Non-destructive spatial heterodyne imaging of cold atoms

S. Kadlec, J. Sebby, R. Newell, and T. G. Walker

Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin, 53706

(October 25, 2018)

We demonstrate a new method for non-destructive imaging of laser-cooled atoms. This spatial heterodyne technique forms a phase image by interfering a strong carrier laser beam with a weak probe beam that passes through the cold atom cloud. The figure of merit equals or exceeds that of phase-contrast imaging, and the technique can be used over a wider range of spatial scales. We show images of a dark spot MOT taken with imaging fluences as low as 61 pJ/cm\(^2\) at a detuning of 11Γ, resulting in 0.0004 photons scattered per atom.

In this paper we demonstrate a new “spatial heterodyne” method for non-destructive imaging of trapped atoms. As with other non-destructive techniques, spatial heterodyne imaging minimizes the number of absorbed photons required for an image and is therefore particularly useful in applications such as Bose-Einstein Condensation [1], magnetic trapping, and far-off-resonance imaging [2] of cold atoms. As with other non-destructive techniques, spatial heterodyne imaging minimizes the number of absorbed photons required for an image and is therefore particularly useful in applications such as Bose-Einstein Condensation [1], magnetic trapping, and far-off-resonance imaging [2].

Non-destructive detection without imaging was recently demonstrated using FM spectroscopy [7]. The most popular of these methods, the phase-contrast technique, uses a small (\(\sim 10 - 100 \mu m\)) \(\pi/2\) phase mask that is inserted into the imaging laser focus at the Fourier plane of an imaging lens. In the image plane the \(\pi/2\) phase-shifted laser field interferes with the signal field produced by the atoms to give an image intensity that is linear with respect to the atom-induced phase shift.

To implement spatial heterodyne imaging, we used two laser beams: a carrier laser beam which does not pass through the trapped atoms, and a probe beam which is phase shifted as it passes through the atom cloud. The beams are coincident on a CCD camera and straightforward digital image processing techniques use the resulting interference pattern to reconstruct the phase shift due to the cloud.

Spatial heterodyne imaging has several practical advantages for non-destructive imaging. First, there is no need for precision fabrication and alignment of a phase plate. Second, it has a significant signal-to-noise advantage for low imaging intensities. Third, at high intensities it has a larger signal per absorbed photon, allowing the large dynamic range of CCD cameras to be better used. Fourth, the method works over a wide range of spatial scales. Finally, rejection of spurious interference fringes due to various optical elements such as vacuum windows is automatically accomplished.

The principle of spatial heterodyne imaging is similar to heterodyne spectroscopy [4], with interference occurring in the spatial rather than the temporal domain. As shown in Fig. 1b) a probe beam of intensity \(I_p\) travels through a cloud of trapped atoms and accumulates a position dependent phase shift \(\phi(r)\) due to the index of refraction of the atoms. A lens placed in this beam images the atom cloud onto a CCD detector. A carrier beam of intensity \(I_c\), and derived from the same laser as the probe beam interferes with the probe beam at an angle \(\theta\). For convenience, we assume equal radii of curvature for the carrier and probe beams. The interference pattern on the CCD detector \(I(r)\) is a set of straight line fringes whose position is determined by an overall phase shift between the beams \(\chi\), and which are distorted by the accumulated phase shift from the atoms:

\[
I(r) = I_c + I_p + 2\sqrt{I_c I_p} \cos(\chi + 2\pi k_L \cdot r - \phi(r))
\]

from which \(\phi(r)\) can be reconstructed. Here \(k_L\) is a unit vector pointing along the direction of the component of the carrier wavevector \(k\) perpendicular to the direction of the probe beam.

The phase shift \(\phi\) is most easily determined in two limits: \(\theta \ll \delta/\lambda\) (parallel mode) and \(\theta \gg \delta/\lambda\) (tilted mode), where \(\delta\) is the desired resolution element on the image. In the parallel mode the phase of the interference pattern is uniform across the cloud image, and the resulting interference pattern is \((\chi = \pi/2)\):

\[
I(r) = I_c + I_p + 2\sqrt{I_c I_p} \sin \phi(r)
\]

If \(I_c = I_p\), this is identical to phase contrast imaging. If not, the signal size is increased by a factor of \(\sqrt{I_c/I_p}\).
The spatial variation of the phase shift from the cloud becomes a spatial variation of the intensity at the CCD detector, producing a real image on the detector. In practice the phase shift $\chi$ between the two beams must be stabilized using feedback.

For this paper we have implemented spatial heterodyne imaging in the tilted mode. In this case a set of high spatial frequency fringes appear and the effect of the atom cloud is to give a spatially varying phase shift to these fringes. The analysis of the fringes then proceeds in a manner highly analogous to lock-in detection: we demodulate the interference pattern to zero spatial frequency and apply a low-pass filter to the result. FFT techniques make the demodulation and filtering efficient (2 sec for a $784 \times 520$ pixel camera on a 400 MHz Pentium). It is not necessary to stabilize the relative phase between the probe and carrier beams.

To demonstrate the method we use an atom cloud with an on-resonant optical thickness of about 15 in a dark spot $^{87}\text{Rb} \quad \text{MOT}$ [8,9]. The experimental arrangement is shown in Fig. 1b. Typically $3 \times 10^7$ atoms from a MOT are accumulated in the dark state at a density of roughly $5 \times 10^{11} \text{ cm}^{-3}$ by imaging a 1 mm obstruction in the MOT repumping laser onto the trap. The atoms in the dark spot are quite sensitive to resonant light and hence absorption imaging is difficult. The imaging laser beam is tuned in the range of $2 - 11\Gamma$ from the $^{87}\text{Rb} \quad 5S_{1/2}(F=1) \rightarrow 5P_{1/2}(F=2)$ resonance, switched via an acousto-optic modulator, and then split into two beams by a non-polarizing beamsplitter. The probe beam is attenuated by a factor of 1-200 by a neutral density filter before passing through the atom cloud, which is imaged onto a CCD array. An interference filter placed in the Fourier plane of the imaging lens rejects $780 \text{ nm}$ fluorescence from the bright state trapped atoms. The carrier passes around the vacuum chamber and is incident on the CCD detector tilted at an angle $\theta \approx 1$ deg. For convenience, we roughly match the radii of curvature of the probe and carrier beams at the CCD, to produce nearly straight fringes. We tilt the fringes at an angle of typically $30^\circ$ from the rows of the CCD chip to avoid aliasing.

Two competing factors determine the optimum angle $\theta$. As with lock-in detection, it is important to modulate the signal at somewhat higher spatial frequency than the smallest feature to be resolved. The finite camera pixel size sets an upper limit on the modulation frequency without loss of fringe contrast. We find that a fringe spacing of 4-5 pixels is a good compromise between resolution and fringe contrast. In the parallel mode the full resolution of the camera is achieved.

To begin processing we subtract off reference images of each laser beam. This leaves only the interference term in Eq. 3 which we Fourier transform. The transform contains the phase image information in two sections centered on spatial wavenumbers $k_0 = \pm 2\pi\theta/\lambda$. We shift one of these sections to zero spatial frequency and attenuate the high frequencies with a filter, typically the Gaussian filter $\exp(-3(k/k_0)^2)$. Finally, we take the inverse transform whose phase ($\tan^{-1}(\text{Im}/\text{Re})$) is $\phi(r)$. This procedure automatically reduces spurious interference fringes that arise from various optical elements since they are likely to be at the wrong spatial frequency. To compensate for slight curvature of the interference fringes, we subtract $\phi(r)$ from another image, similarly processed, but taken in the absence of atoms. This also reduces distortion due to spatial inhomogeneities in $L_c$ and $L_p$.

Figure 2 shows several images $\phi(r)$ taken using the above procedure. At a typical line-center optical thickness of 3-15 we have successfully imaged the dark spot trap for a variety of detunings and carrier-to-probe intensity ratios $r$. Fig. 2a) shows a typical image with $r = 20$, $\Delta = -11\Gamma$, and about $1.2 \times 10^{-3}$ scattered photons per atom. As another example, Fig. 2b) shows an image taken at $\Delta = -11\Gamma$ and $r = 60$. The total fluence used to make the image was only 61 pJ/cm$^2$, corresponding to 0.0004 photons scattered per atom. The S/N ratio on a given resolution element is about 10 for this image.
Depending on the details of the imaging system, filtering of the Fourier transform may limit the spatial resolution of the final image. In our system, with a magnification of 5 and a CCD pixel spacing of 8.8 $\mu$m, the resolution is limited to about 20 $\mu$m, compared to a theoretical diffraction limit of about 5 $\mu$m. Fig. 2 shows an image of a 50 $\mu$m wide trap.

Depending on the application, the figure of merit for spatial heterodyne imaging is comparable with or superior to phase contrast imaging. For simplicity, we consider here the parallel mode. The intensity pattern is $I_c + I_p + 2\sqrt{I_c I_p} \cos(\chi - \phi(x))$, $I_c$ and $I_p$ are measured in numbers of photons. For small phase shifts and $\chi \approx \pi/2$, the signal size is approximately $2\eta \sqrt{I_c I_p} \phi$ where $\eta$ is the quantum efficiency of the detector, typically $\sim 0.3$ for CCD chips in the near infrared. Noise sources include shot noise and other sources of technical noise, $b$, such as the camera read noise and finite resolution of the camera’s A/D converter. The signal-to-noise ratio is therefore

$$\frac{S}{N}_{\text{SH}} = \frac{2\eta \sqrt{I_c I_p} \phi}{\sqrt{I_c + I_p} + b^2}$$

The maximum $S/N$ occurs for $I_c \gg I_p, b^2/\eta$, giving

$$\frac{S}{N}_{\text{max}} = 2\phi \sqrt{\eta I_p}$$

which shows that there is a minimum number of photons that must be scattered from the atoms to achieve a given S/N. A similar relation holds for phase contrast imaging.

A natural figure of merit for non-destructive imaging is the number of absorbed photons required to attain the desired signal to noise ratio. For optically thick clouds this number is greatly reduced because the probing can be done at large detuning [2]. Thus the shot-noise limited figure of merit for either technique is

$$\frac{S}{N} \approx \frac{2\phi \sqrt{\eta I_p}}{\alpha I_p} \approx \frac{2\Delta}{\Gamma} \sqrt{\frac{\eta}{I_p}}$$

for $\Delta \gg \Gamma$.

When the technical noise $b$ is significant, however, spatial heterodyne imaging has a better S/N ratio than phase contrast imaging. Figure 3 compares the S/N ratio per radian of phase shift for the two techniques. As with any heterodyne method, the interference between the carrier and the signal boosts the signal level at a given probe intensity.

Furthermore, for highest quality images it is desirable to maximize signal size and thereby minimize the discretization errors from the A/D converter. In this case the spatial heterodyne method offers a $\sqrt{r}$ performance enhancement as compared to the phase contrast technique. Fig. 2b shows an image taken with $r = 60$, representing 3 bits of increased signal size for fixed absorption.

We have demonstrated the spatial heterodyne method for non-destructive imaging of trapped atoms and shown that it has some advantages over other techniques. Our method is a special case of of a more general class of holographic imaging techniques that could be used with cold atoms.

Support for this research came from the NSF. We acknowledge helpful communications with D. Jin, W. Ketterle, and S. Rolston, and assistance from N. Harrison.

[1] M. Anderson et al., Science 269, 198 (1995); K. Davis et al., Phys. Rev. Lett. 75, 3969 (1995); C. Bradley, C. Sackett, and R. Hulet, Phys. Rev. Lett. 78, 985 (1997).
[2] W. Ketterle, D.S. Durfee, and D.M. Stamper-Kurn, In "Bose-Einstein condensation in atomic gases, Proceedings of the International School of Physics "Enrico Fermi", Course CXL," edited by M. Inguscio, S. Stringari and C.E. Wieman (IOS Press, Amsterdam, 1999) pp. 67-176.
[3] M. R. Andrews, M.-O. Mewes, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle, Science 273, 84 (1996).
[4] C. C. Bradley, C. A. Sackett, and R. G. Hulet, Phys. Rev. Lett. 79, 985 (1997).
[5] M. R. Andrews, D. M. Kurn, H.-J. Miesner, D. S. Durfee, C. G. Townsend, S. Inouye, and W. Ketterle, Phys. Rev. Lett. 79, 553 (1997).
[6] A. Yariv, Optical Electronics (New York: Holt, Rinehart, and Winston) 305 ff.
[7] V. Savalli, G. Horvath, P. Featonby, L. Cognet, N. Westbrook, C. Westbrook, Opt. Lett. 24, 1552 (1999).
[8] W. Ketterle, K. B. Davis, M. A. Joffe, A. Martin, and D. E. Pritchard, Phys. Rev. Lett. 70, 2253 (1993).
[9] M. H. Anderson, W. Petrich, J. R. Ensher, and E. A. Cornell, Phys. Rev. A 50, R3597 (1994).