Atom Camera: Super-resolution imaging of an optical field with a single ultracold atom in an optical tweezers

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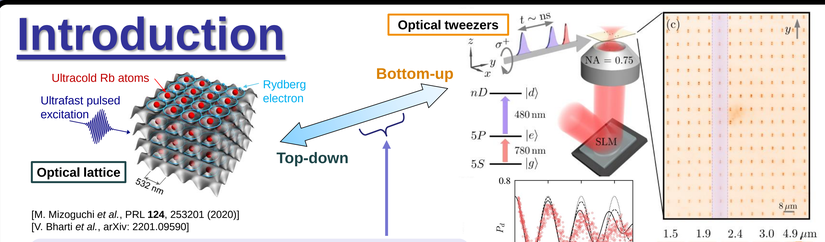
Introduction



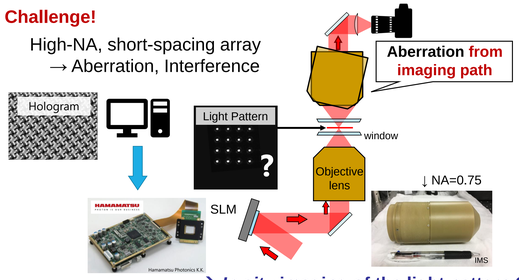
[M. Mizoguchi *et al.*, PRL **124**, 253201 (2020)]
[V. Bharti *et al.*, arXiv: 2201.09590]

Arbitrary-shape array with spacing < 1 μm ?
→ New hologram design with Hamamatsu Photonics

[Y. Chew *et al.*, arXiv: 2111.12314, in press]

Challenge!

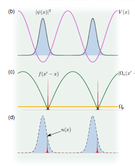
High-NA, short-spacing array
→ Aberration, Interference



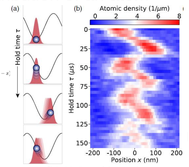
→ ***In situ*** **imaging of the light pattern ?**

Super-resolution imaging

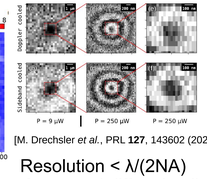
➢ Position/distribution of an atom



[S. Subhankar *et al.*, PRX **9**, 021002 (2019)]



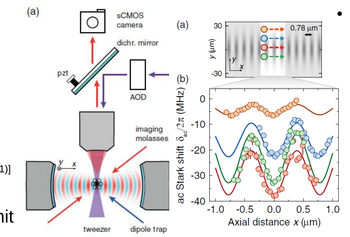
[M. McDonalds *et al.*, PRX **9**, 021001 (2019)]



[M. Drechsler *et al.*, PRL **127**, 143602 (2021)]

Resolution < λ/(2NA)
→ Beyond diffraction limit

➢ Optical field

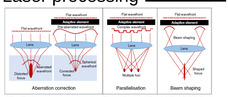


[E. Deist *et al.*, PRL **128**, 083201 (2022)]

- Diagnose light patterns
  → Precise beam shaping for
  - Microscopic quantum control

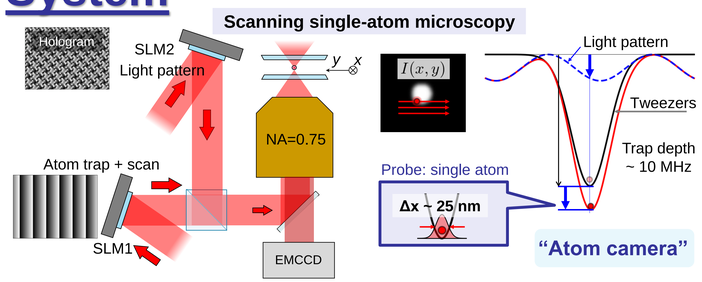
[P. Zupancic *et al.*, Opt. Express **24**, 13881 (2016)]

- Laser processing

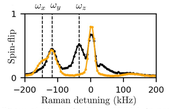


[P. Salter *et al.*, Light Sci. Appl. **8**, 110 (2019).]

System



- ☐ Measure the additional light shift with the **hyperfine spin: quantum sensing**
- ☐ Scan the atom position → Image the light profile
- ☐ Apply the **Raman sideband cooling** to cool the atom in the motional ground state of the tweezers.

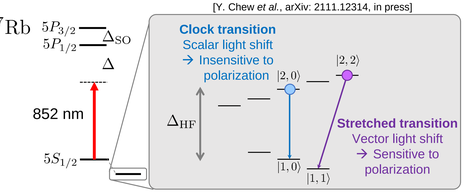


[Y. Chew *et al.*, arXiv: 2111.12314, in press]

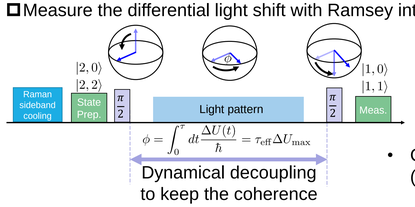
- ☐ Differential light shift:
  $\Delta U = U_{F=2} - U_{F=1}$

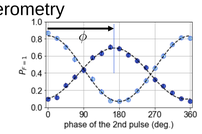
Clock transition:
$\Delta U_s = \eta_s U_s$
$\eta_s \sim \frac{\Delta_{\mathrm{HF}}}{\Delta} = 2.34 \times 10^{-4}$

Stretched transition:
$\Delta U_v = \eta_v C U_s$
$\eta_v \sim \frac{\Delta_{\mathrm{SO}}}{3\Delta} = 8.74 \times 10^{-2}$ C: Ellipticity



- ☐ Measure the differential light shift with Ramsey interferometry

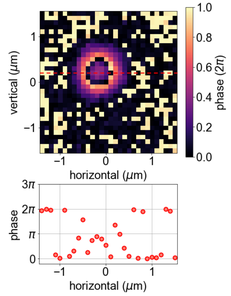




- Coherence time ~ 100 ms with XY-4 (Clock transition)

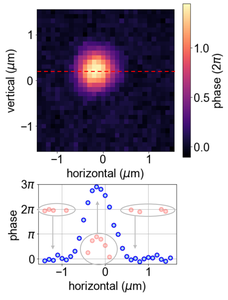
Result

☐ Intensity profile: scalar light shift measurement



Tightly-focused Gaussian beam
- Scan step: 100 nm
- N = 100 shots (~ 50shots w/ atom)
- $\tau_{\mathrm{eff}} = 16$ ms
- $\phi = 2\pi \Leftrightarrow \Delta U/h = 62.5$ Hz
  $\Leftrightarrow U/h = 267$ kHz

Phase unwrapping
Restoring the physical continuity of the phase



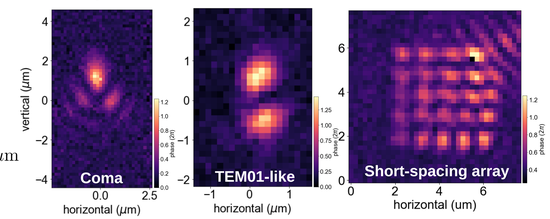
➢ **Resolution**

For a gaussian beam,
$w_{\mathrm{image}} = \sqrt{w^2 + r^2}$
r : Width of the PSF =: "Resolution"
$w = 0.67(3)\ \mu\mathrm{m}$ $\quad w_{\mathrm{image}} = 0.63(1)\ \mu\mathrm{m}$

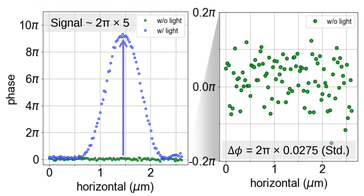
Consistent with the probe size ~ 25 nm
$r < 0.2\ \mu\mathrm{m} : r = 0.2\ \mu\mathrm{m} \Rightarrow w_{\mathrm{image}} = 0.73\ \mu\mathrm{m}$

→ **Beyond diffraction limit**

➢ **Gallery**



➢ **S/N ratio: ~ 200**



- Quantum projection noise
  $\Delta\phi_{\mathrm{QPN}} \leq \frac{1}{C\sqrt{N}} = 2\pi \times 0.0283$
  C: Ramsey fringe contrast
  N: Number of data

→ **Quantum projection noise limited**

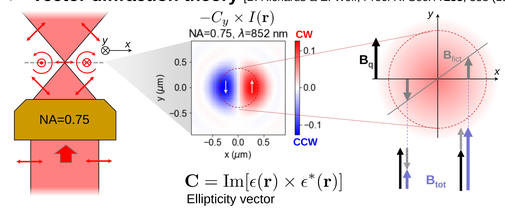
- Noise level
  $\phi = 2\pi \times 0.0275 \Leftrightarrow \Delta U/h = 1.72$ Hz
  $\Leftrightarrow U/h = 7.34$ kHz
  $\ll \Gamma/2\pi = 6$ MHz
- Intensity of the light
  $U/h = \tilde{\alpha} I$: $\tilde{\alpha}$ polarizability
  $\tilde{\alpha} = 0.12\ \mathrm{kHz}/(\mathrm{W/cm^2})$ for $\lambda = 852$ nm
  → Noise level ⇔ 0.6 μW/μm²

☐ Polarization profile: vector light shift measurement

Target: tightly-focused gaussian beam: the polarization distribution is not homogeneous…!

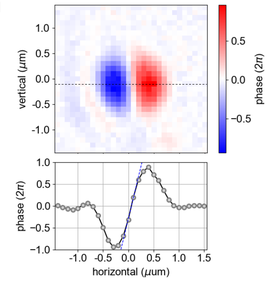
Cold atom experiment: [J. D. Thompson *et al.*, PRL **110**, 133001 (2013); B. Albrecht *et al.*, PRA **94**, 061401(R) (2016); K.-P. Wang *et al.*, Chin. Phys. Lett. **37**, 044209 (2020)]

➢ **Vector diffraction theory** [B. Richards & E. Wolf, Proc. R. Soc. A **253**, 358 (1959)]



$\mathbf{C} = \mathrm{Im}[\epsilon(\mathbf{r}) \times \epsilon^*(\mathbf{r})]$
Ellipticity vector
- Linear: |C| = 0
- Circular: C = 1(CCW), C = -1(CW)

$\epsilon(\mathbf{r})$:Normalized E-field



- Incident beam : linear along the *x* axis
- Focal plane (off-axis):
  → Spatially varying **elliptic polarization** along the ***y*** axis

  Largest gradient of *C* : $\frac{dC_y}{dx} = 3.1\mathrm{NA}\sin\mathrm{NA}/\lambda = 2.3/\mu\mathrm{m}$

- Vector light shift
  = Zeeman shift by "**fictitious B-field**" $\mathbf{B}_{\mathrm{fict}} \propto -\mathbf{C}$

- $\tau_{\mathrm{eff}} = 100\ \mu\mathrm{s}$
- $\phi = 2\pi \Leftrightarrow \Delta U/h = 10$ kHz
- Trap depth (scalar) = 330 kHz
- Largest gradient of B_{fict}
  $\frac{dB_{\mathrm{fict},y}}{dx} = 24\ \mathrm{mG}/\mu\mathrm{m}$
  $0.8\ \mathrm{G}/\mu\mathrm{m}$ for 10 MHz trap

Summary / Prospect

- ✓ Scanning microscopy with a single ^{87}Rb atom
- ✓ The atom is cooled down to the motional ground state in the tweezers by the Raman sideband cooling.
- ✓ The resolution is beyond diffraction limit: consistent with the spread of the atom ~ 25 nm.
- ✓ The intensity / polarization of light is detected by the hyperfine spin in the atom with the Ramsey interferometry.
- ✓ Reduction of the data taking time: 1 min./px → multi-probe, non-destructive measurement
- ✓ Z-axis scanning for 3D imaging
- ✓ Hologram design for light patterns with sub-micron structure