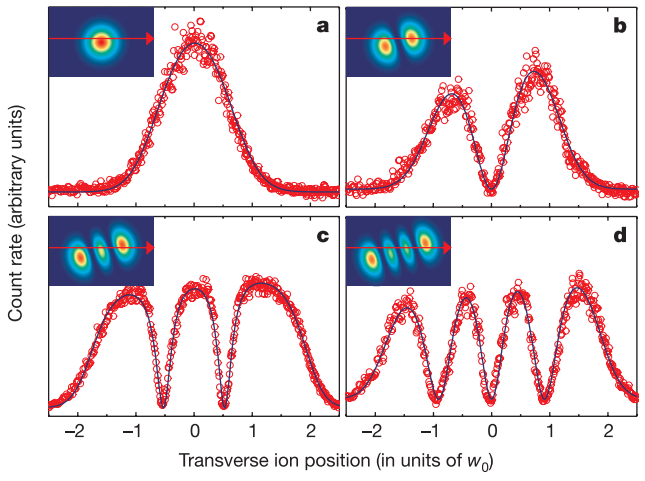

Figure 2 Transverse profiles of the Hermite–Gauss modes of the cavity, obtained by monitoring the ion's fluorescence while scanning over a range of 120 μm. The solid line is a fit including saturation of the transition. The inset shows the calculated intensity distribution of the mode and indicates the scan path. The modes are TEM_{00} (**a**), TEM_{01} (**b**), TEM_{02} (**c**) and TEM_{03} (**d**). Note the influence of saturation in **c**, where a slightly higher laser intensity was injected into the cavity. w_0, beam waist.

experiment, a particular cavity mode is excited by a laser beam with a power of a few hundred nanowatts at a wavelength of 397 nm. The length of the cavity is actively stabilized to this mode.

An ion is loaded in the trap after electron-impact ionization of calcium atoms. As the electron beam and the calcium beam would degrade the optical mirrors and make stable trapping difficult, we use a linear trap and load it in a region spatially separated from the observation zone, as shown in Fig. 1. Subsequently, d.c. electrodes along the axis are employed to shuttle the ion over a distance of 25 mm to the uncontaminated end of the trap, where the cavity is located, oriented at right angles to the trap axis. Residual d.c. fields in the radial direction must be carefully compensated with correctional d.c. voltages to place the ion precisely on the nodal line of the r.f. field (coinciding with the trap axis), to avoid the trapping field exciting an oscillatory motion of the ion (micromotion).

In the direction of the trap axis, the ion is confined in a d.c. potential well, which is approximately harmonic with an oscillation frequency of $\omega_z/2\pi \approx 300$ kHz. By applying asymmetric voltages, the minimum of the potential well and thus the equilibrium position of the ion is moved along the trap axis. By simultaneously monitoring the fluorescence, we have sampled one-dimensional cross-sections of the cavity mode. The width of the ion's wavefunction in the axial potential well is a few hundred nanometres, which provides sufficient resolution to map the transverse mode pattern with an intensity distribution varying on a scale given by the cavity waist w_0.

Figure 2 shows scans of the first four TEM_{0n} modes of the cavity obtained in this way. The indices 0 and n specify the number of nodes of electromagnetic field in the vertical and horizontal direction, respectively. The fluorescence data are not entirely symmetric because of a small displacement and rotation of the cavity eigenmodes with respect to the trap axis. In each plot, an inset indicates the path along which the ion was scanned. The solid curves in Fig. 2 are obtained from a fit using Hermite–Gauss functions, and take into account saturation of the ion's transition. In all cases, the correspondence with the measured fluorescence is excellent.

The ion's motion must be restrained to the trap axis, because off the axis the r.f. field of the trap would lead to micromotion. To scan other dimensions of the field, the sample needs to be moved. In our experiment this is done by translating the entire cavity assembly perpendicular to the trap axis, using a piezoelectric transducer. Examples of two-dimensional mode maps, scanned by combining the horizontal movement of the ion with a vertical movement of the cavity, are given in Fig. 3.

Radio-frequency confinement of the ion perpendicular to the trap axis is also harmonic, but the corresponding oscillation frequency $\omega_r/2\pi \approx 1.1$ MHz is larger than the axial frequency ω_z, so that field structures in the radial direction of the trap are better resolved. The resolution achieved with our method may be determined most accurately by probing the standing-wave field created between the cavity mirrors, which oscillates on a scale of $\lambda/2$. To this end, the cavity was moved parallel to its axis while keeping the ion stationary and monitoring its fluorescence. Figure 4 shows the mapping of the cavity field obtained in this way. A pronounced standing-wave pattern is observed with a visibility of 40%.

At present, the visibility in our experiment is given by the thermal wave packet spread of the calcium ion under conditions of Doppler cooling. In the direction of the cavity axis, cooling is provided by the cavity field itself, which is red-detuned with respect to the ion's transition for this purpose. The limiting temperature is then determined by the linewidth Γ of the atomic transition and is given by $\hbar\Gamma/2k_B \approx 500$ μK. The transverse degrees of freedom of the ion are cooled with an additional laser beam injected from the side of the cavity, which is switched off during the measurement. Assuming thermal equilibrium, there is a direct connection between the spread b of the ion's wavefunction, which is identical to the resolution, and the visibility V:

$$V \approx \exp[-(2\pi b/\lambda)^2] \quad (1)$$

The observed visibility corresponds to a wave packet 60 nm wide, indicating a temperature of the ion slightly above the Doppler temperature. The resolution of single-ion mode mapping in this case is almost one order of magnitude better than the wavelength of the transition.

Even higher resolution is within reach of standard ion-trapping technology. By using larger driving frequencies and higher voltages, the trap is made steeper, implying a wave packet size below 10 nm. Another factor of two is gained by cooling the ion to the ground state of motion, which has been achieved in several experiments[12–14]. Finally, the technique of motional squeezing[15] of the ion's wavefunction may be employed to create a 'breathing' wave packet which

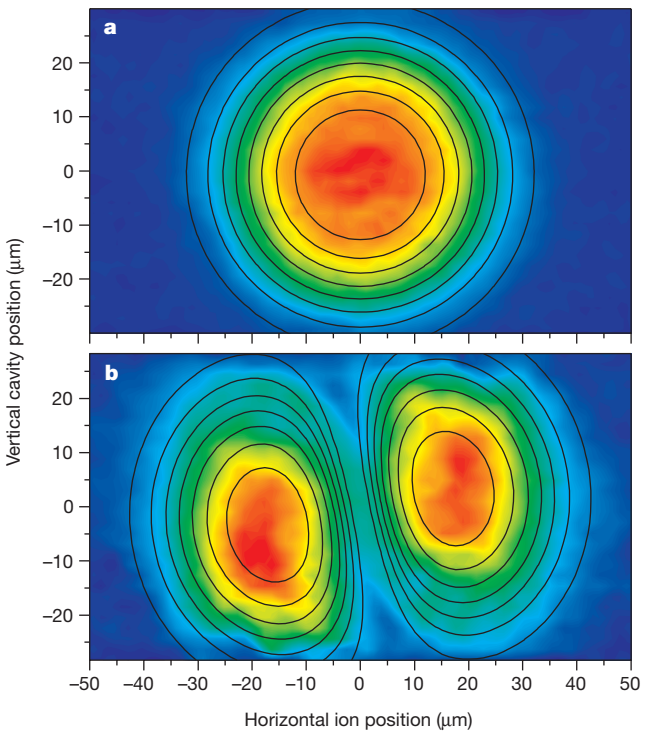

Figure 3 Two-dimensional images of the cavity field taken over an area of $100 \times 60\ \mu m^2$. **a**, TEM_{00} mode. **b**, TEM_{01} mode. In the horizontal direction the ion was moved, while vertically the cavity position was changed relative to the ion. False colours represent the measured fluorescence count rate; the contour lines indicate the theoretical fluorescence pattern.

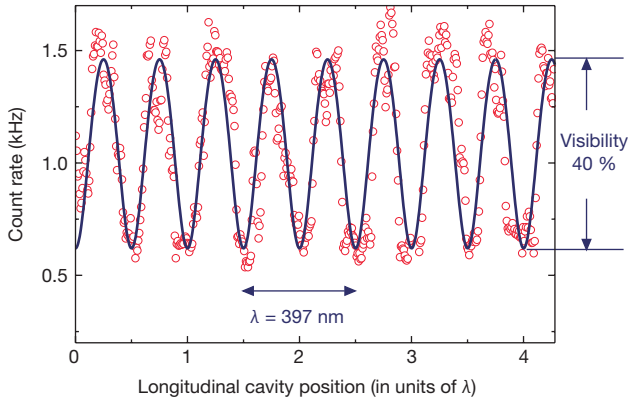

Figure 4 Single-ion mapping of the longitudinal structure of the cavity field. The visibility is determined by the residual thermal motion of the Doppler-cooled ion, and corresponds to a resolution of 60 nm. The localization of the ion's wave packet in this measurement is 16 nm.

periodically reaches a position uncertainty below 1 nm. In this case, stroboscopic detection must be used. Thus a single ion as a probe of the optical field has the potential for atomic-scale resolution, and it does not disturb the field to be measured.

An important issue, especially with regard to applications in cavity quantum electrodynamics (QED) is the question of how well the ion is localized in the optical field—that is, how accurately the centroid of the ion's wavefunction may be determined. With the spatial variation of the local fluorescence rate as the only parameter available from which to infer a change of position of the ion, the largest position sensitivity in our set-up is obtained at maximum slope of the standing wave. At this point, the localization Δx is completely determined by the signal-to-noise ratio SNR and the visibility V:

$$\Delta x \approx \frac{\lambda}{4\pi V(\mathrm{SNR})} \qquad (2)$$

With a signal-to-noise ratio of 5:1, reached with an integration time of 200 ms at each point, a localization of approximately 16 nm or $\lambda/25$ was measured. Even in the presence of noise, our measurement with a scanned single particle thus constitutes the most precise measurement to date of the spatial structure of an optical field[6–9]. In principle, Δx could be further reduced if the signal-to-noise ratio were improved by using a longer averaging time.

As excellent spatial resolution is achieved without material support structures, a single ion is a valuable probe when minimal perturbations of the optical field are desired. However, the technique of localizing an ion in a resonator has applications beyond subwavelength imaging. The interaction of a single atom with a single field mode of a high-finesse cavity has been the subject of a number of experiments in the field of cavity QED[4,5]. But most of these investigations have suffered from a lack of control over the position of the atom, which results in non-deterministic fluctuations of the coupling between atoms and field. In this context, the strong localization and position control, demonstrated here for a single ion in a cavity field, is an important advance, and we expect that it will be a key to future progress in the field. We plan to implement two experiments exploiting the localization of an ion in a cavity in our system. By pulsed excitation of a maximally coupled ion, single-photon wave packets may be emitted from the cavity on demand[16,17] (single-photon gun). Under conditions of strong coupling, a single calcium ion in the cavity provides sufficient gain to build up a laser field[18]. Analogous to a single ion in free space, which has been shown to be an excellent source of antibunched light[10,19], radiation from a single-ion laser has non-classical photon statistics and correlations.

An equally attractive goal in the area of cavity QED is the simultaneous interaction of two or more ions with a single cavity mode. Owing to its linear geometry, our trap is well suited to storing multiple ions along the axis. As a first test, we have placed an array of two ions in the cavity field and observed the total fluorescence. We succeeded in matching the ion crystal to the two maxima of the TEM_{01} mode of the cavity. In such a configuration, the cavity field may be used to entangle the two ions[20,21]. This is a promising alternative to schemes involving the ions' motional degrees of freedom, as there is no need for cooling the vibrational modes of the ion chain below the Doppler temperature. We consider that using a cavity to perform quantum operations on adjacent pairs of ions in a long chain is a viable route to a scalable quantum computer. □

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Ultrafast generation of magnetic fields in a Schottky diode

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For the development of future magnetic data storage technologies, the ultrafast generation of local magnetic fields is essential. Subnanosecond excitation of the magnetic state has so far been achieved by launching current pulses into micro-coils and micro-striplines[1–6] and by using high-energy electron beams[7]. Local injection of a spin-polarized current through an all-metal junction has been proposed as an efficient method of switching magnetic elements[8,9], and experiments seem to confirm this[10–13]. Spin injection has also been observed in hybrid ferromagnetic–semiconductor structures[14,15]. Here we introduce a different scheme for the ultrafast generation of local magnetic fields in such a hybrid structure. The basis of our approach is to optically pump a Schottky diode with a focused, ~150-fs laser pulse. The laser pulse generates a current across the semiconductor–metal junction, which in turn gives rise to an in-plane magnetic field. This scheme combines the localization of current injection techniques[11–13,16] with the speed of current generation at a