Superresolution Microscopy of Optical Fields Using Tweezer-Trapped Single Atoms

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We realize a scanning probe microscope using single trapped 87Rb atoms to measure optical fields with subwavelength spatial resolution. Our microscope operates by detecting fluorescence from a single atom driven by near-resonant light and determining the ac Stark shift of an atomic transition from other local optical fields via the change in the fluorescence rate. We benchmark the microscope by measuring two standing-wave Gaussian modes of a Fabry-Pérot resonator with optical wavelengths of 1560 and 781 nm. We attain a spatial resolution of 300 nm, which is superresolving compared to the limit set by the 780 nm wavelength of the detected light. Sensitivity to short length scale features is enhanced by adapting the sensor to characterize an optical field via the force it exerts on the atom.

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Neutral atoms make excellent sensors, owing largely to the identical physical properties of all atoms of a given isotope [1]. Further, neutral atoms can be isolated from decoherence, enabling highly sensitive measurements of fields, forces, acceleration, rotation, and the passage of time [2–5]. While, to date, atomic sensors have mostly made use of gaseous atomic ensembles, new techniques allow exceptional control of single atoms [6,7] and of structured arrays of single atoms [8,9], motivated by the goals of quantum simulation [10], communication [11], metrology [12,13], and computation [14,15].

A number of techniques use cold atoms for spatial tomography of material properties and electromagnetic fields [16–21]. Complementary techniques use electromagnetic fields to perform superresolution microscopy of cold atom systems [22,23]. Here, we harness the ability to trap, position, and detect single neutral atoms to construct a scanning probe quantum sensor [24] that measures optical fields with high spatial resolution. The sensing medium is a single 87Rb atom trapped within a tightly focused optical tweezer trap and driven with near-resonant light. By measuring the optical fluorescence rate, we determine the shift induced on the atomic resonance frequency by local optical fields and, thereby, the local background optical intensity. We apply our sensor to optical test patterns formed by long-wavelength (LW, 1560 nm) and short-wavelength (SW, 781 nm) TEM00 standing-wave modes of a Fabry-Pérot optical resonator. We measure a sensor spatial resolution of 300 nm, below the resolution limit set by the detected fluorescence light at a wavelength of 780 nm, thus achieving superresolution.

Operation of the sensor relies on basic properties of light-atom interactions. An atom in free space scatters light at a rate given by

$$\Gamma_{ac} \propto \frac{1}{(\omega_L - \omega_0 - \delta_{ac})^2}. \quad (1)$$

Here, we consider the scattering of imaging light at a frequency $\omega_L$ that is near that of a single atomic transition, with the atomic resonance frequency being the sum of $\omega_0$, the bare resonance frequency, and $\delta_{ac}$, the transition ac Stark shift. We consider the ac Stark shift due to linearly polarized optical fields with detunings much larger than the atomic state hyperfine splittings, and thus treat the atom as a two-level system, ignoring degeneracies and optical polarization effects. We require the detuning of the imaging light to be large compared to the atomic resonance linewidth and neglect saturation by considering the weak scattering regime. The transition ac Stark shift is determined by the intensity $I$ of a local optical field of frequency $\omega$ as $\delta_{ac} = -(2\hbar c \epsilon_0)^{-1} (\alpha_g(\omega) - \alpha_e(\omega)) I$, where $\alpha_g,e(\omega)$ are the scalar dynamical electrical polarizabilities of the ground and excited states [25]. These polarizabilities are fixed for 87Rb atoms; thus, the measurement of $\delta_{ac}$ realizes an absolutely calibrated light intensity meter.

Our sensor employs a one-dimensional array of as many as ten atoms trapped individually in optical tweezer traps. The tweezers, each formed by focusing light at a wavelength of 808 nm through a NA = 0.5 objective to a Gaussian beam waist of around 750 nm, are located near the center of an in-vacuum, near-concentric Fabry-Pérot optical cavity, whose mirrors are coated to be highly
reflective for LW and SW light. The array is oriented perpendicular to the cavity axis and translated along the cavity axis using a piezo-controlled mirror; see Figs. 1(a) and 1(b).

We load atoms into the tweezers by overlaying the tweezers on a large-volume optical trap containing a gas of $^{87}\text{Rb}$ atoms at a temperature of 30 $\mu$K. The atoms are then exposed both to counterpropagating fluorescence imaging beams, with a variable red detuning $\Delta = \omega_0 - \omega_0 < 0$ from the $D_2 F = 2 \rightarrow F' = 3$ optical transition, and also to repump light resonant with the $D_2 F = 1 \rightarrow F' = 2$ transition. The dipole trap is extinguished after 10 ms. The imaging light reduces the atom number in each tweezer to either zero or one [6], cools the atoms to a thermal energy $k_B T = 0.005$ mK (blue) and subject to increasing intensities of LW cavity field (lightening shades of red). Error bars indicate estimated single-shot uncertainty based on photon detection noise. Solid lines are fits to Eq. (1). The inset compares $\delta_{ac}$ from LW light measured at $\Delta/2\pi = -37$ MHz [gray line in Fig. 2(b)] with a prediction that is based on the estimated cavity circulating intensity, with a correction factor of 0.7 applied to account for a reduction in the ac Stark shift measured at the LW antinode due to spatial averaging by the finite temperature atomic distribution.

The detected photon counts provide a measure of $\delta_{ac}$, as demonstrated in Fig. 2(b). We place a tweezer-trapped atom at the antinode of the LW cavity mode and detect atomic fluorescence at different imaging detunings $\Delta$ and linearly increasing LW cavity intensities. For each LW intensity, we fit the dataset of photon counts vs $\Delta$ to the prediction of Eq. (1) and observe good agreement with the model. As expected from the level structure of $^{87}\text{Rb}$ [see Fig. 1(c)], increasing LW light shifts the atomic resonance downward ($\delta_{ac} < 0$), bringing the effective imaging-light detuning $\Delta - \delta_{ac}$ closer to resonance and increasing the atomic fluorescence.
For normal sensor operation, we determine the LW-light-induced $\delta_{ac}$ from the photon counts detected at a single $\Delta$. We convert the detected photons counts to $\delta_{ac}$ using Eq. (1) with parameters, such as the ac Stark shift due to the tweezer light, calibrated by a fit to reference data taken in absence of LW light [blue data in Fig. 2(b)]. As shown in the Fig. 2(b) inset, the measured values of $\delta_{ac}$ are consistent, to within systematic error, with our estimates of $\delta_{ac}$ based on measurements of the LW power at the cavity output, thus demonstrating the accuracy of the sensor. The uncertainty in the output power estimate of $\delta_{ac}$ is dominated by 20% uncertainty in the transmissivity of the cavity out-coupling mirror [26].

The sensitivity of a single $\delta_{ac}$ measurement is limited by photodetection noise, improving as $|\Delta - \delta_{ac}|$ decreases and the atomic scattering rate increases, until the atom is lost from the tweezer trap owing to ineffective laser cooling under imaging light that is too close to atomic resonance. The best sensor performance that we demonstrate occurs at a minimum imaging detuning of $|\Delta - \delta_{ac}| = 2\pi \times 30$ MHz. At this setting, pure shot noise on the photon number detected from a single atom would yield an ac Stark shift measurement sensitivity of $2\pi \times 250$ kHz/$\sqrt{Hz}$. In practice, read noise, background light, and additional noise due to atomic internal and motional dynamics increases the measured sensitivity to $2\pi \times 500$ kHz/$\sqrt{Hz}$.

By scanning the positions of several tweezer-trapped atoms and performing a fluorescence measurement at each position, we obtain a scanning-probe image of the LW cavity mode, shown in Fig. 3. We resolve both the coarse radial variation and also the fine-scale axial variation of the standing-wave Gaussian mode. By averaging repeated axial scans of the cavity field, we identify and correct for a slow drift of the tweezer positions relative to the optical cavity of up to 800 nm.

The contrast of the observed axial variation in $\delta_{ac}$ provides a measure of the spatial resolution of our sensor. The convolution of a full-contrast sinusoidal intensity pattern of period $d$ with a Gaussian point spread function of rms width $\sigma$ yields an expected contrast of $C = e^{-\pi r^2 / 2d^2}$, where $r = 2\sigma$ is the resolution limit according to the Sparrow criterion. The contrast achieved at various radial positions in Fig. 3(b) ranges between 0.30 and 0.47, which, with $d = 780$ nm, corresponds to $r$ between 380 and 300 nm. For comparison, the diffraction-limited Sparrow resolution of our NA = 0.5 microscope is 657 nm, and the fundamental free-space far-field diffraction limit for our imaging wavelength is 328 nm. We achieve superresolution with respect to both limits. Decreasing contrast at higher cavity field intensity indicates that the temperature of the atomic sensor increases, perhaps owing to poorer laser cooling in the presence of large state- and position-dependent ac Stark shifts. Using the axially averaged values of the ac Stark shift $\delta_{ac}$, we reproduce the radial Gaussian profile of the cavity intensity, observing a beam waist of 25.9(3) $\mu$m, in agreement with our a priori estimate of 24.3 $\mu$m based on the cavity geometry [27].

Next, we explore the limits of the single-atom sensor by applying it to map an optical field generated by shorter-wavelength light, the standing-wave Fabry-Pérot cavity mode at a wavelength of 781 nm, $2\pi \times 400$ GHz red-detuned from the atomic $D_2$ resonance. The shorter-wavelength light presents two coupled challenges to our sensing application. First, at fixed resolution, shorter-wavelength axial intensity variation with periodicity $d = 390.5$ nm is measured with lower contrast, estimated at just $C = 0.05$ for $r = 300$ nm. For our measurement times and sensitivities, this low contrast allows only relatively large ac Stark shifts to be measured. Second, large ac Stark shifts modulated at short length scales lead to strong optical forces that displace the trapped atom within the optical tweezer, complicating the interpretation of the measurement. Further, unlike the LW light, the SW light produces ac Stark shifts on the ground and excited atomic states that are comparable in magnitude, exacerbating the deflection of the ground-state atomic sensor.

We overcome these obstacles by driving the Fabry-Pérot cavity simultaneously at both its SW and LW resonances and measuring the total transition ac Stark shift provided by both optical fields. In a simplified interpretation, we use the
We note three distinct features that arise due to the SW light. First, the axial average of observed axial variation of the ac Stark shift from the LW light. Altogether, the SW lattice narrows and displaces the atomic distribution. If these antinodes overlap with the antinodes of the SW cavity mode, the cavity-light potential (green) and thermal atomic distribution (orange) due to the tweezer (left) and the sum of the tweezer and SW cavity field (right). The SW lattice narrows and displaces the atomic distribution. The SW light enhances the amplitude of the LW standing wave, the narrowing atomic distribution. If these antinodes overlap with the antinodes of the SW cavity mode, the cavity-light potential (green) and thermal atomic distribution (orange) due to the tweezer (left) and the sum of the tweezer and SW cavity field (right). The SW lattice narrows and displaces the atomic distribution.

FIG. 4. Force sensing measurement of SW cavity lattice through distortion of LW measurement. (a) Optical trapping potential (green) and thermal atomic distribution (orange) due to the tweezer (left) and the sum of the tweezer and SW cavity field (right). The SW lattice narrows and displaces the atomic distribution.

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