Phase Shifting Interferometry of Cold Atoms

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Outline

- Introduction
- Research Motivation
- Phase Shifting Interferometry (PSI) - Theoretical Background and Practical Scheme for Experiment
- Simulation Results
- Possible Future Applications
- Conclusions

Introduction

Direct imaging on cold atoms provides information in both spatial and momentum spaces!

Typical ***single-beam*** imaging methods:

Destructive imaging:

fluorescence and absorption

Nondestructive imaging:

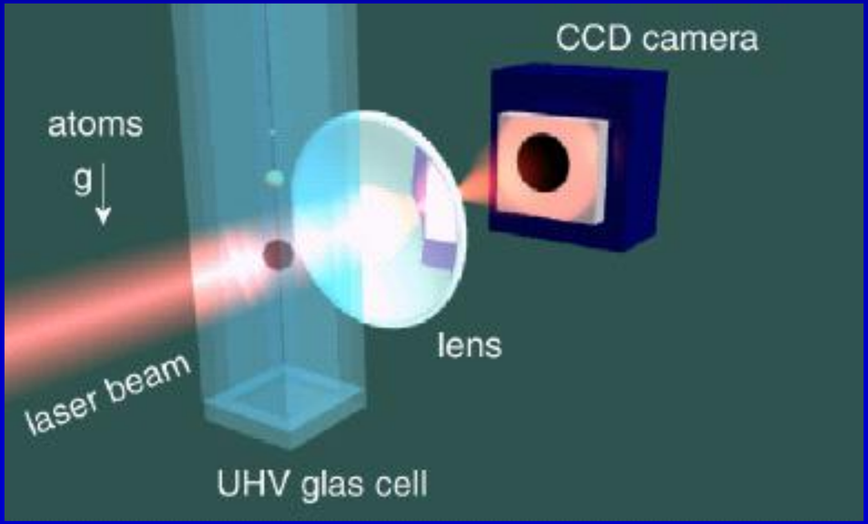
phase contrast and dark-ground

Andrews et al., Science **273**, 84 (1996)
Bradley et al., Phys. Rev. Lett. **78**, 985 (1997)

Destructive Imaging

Fluorescence and absorption methods:

- Relies on photon absorption!
- Works on Near resonance condition!
- Deposits large heating and accompanies with large inelastic collisions!



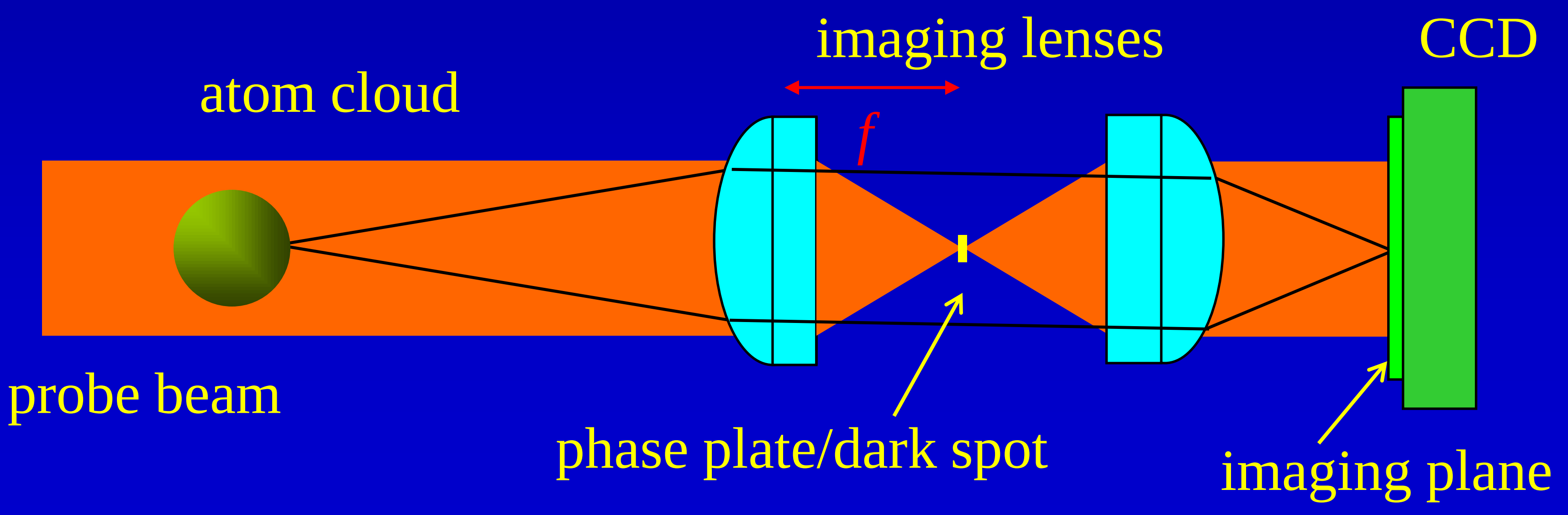
Harmful to the cold clouds, but relatively easier to set up!!

Nondestructive Imaging

Phase contrast (homodyne detection) and dark-ground methods:

- Relies on photon refraction!
- Works on Far-off resonance condition!
- Deposits less/negligible heating and accompanies almost no inelastic collisions!

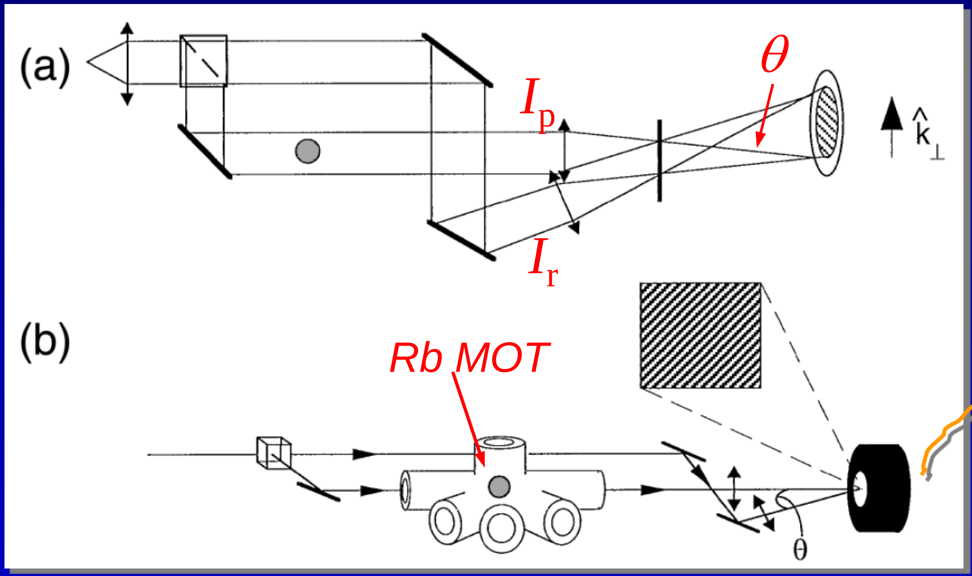
Less harmful!!
Very sensitive working condition, however!!



Nondestructive Spatial Heterodyne Imaging (SHI)
(two-beam detection)

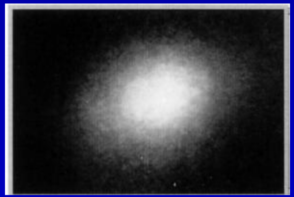
Kadlecek et al., Opt. Lett. **26**, 137 (2001)

$$I(x) = I_r + I_p + 2\sqrt{I_r I_p}\,\cos[\Delta\varphi + 2\pi\theta \hat{k}_\perp \frac{\vec{x}}{\lambda} - \phi(\vec{x})]$$



$\Delta\varphi = \varphi_1 - \varphi_2$
= *phase difference between the two beams!*

position-dependent phase shift: phase image
$\phi(\vec{x})$



Due to θ ≠ 0, phase image is imbedded in spatial fringes of frequency $f \sim \theta/\lambda$, with f >> characteristic frequency of the cloud!

Specialties about SHI

1. To retrieve phase image it requires time-consuming and case sensitive algorithms, such as FFT and spatial filtering! (Bad!)
2. The minimum spatial resolution in the above SHI is strongly limited by the spatial frequency of the interference fringes! (Bad!)
3. The S/N ratio can be kept invariant by lowering I_p while increasing I_r the same proportion! It thus allows much lower probe power! (Good!)

Working in another extreme where $\theta = 0$ and thus no spatial fringe appears should eliminate the above disadvantages!

However, a different approach to retrieve the phase image is required!

Research Motivation

(find an alternative solution for phase image retrieval!)

Conventional phase shifting interferometry (PSI) has been widely used for nondestructive detection on living cells and microfabricated chip surface measurements!

Allows to reach depth resolution of few nm!

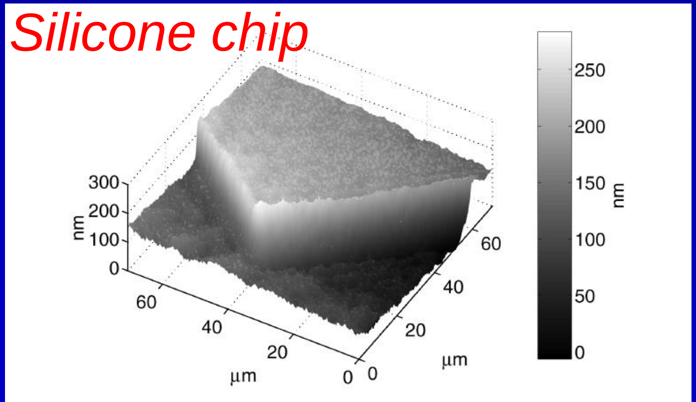


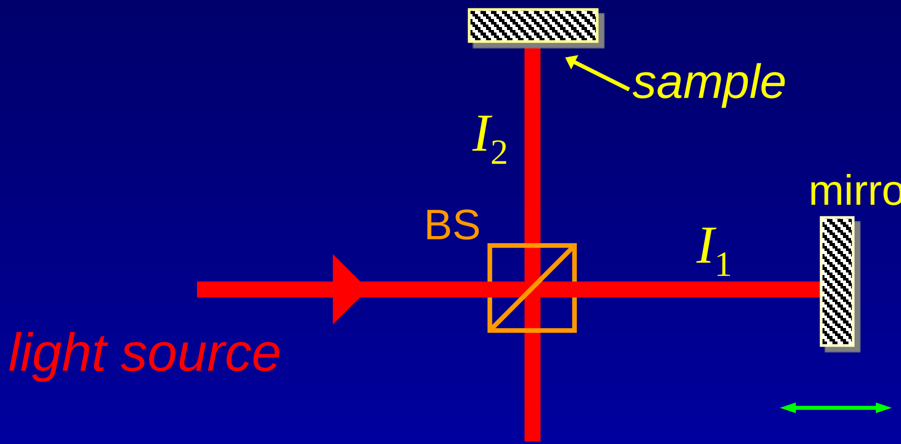
Fig. 3. Reflection phase image at the corner of a micro-fabricated silicon structure. The phase distribution is expressed as a surface height profile.

Iwai et al., Opt. Lett. ***29****, 2399 (2004)*

Phase Shifting Interferometry (PSI)

A stable optical phase shifter is required!

- *Fast measurement allowed*
- *High longitudinal accuracy*
- *Offset effects from the detected signal are cancelled out by subtraction*
- *Gain effects are eliminated by taking the ratio*



moving for phase adjustment

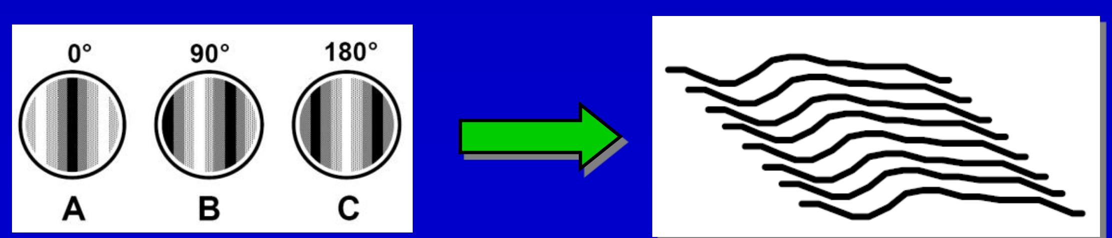
I_T: *interferograms under different* $\Delta\varphi$

$$I_T(x, y) = I_1 + I_2 + 2\sqrt{I_1 I_2}\,\cos\,[\Delta\varphi + \phi(x, y)]$$

Typically, taking minimum 3 interferograms by setting different values on $\Delta\varphi$
optical phase difference Θ(x, y) can be retrieved by

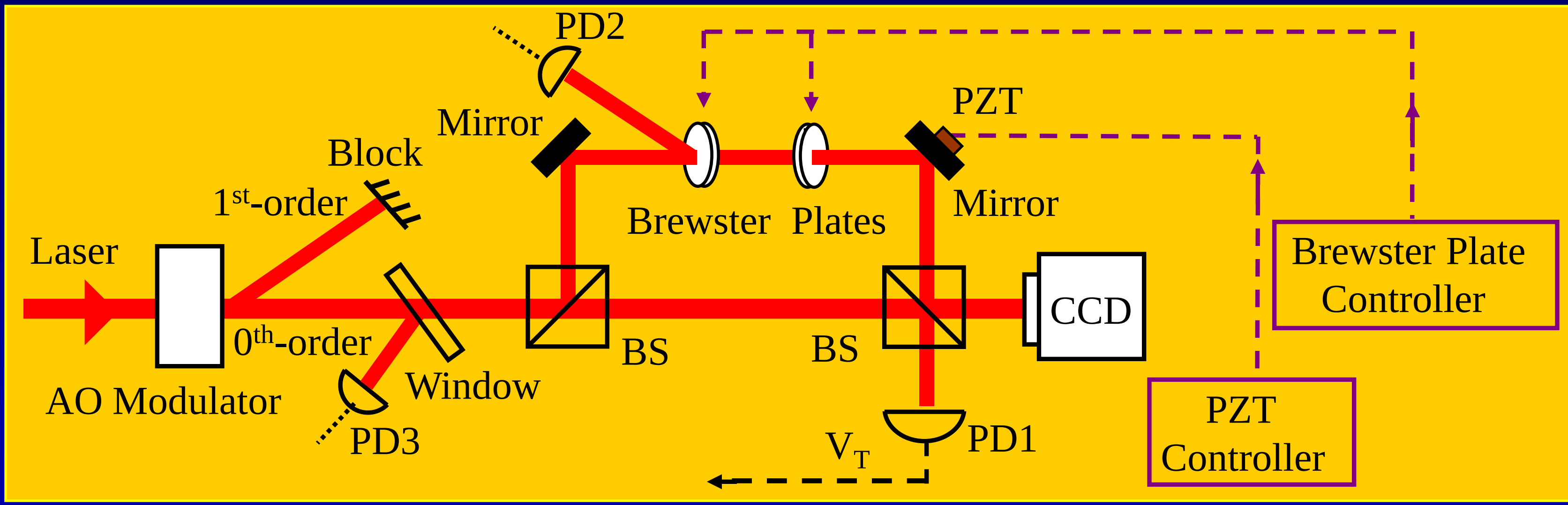
$$\phi(x, y) = \frac{\lambda}{2\pi}\tan^{-1}\left(\frac{C\text{-}B}{A\text{-}B}\right)$$

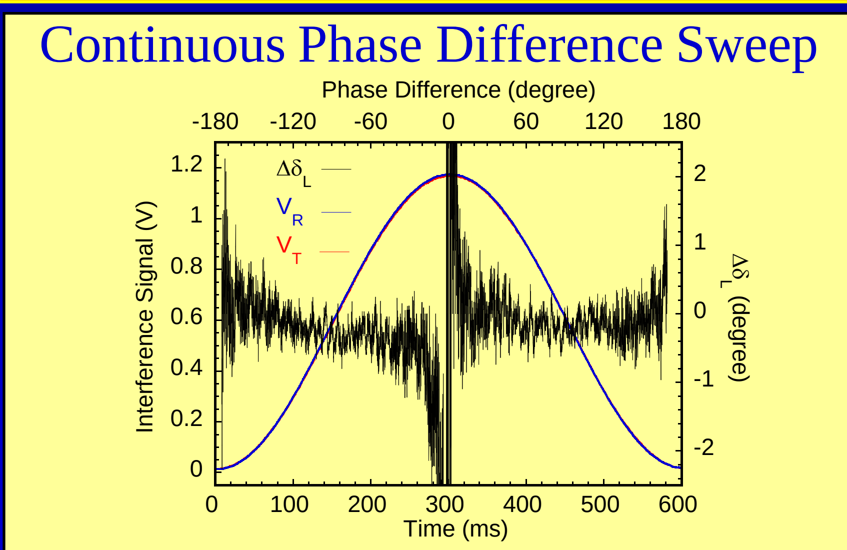
$\Delta\varphi \rightarrow$

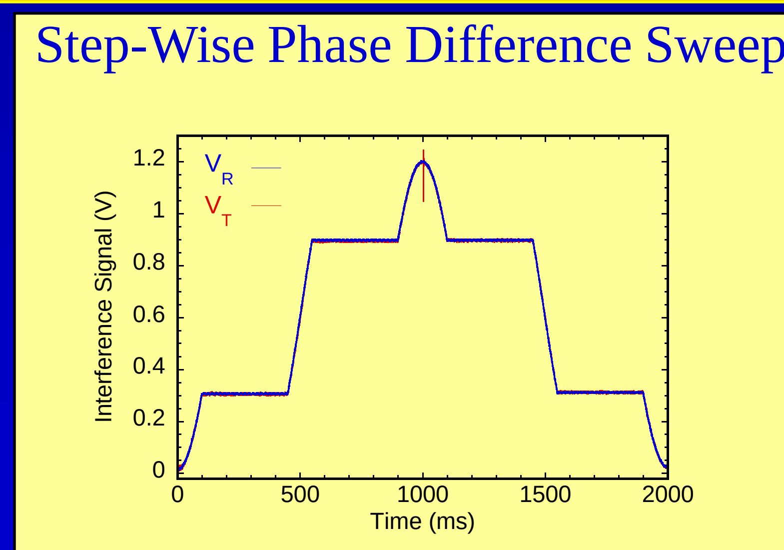


phase image
Θ(x, y)

Our previous work on real-time tunable optical phase shifter using a Mach-Zehnder interferometer should allow to engage PSI for cold atoms!







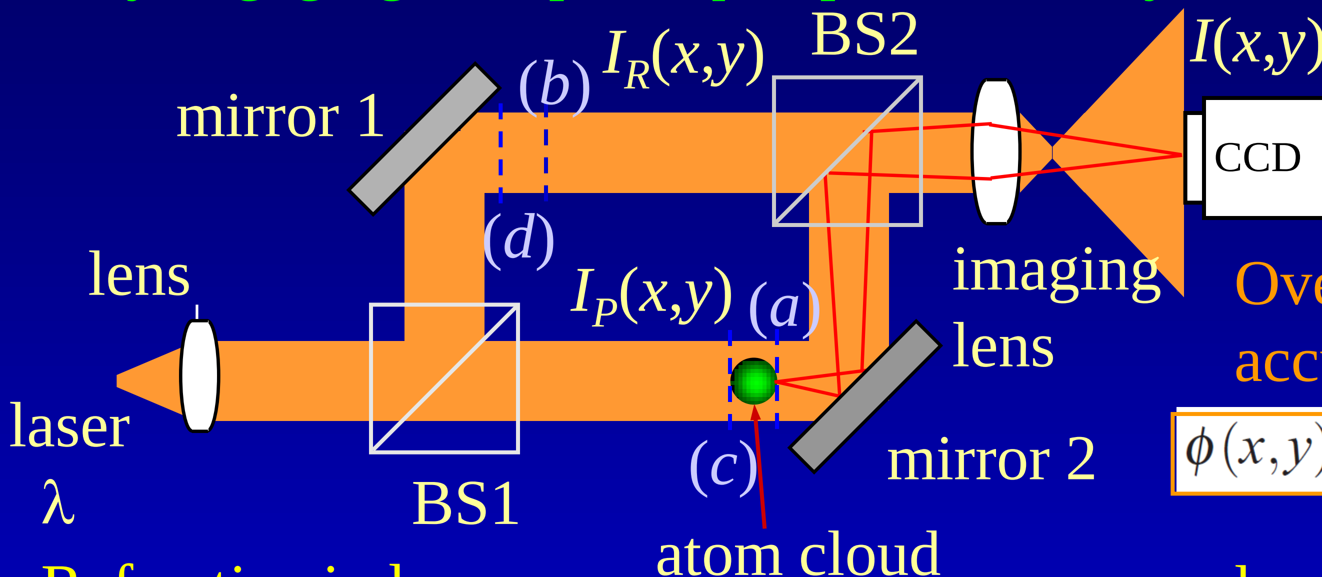
phase fluctuation < 1°!

Shiau et al., JPSJ **79**, 034302 (2010)

Our Scheme for Nondestructive SHI Using PSI

Spatial heterodyne imaging under $\theta = 0$!

By engaging 4-step of equal phase shift by $\pi/2$!



Overall additional phase accumulated by probe:

$$\phi(x,y) = \left(\frac{2\pi}{\lambda}\right) \cdot \int_c [n(\vec{\mathbf{r}}) - 1]\,dz$$

Refractive index:

$$n(\vec{\mathbf{r}}) = 1 + \rho(\vec{\mathbf{r}}) \frac{\sigma_0 \lambda}{4\pi} \frac{i - 2\Delta}{1 + 4\Delta^2} \equiv n_R + i n_I$$

ρ: cloud density distribution

Δ: probe detuning

σ_0: on-resonance absorption cross section

Phase distribution (image):

$$\phi(x,y) = \tan^{-1}\left\{\frac{[I_\pi(x,y) - I_0(x,y)]\sin(\pi\zeta/2)}{[I_{\pi/2}(x,y) - I_{3\pi/2}(x,y)] - [I_\pi(x,y) - I_0(x,y)]\cos(\pi\zeta/2)}\right\} - \frac{\pi\zeta}{2}$$

$\zeta = \lambda_L/\lambda$, λ_L = locking beam wavelength!

Special Concerns on Cold Atoms

Cloud heating and state flipping must be small!

Heating rate: $\frac{dT}{dt} = 2\gamma_S \cdot E_R$

$$\gamma_S = \frac{\Gamma}{2}\frac{S}{1+S}$$

$$S = \frac{I}{I_S}\frac{1}{4\Delta^2+1}$$

Γ: spontaneous decay rate

I_s: saturation intensity

$E_R = \frac{\hbar^2 k^2}{2m}$ recoil energy

Requirement:

$$\frac{2\gamma_S \cdot E_R \cdot t_p}{k_B} << T$$

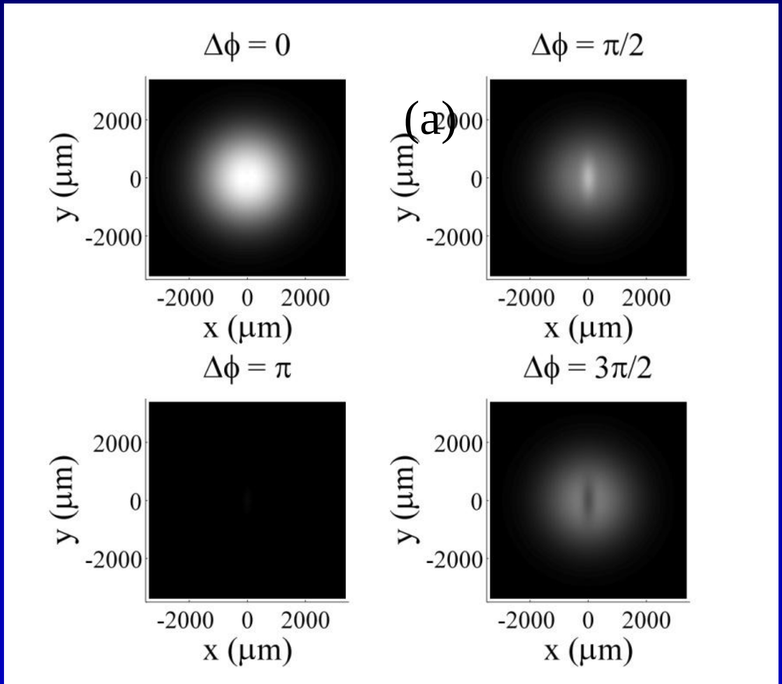
t_p: probe time

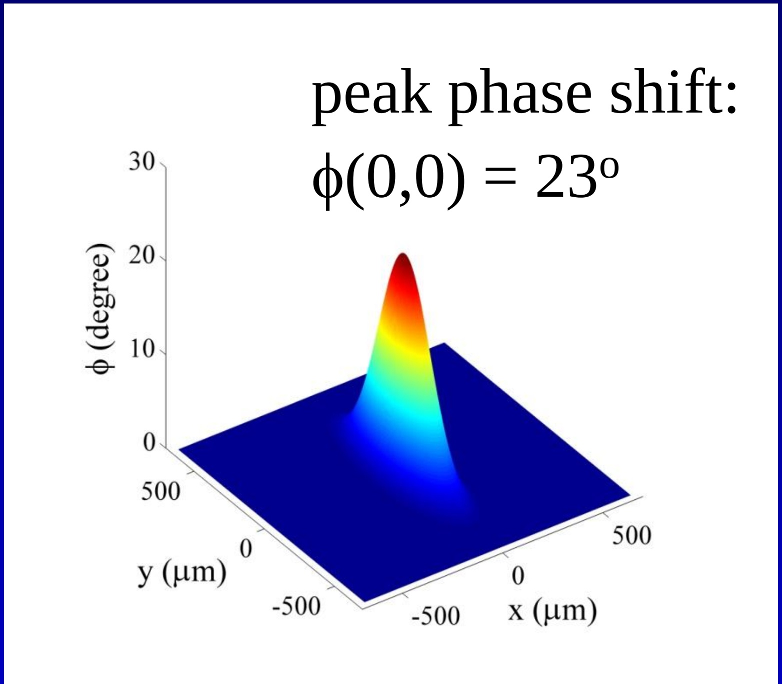
T: cloud temperature

k_B: Boltzmann constant

Simulation Results

A cigar shape cloud (under typical evaporation condition)!





$N = 8\times10^6$ atoms, T ~ few μK

$\rho_0 = 1.0\times10^{12}$ atoms/cm^3

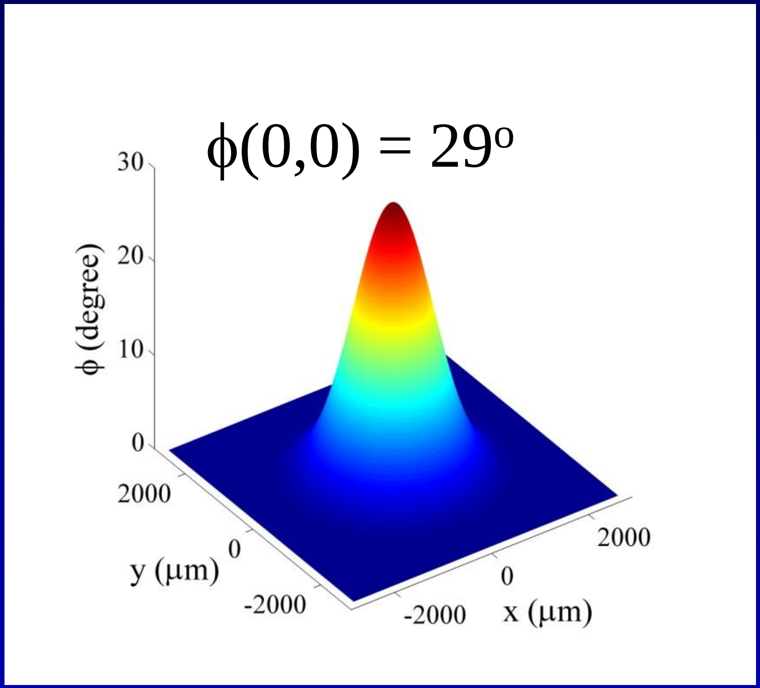
$\sigma_y/\sigma_x = 3$ $\sigma_x = \sigma_z = 55$ μm

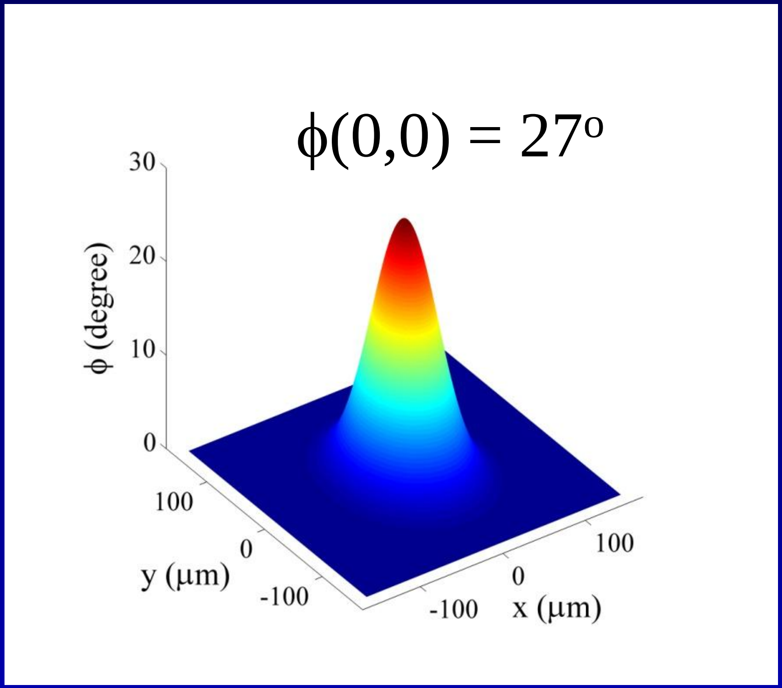
$\Delta = 100$ MHz

$t_p = 1$ ms

ΔT ~ 63 nK (negligible!)

t_p = 1 ms!





An isotropic cloud (dark MOT)!

$N = 1\times10^9$ atoms, $T \sim 200\ \mu$K

$\rho_0 = 2.0\times10^{11}$ atoms/cm^3

$\sigma_x = \sigma_y = \sigma_z = 680\ \mu$m

$\Delta = 200$ MHz

$\Delta T \sim 63$ nK (negligible!)

A near pancake cloud!

$N = 6\times10^6$ atoms, $T \sim 2\ \mu$K

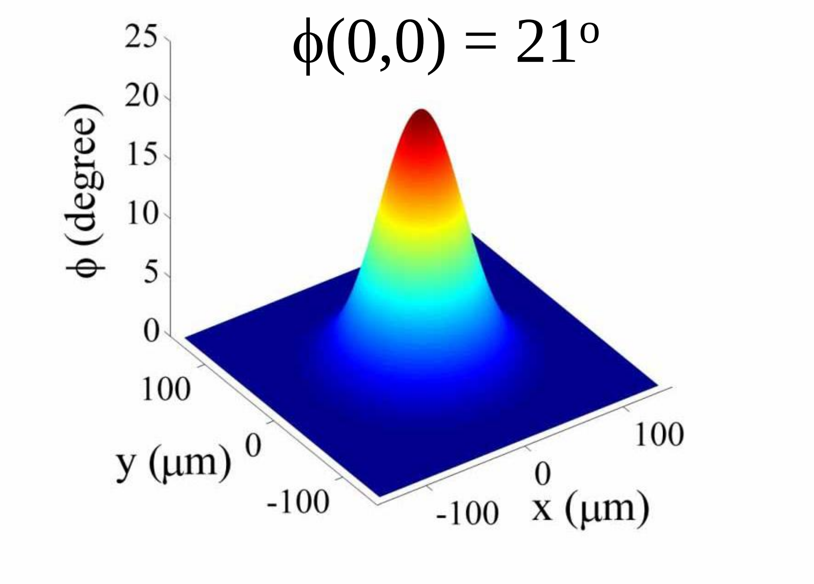
$\rho_0 = 1\times10^{14}$ atoms/cm^3

$\sigma_x = 30.8\ \mu$m, $\sigma_y \sim 38.5\ \mu$m

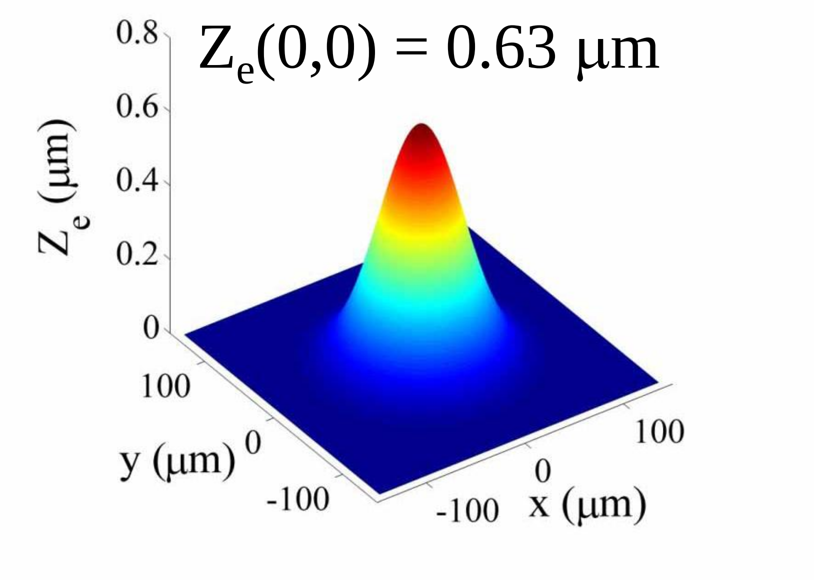
$\sigma_z = 3.2\ \mu$m

$\Delta = 500$ MHz $\quad \Delta T \sim 3$ nK

Longitudinal Resolution for A Pure 2D Cloud



lens diffraction limit ~ 1.9 μm!



$N = 1\times10^6$ atoms, T ~ few μK

$\rho_0 = 5.0\times10^{14}$ atoms/cm^3

$\sigma_x = \sigma_y \sim 35$ μm, $\sigma_z \sim 0.25$ μm

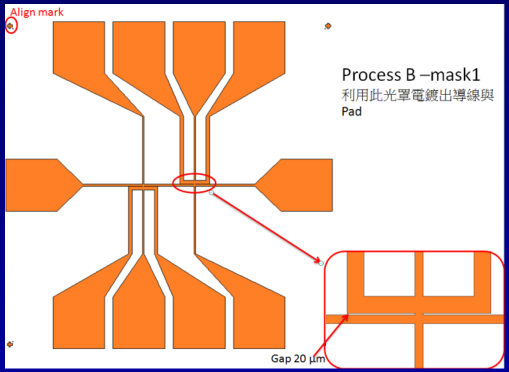
$\Delta = 100$ MHz

$t_p = 1$ ms

$\Delta T \sim 63$ nK (negligible!)

Effective thickness: $Z_e(x,y) = -\dfrac{(1+4\Delta^2)}{\rho_0\sigma_0\Delta}\cdot\phi(x,y)$

Special Features for Application on Atom Chip



- ✓ A reflection type PSI!
- ✓ Phase shift thus doubled!
- ✓ Imaging both chip wires and cloud altogether!
- ✓ Precise delivery of cloud to the desired position for further manipulation!
- ✓ Possible mapping out the B-field on chip surface too!

Comparison between Our Scheme and the Tilted SHI

Advantages (Ours):

1. Phase image reconstruction is rather straightforward!
2. More robust against phase noise since an active stabilized phase shifter is injected! Thus it provides better longitudinal resolution!
3. The transverse resolution of phase image in our scheme is mainly set by the diffraction limit of the final imaging lens. Our scheme is also superior in transverse resolution, especially for imaging a small cloud like BEC!!

Disadvantage (Ours):

Need a real-time optical phase shifter!

Ku et al., Opt. Express ***19****, 3730 (2011)*

Conclusions

- Propose an experimental scheme to engage PSI for nondestructive imaging of atom clouds
- Feasible for experimental realization!
- Allow to reach longitudinal resolution better than the diffraction limit!
- Provides special features for chip-trapped clouds!
- Might be extended to far-field lensless PSI!