Interferometric Manipulation of Atoms and Photons

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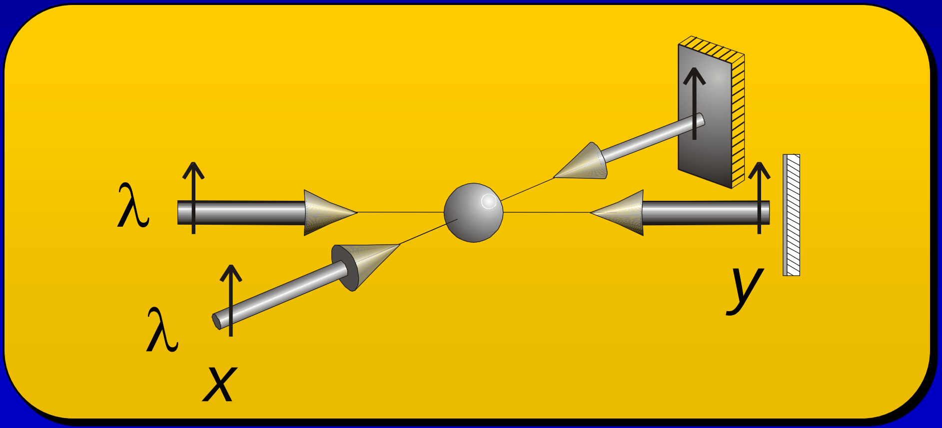
Outline

- Research Motivation
- Matter-Wave Manipulation
- Interferometric Measurements of EM Wave Phases Induced by Atomic Samples
- Simulation and Experimental Results
- Possible Future Applications
- Conclusions

Motivation

- The original goal was simply to build 2D/3D optical lattices for cold atoms!
- Our way to set up the optical lattices requires an optical phase stabilizer to lock the relative phase of the two-arm beams in an interferometer!

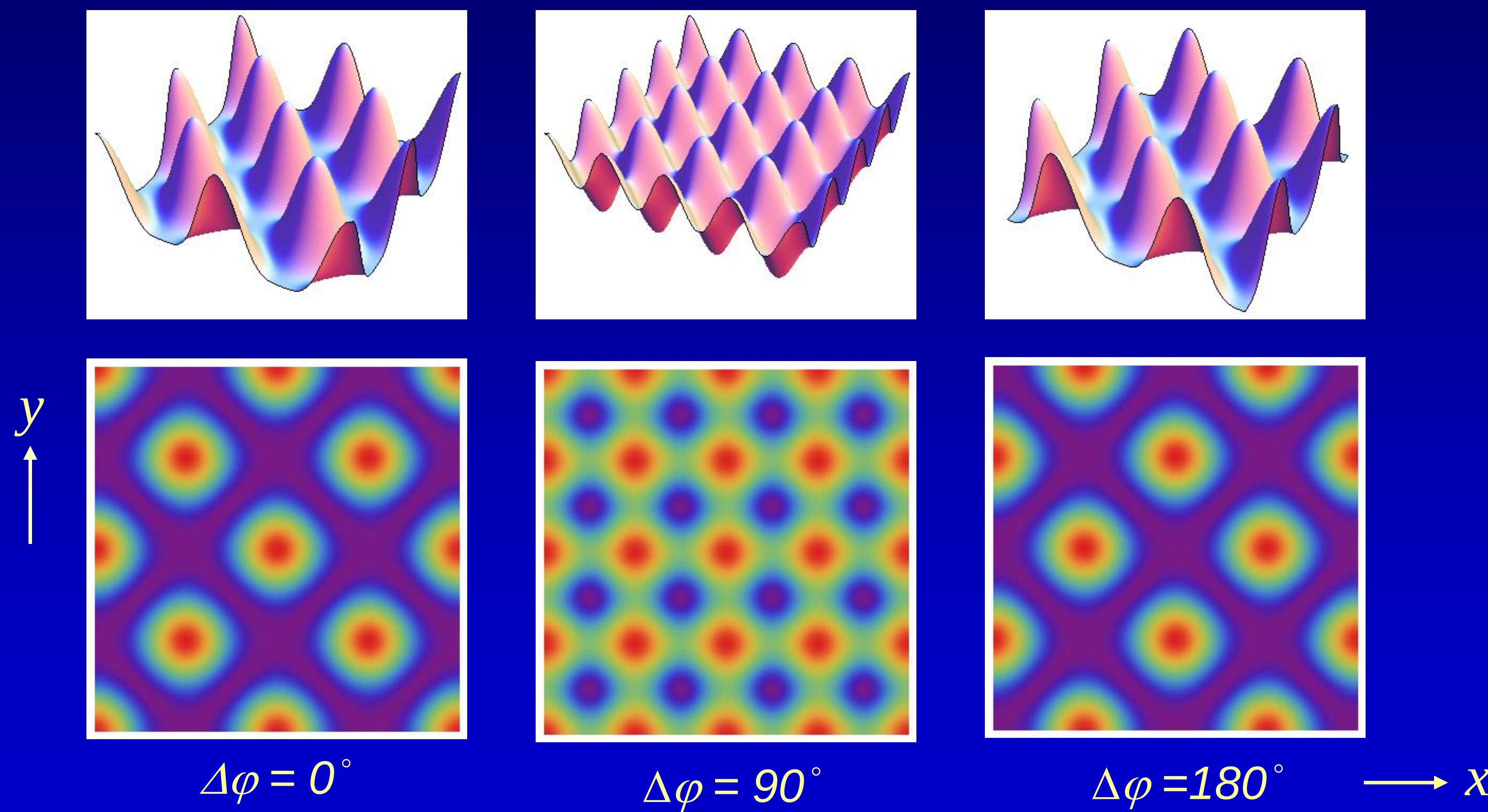


$$U \approx U_o \cdot [\cos^2(k_x x) + \cos^2(k_y y) + 2\cos(k_x x)\cdot\cos(k_y y)\cos(\Delta\varphi)],$$

$$\Delta\varphi = \varphi_x - \varphi_y = \text{phase difference.}$$

2D Optical Lattice Configuration Control

Lattice configuration changes while $\Delta\varphi$ varies!



Indeed, this can be done via tuning the locking beam phase!

- A Michelson-type interferometer was built with a relative phase stability better than 0.1°!

Phase is tuned manually and limited to 160°!

Li *et al*., JPSJ **77**, 024301 (2008)

- A Mach-Zehnder interferometer was also built with real-time control capability while the relative phase is locked better than 0.9°!

Phase can be tuned by programming and is limited to 350°!

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

Matter-Wave Manipulation

2D Bloch Oscillation, Bragg Reflection, and Landau-Zener Tunneling

Collaboration with Prof. Sin-Tze Wu!

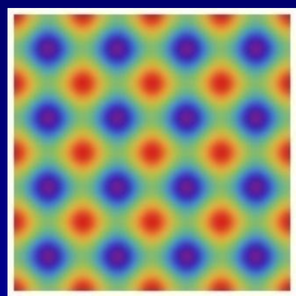
g: acceleration

T_B: Bloch period$=(1/g)(8E_R/m)^{1/2}$

$$U = U_0 \cdot [\cos^2(k_x x) + \cos^2(k_y y)]$$

$\longrightarrow y$

$x \downarrow$



g

$\Delta\varphi = 90^\circ$!

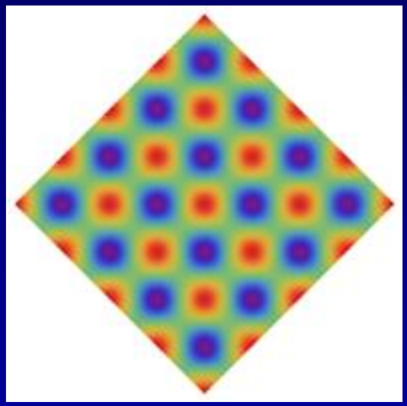
$x' = (x+y)/2^{1/2}$

$y' = (y-x)/2^{1/2}$

coordinate transformation

$y' \longrightarrow$

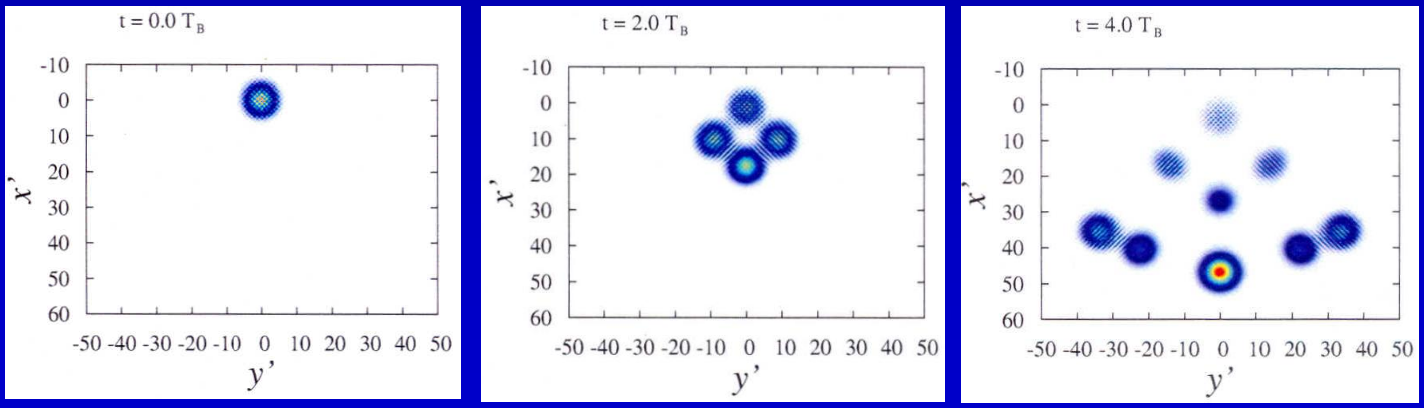
$x' \downarrow$



$g \downarrow$

Tunneling probability at zone boundary with energy gap E_g:

$$P_{LZ} \propto \exp(-E_g^{\,2}/mgaE_0)$$



Ting *et al.*, New J. Phys. **12**, 083059 (2010)

Two-beam Nondestructive Imaging

Phase-Shifting Interferometry with Imaging Lens and Lensless Type

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!

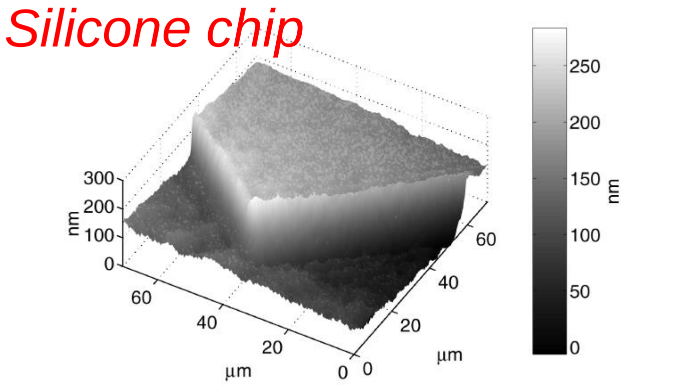


Fig. 3. Reflection phase image at the corner of a microfabricated silicon structure. The phase distribution is expressed as a surface height profile.

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

Phase Shifting Interferometry on Cold and Hot Atoms

A novel way for nondestructive imaging for cold atoms!

- ✓ Two-beam configuration

  allowing much lower probe beam power due to reference beam enhancement!

  less heating and longer probe time!

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

- ✓ Phase retrieving made by accompanying a separate phase-locking beam

  robust and precise phase retrieval!

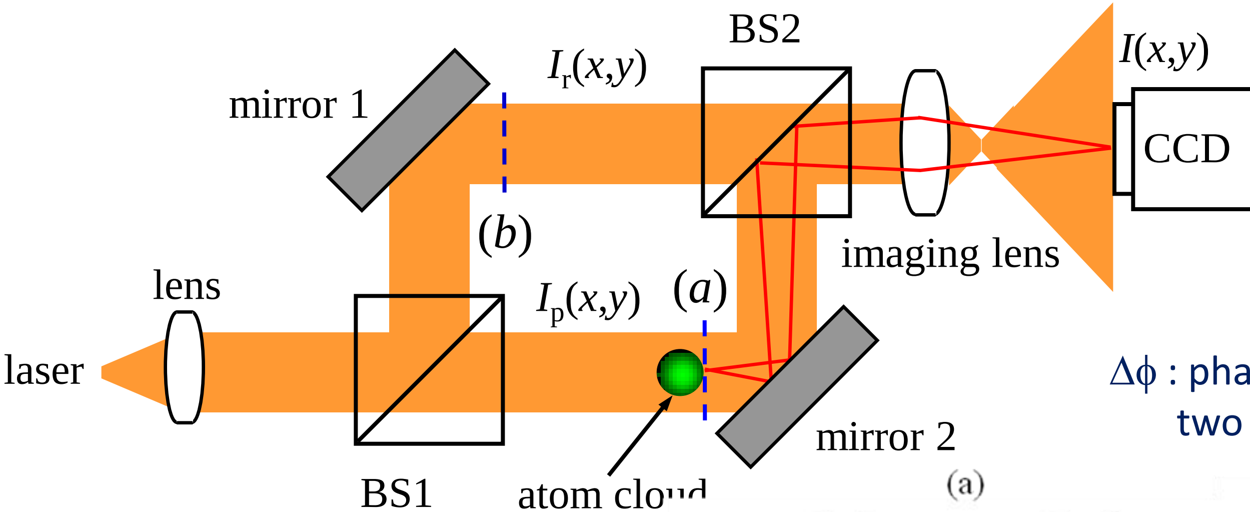
  longitudinal depth resolution is not limited by diffraction!

- ✓ Potential applications on atom chip related measurements

  possible to image the wires and cloud simultaneously!

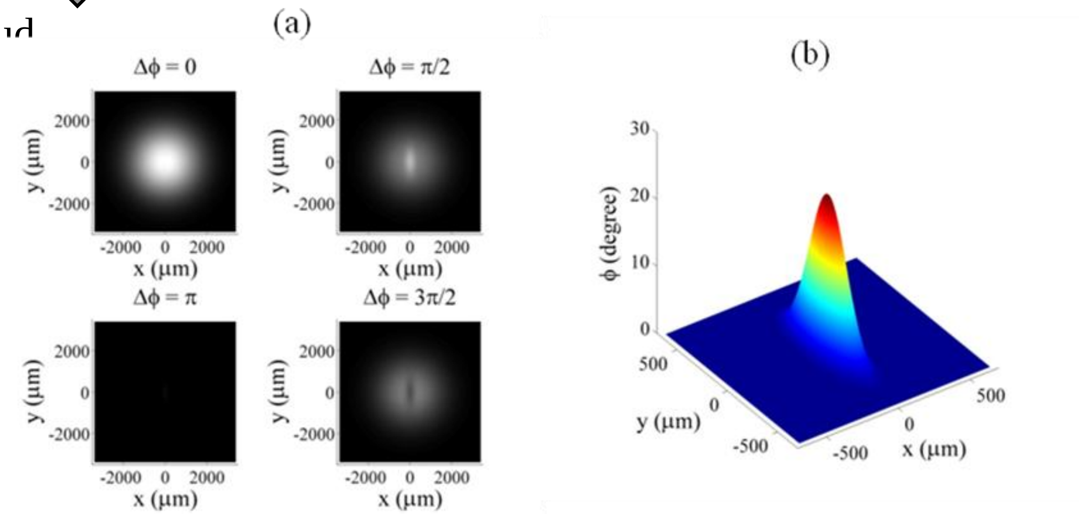
Phase Shifting Interferometry

(Scheme with imaging lens!)



$\Delta\phi$: phase difference between the two arms while without atoms!

a phase object
with distribution $\phi\,(x, y, z)$!



Taking 4 interferograms $I_{\Delta\phi}$ by sequentially setting $\Delta\phi$ to to 0, $\pi/2$, π, $3\pi/2$ allows to reconstruct the phase image!

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

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

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:

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

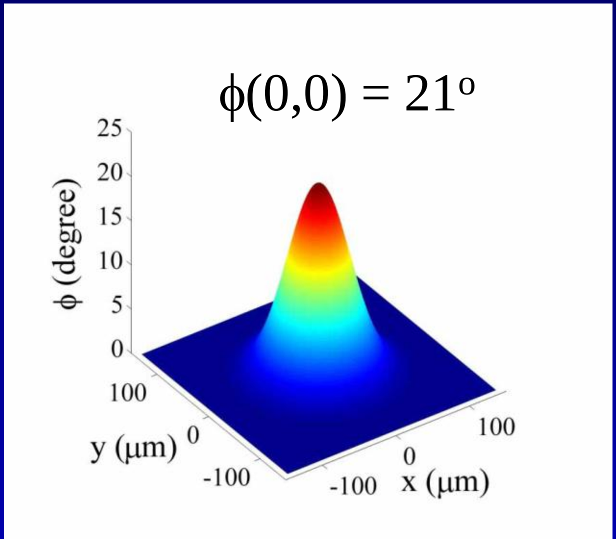
t_p: probe time

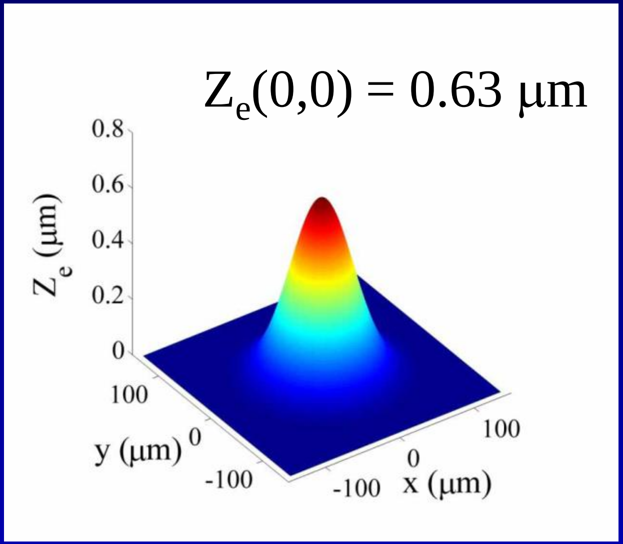
T: cloud temperature

k_B: Boltzmann constant

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

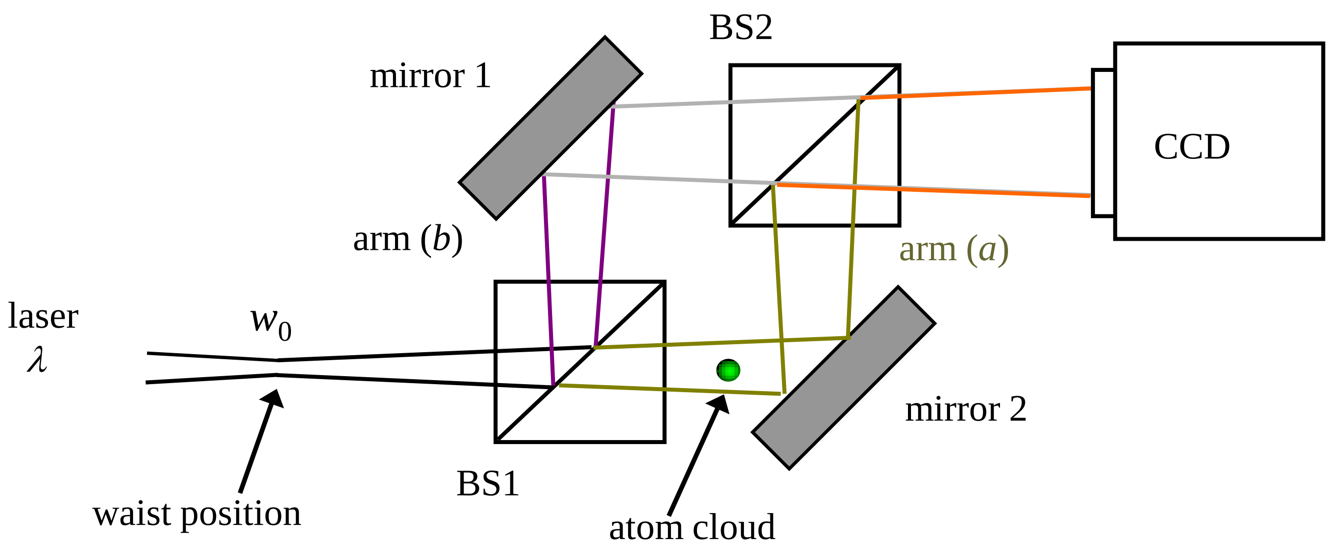
$\Delta = 100$ MHz

$t_p = 1$ ms

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

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

PSI for Lensless Scheme
(another configuration)



Special advantages:

No aberration associated with imaging lens!

No mechanical focusing required!

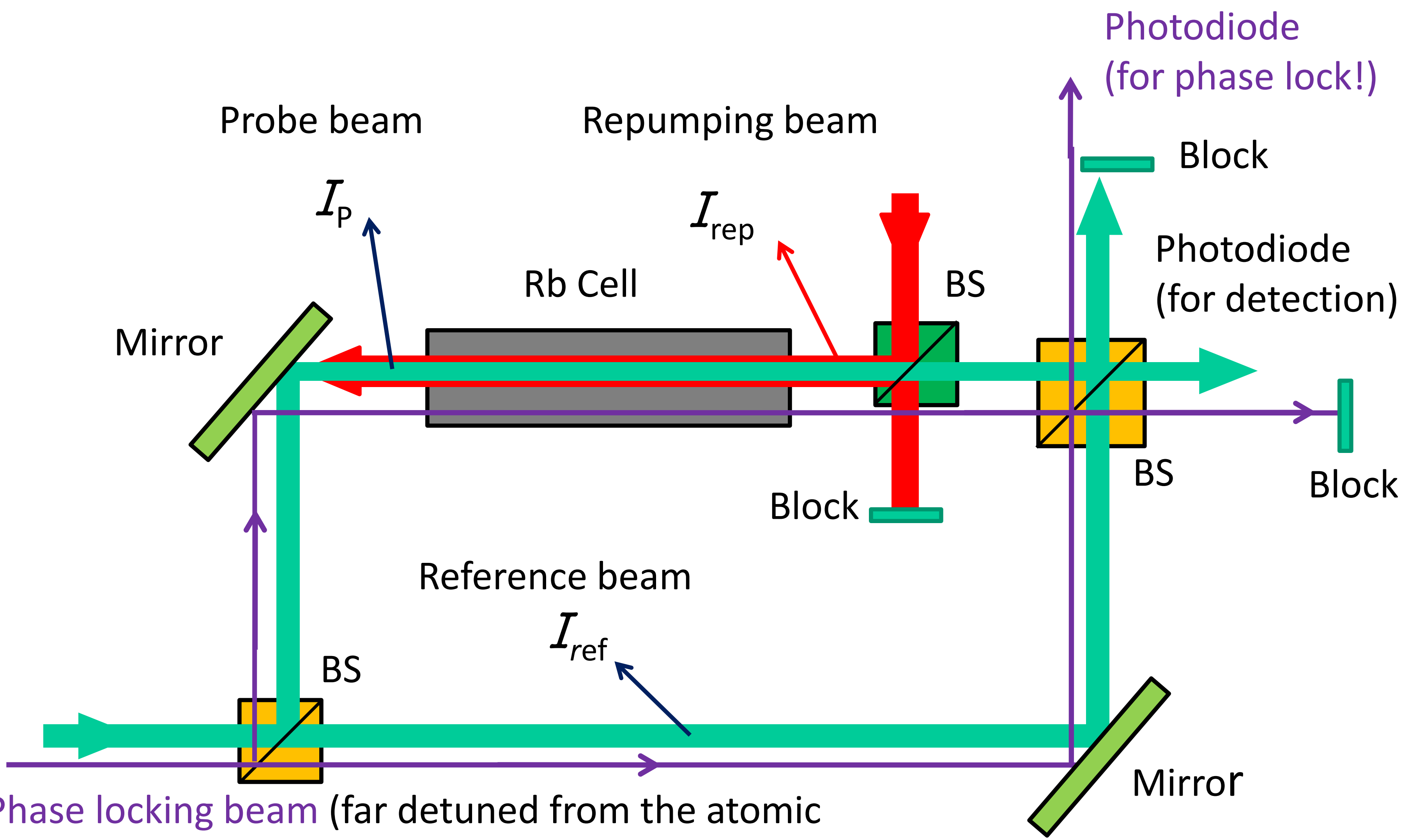
Desired magnification is still possible!

Huang *et al.*, "Lensless Phase-Shifting Imaging of Cold Atoms", in preparation.

Group Index Measurement

Group Index Measurement

a direct application using interferometer on saturation absorption spectroscopy



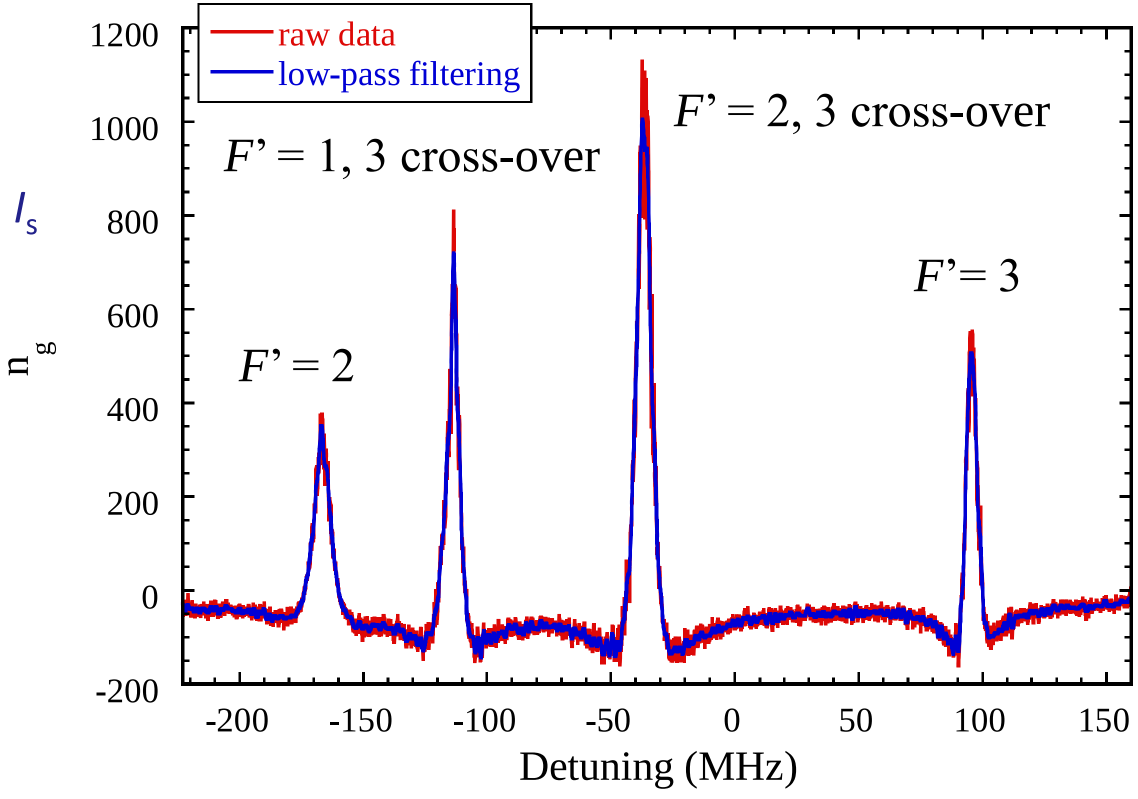
Phase locking beam (far detuned from the atomic resonances!)

Group index could be enhanced in Doppler-broadened two-level systems!

G.S. Agarwal et al., Phys. Rev. A **68**, 063816 (2003).
Perdian et al., Optics Commun. **248**, 485 (2005).

$^{87}Rb \quad F = 2 \rightarrow F' = 1, 2, 3$

cell temperature T = 85 °C
cell length L: 0.3 cm
probe intensity $I_p = 0.3\ I_s$
pumping beam intensity: $I_{rep} = 1.5\ I_s$
I_s: saturation intensity

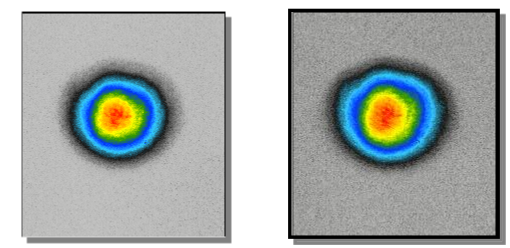


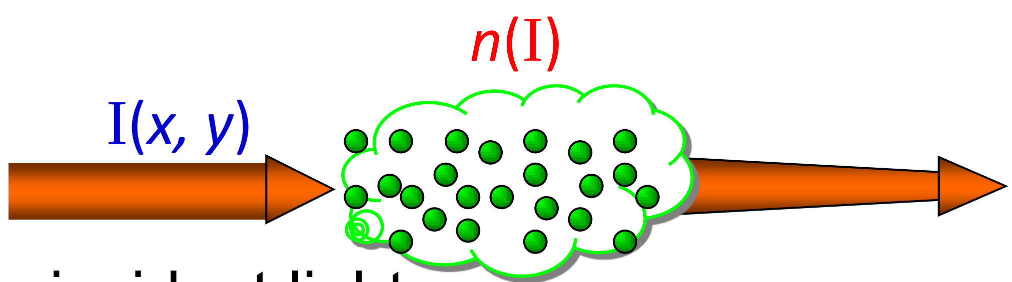
Photonic Lattices Made by Atomic Gases

Z-scan Measurements on Rb and Cs Atoms

Collaboration with Prof. T.H. Wei!

beam focusing and defocusing!





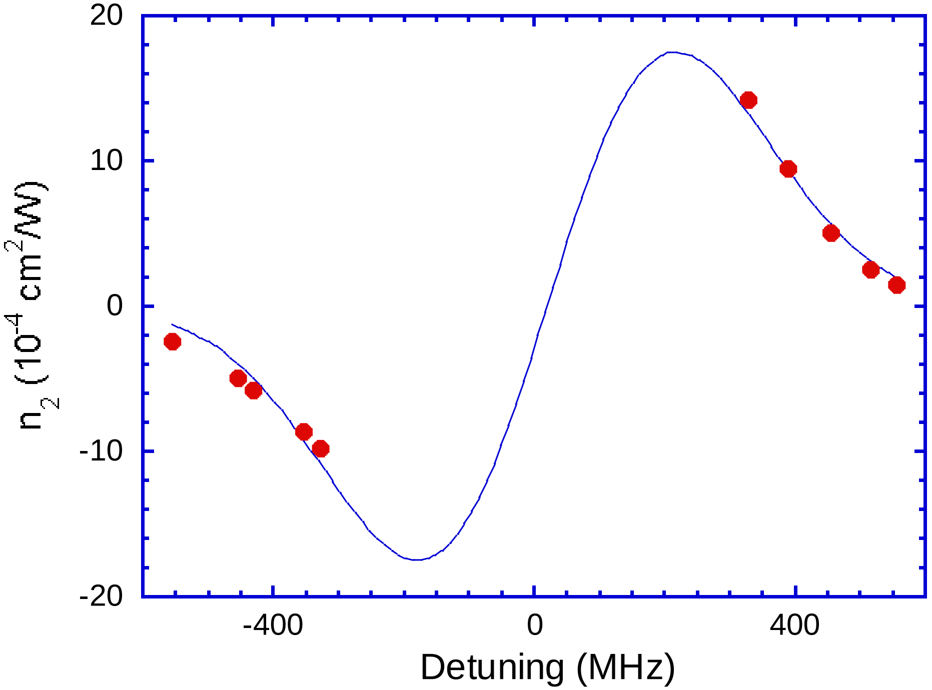
Intense incident light

Alkaline gas: $\boxed{n(\mathrm{I})=n_0+n_2\mathrm{I}}$

nonlinear coefficient
of refractive index

Experimental Measurements of Kerr Coefficient for Cs Atoms

T= 78 °C

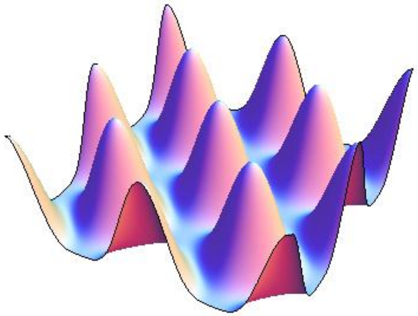


ground hyperfine transitions $F = 4 \rightarrow F' = 3, 4, 5$

Photonic Lattices Made by Atomic Gases

Optical lattices for cold atoms

made by light interference potential as shown previously!



Photonic lattices for light waves

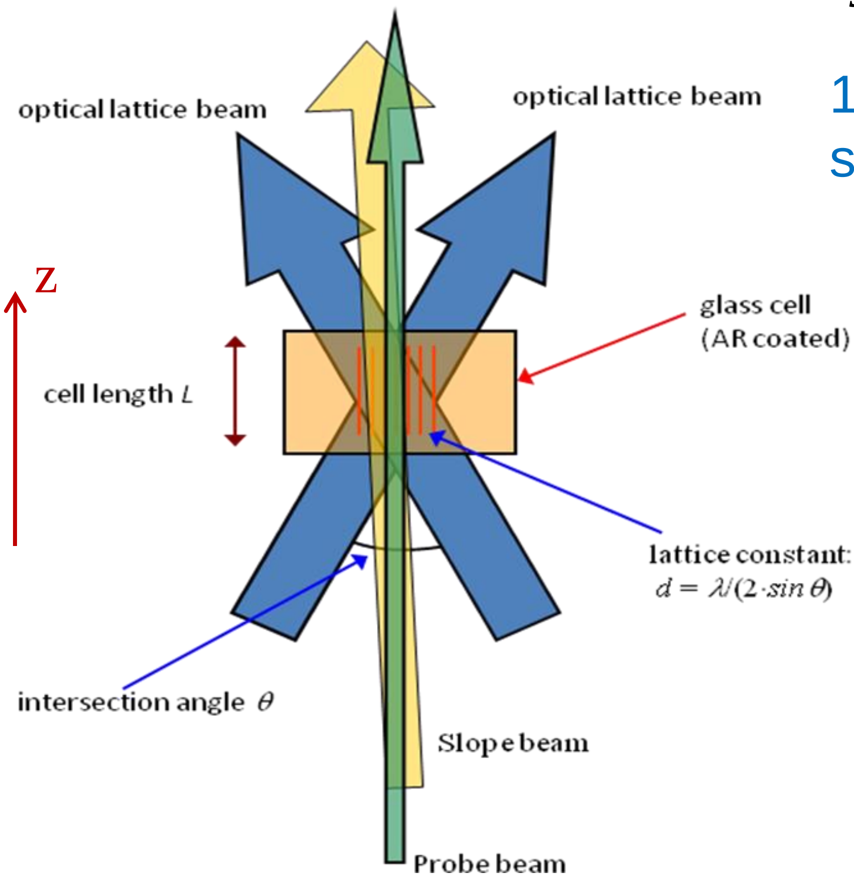
made by spatial modulation of refractive index in atomic vapor

large n_2 observed in Cs and Rb vapor provides a possible route to realize this structure!

Tunneling of Light Wave in 1D Photonic Lattice

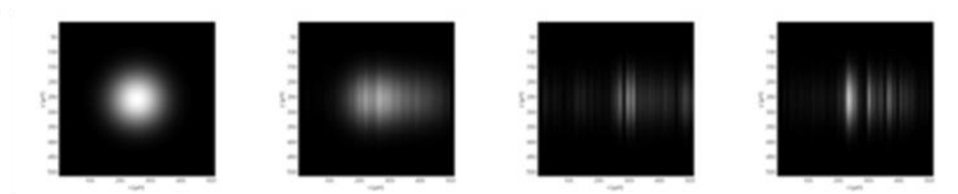
H. Trompeter *et al.*, Phys. Rev. Lett. 96, 023901 (2006).

$$i\frac{\partial E}{\partial z}+\frac{\lambda}{4\pi n_0}\left(\frac{\partial^2 E}{\partial x^2}+\frac{\partial^2 E}{\partial y^2}\right)+\frac{2\pi}{\lambda}\Box n(x,y)E=0$$



1D photonic lattice superimposed by a sharp ramp from a slope beam!

Plays the role of a force!



(a) z = 0 cm

(b) z = 0.2 cm

(c) z = 0.8 cm

(d) z = 3 cm

probe beam profile

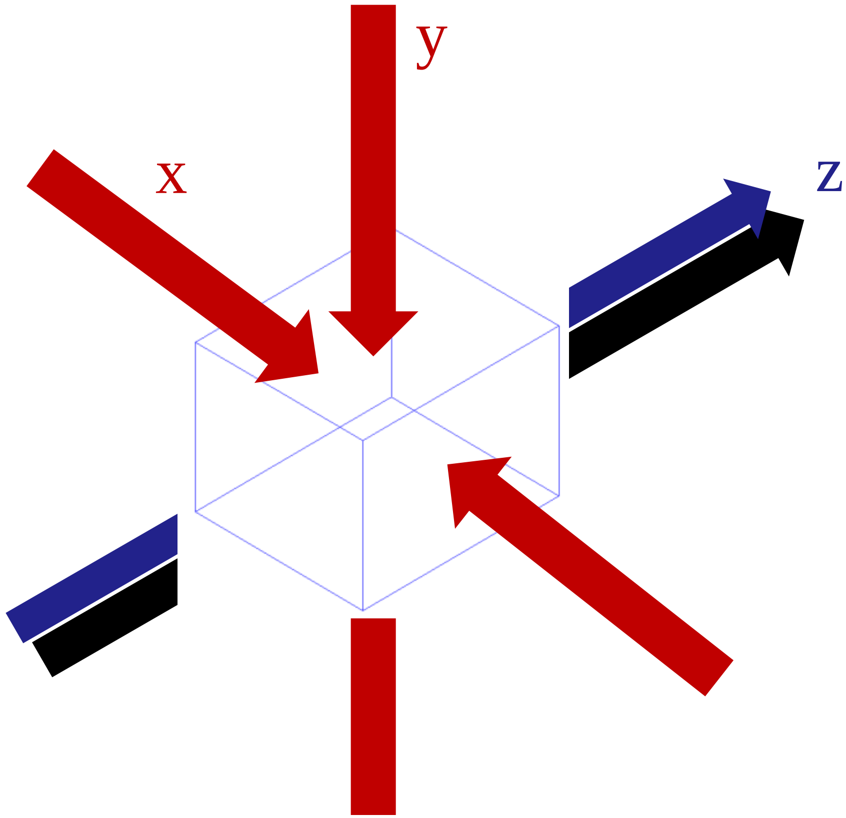
Tunneling of Light Wave in 2D Photonic Lattice
(Theoretical Simulation)

Δ = 400 MHz

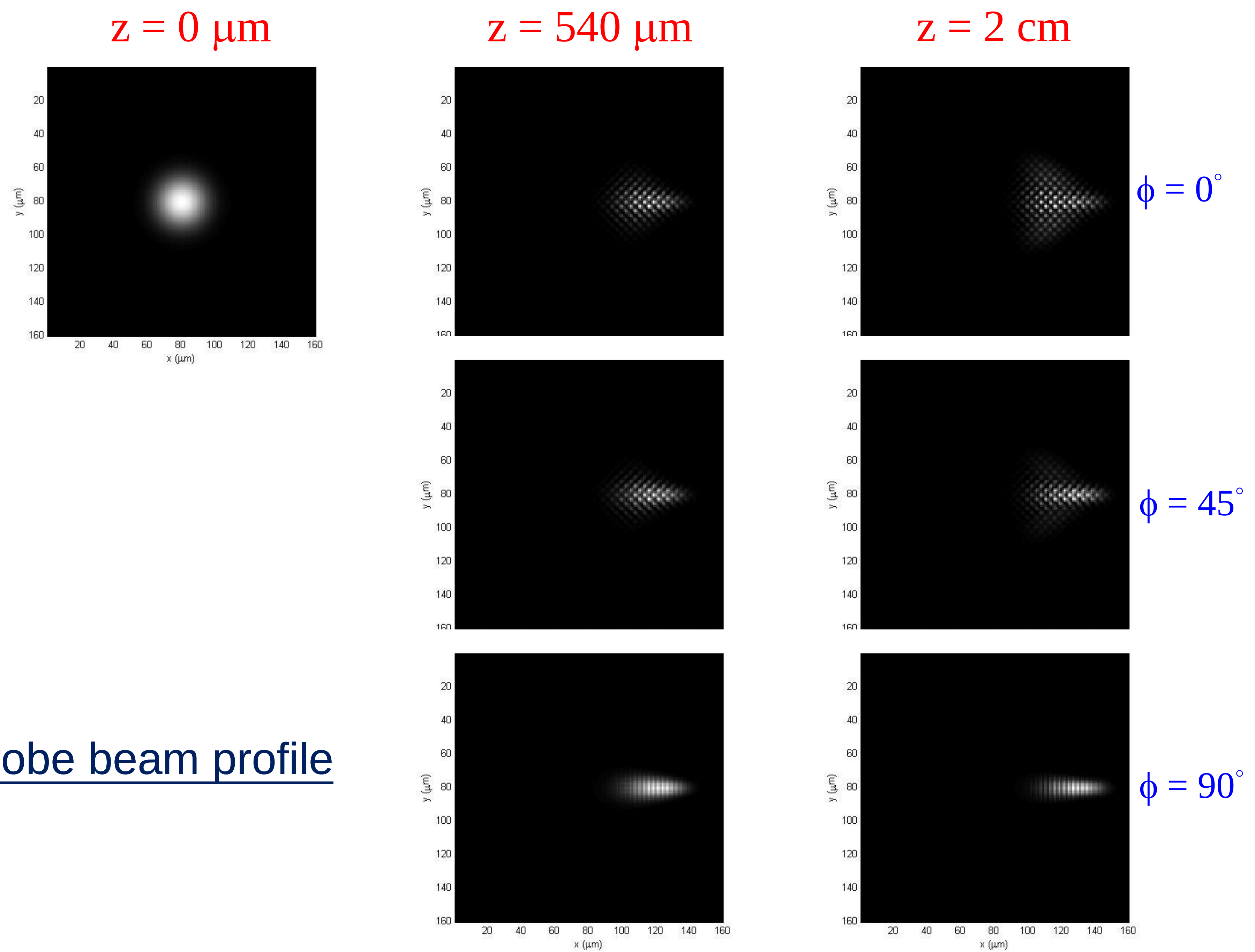
lattice beam:
P_{lat} = 15 mW
w_{lat} = 300 μm

slope beam:
P_s = 50 mW
w_s = 85 μm

probe beam:
P_p = 38 μW
w_p = 20 μm



$n_2 = 5 \times 10^{-5}$ cm^2/W



probe beam profile

Conclusions

- We introduce several applications using phase locked interferometers!
- Some of them are realized experimentally!
- We expect to experimentally demonstrate the rest proposed ideas and schemes!

Acknowledgements

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