Outline

Atoms in touch with standing light fields

- Geometrical optics: atom lithography
- Optics with cold atoms: integrated optics, Bragg diffraction
- Backaction on light: slow light in BECs
- Collective effects: Matter wave amplification
- Future
Optics with Atoms and Light (ITP Quantum Info Program 10/15/01)

**Light and Matter**

- Propagation of a Photon through a Medium
- Propagation of a Photon through a Vacuum

**Matter and light**

- Induced dipole interaction
- Harmonic osc. model

\[
\hat{H} = -\hat{d} \cdot \mathbf{E} \\
V_{pot} = -\alpha_{dc} E^2 / 2 < 0
\]

Greek:

- \( \omega < \omega_0 \):
  \[ \hat{d} \cos \alpha \]
- \( \omega > \omega_0 \):
  \[ \hat{d} \cos \alpha \]

- High field seekers
- Low field seekers

See dispersion theory for light.

Dr. Tilman Pfau, University of Stuttgart
Atom lithography

G. Timp et al. PRL 69 1636 (1992)
2D structures: hexagonal

light field configuration

red detuning  blue detuning

a = \frac{2}{3}\lambda = 284 \text{ nm}

long range order

various structures

Intensity gradients \( \frac{\lambda}{2} \) limit
**Polarization gradients**

- \( \sigma_- \) and \( \sigma_+ \) for \( J=1/2 \to J'=3/2 \) atom
- \( \sigma_- \) and \( \sigma_+ \) for \( J=2 \to J'=3 \) atom

**Nano structures**

- DRAM, Full pitch: 360 nm (1999)
- 260 nm (2002)
- 200 nm (2005)
- 140 nm (2008)
- 100 nm (2011)
- 70 nm

1. D. lithography (J. Guptt et al., PRL 76, 4689 (1996))
2. D. lithography (T. Neubauer et al., Proceedings MNE '08)
Unconventional application

light mask is selective
structured doping
possible application:
photonic crystals

SEM AES Analysis

Chromium map by AES
20nm etching, probe volume 20nm x 2nm

In coll. with
Dr. E. Nold FZ Karlsruhe
Th. Schulze et al.
APL, 78, 1781 (2001)
New optical materials?

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*integrated atom optics*

Setup
Cold atoms approaching a surface

\[ \Delta = 500 \text{ MHz} \]
\[ I = \frac{P}{(6 \text{ mm}^2)} \]

Ar*: Loading by optical pumping

Ar*

Level scheme:

\[ |a> \]
\[ |g> \]

\[ \lambda_{\text{th}} \]

reflection

pump

slow atoms

trap beam
**Linear wave guide & Beam shutter**

(Top view)

Waveguide potential

Shutter

Cyl. focussed laser forms linear waveguide

Shutter position

1 mm

**Linear waveguide on surface**

(Top view)

Waveguide potential

Shutter

Red detuned cyl. beam $\delta\lambda=1.2$ nm forms linear waveguide

Load for 200 ms

& open shutter

3 mm

Total time 35 msec
cw integrated circuit

local ev. attraction field
red detuned

parallel:

~ 30% in first well
i.e. 820 nm from surface

1D surface lattice

steady state with point source in lattice

Dr. Tilman Pfau, University of Stuttgart
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**Split a condensate**

Laser beam

**A giant matter wave interferes**

40 msec time of flight

Bragg diffraction

\[ p_f = p_i + G \]

\[ G = 2hk \]
Bragg diffraction

\[ p_f = p_i + G \]

\[ G = 2\hbar k \]

Matter waves in touch with light waves

\[ \Delta p = 2\hbar k \]

\[ \Delta E = \frac{(2\hbar k)^2}{2m} \]
Bragg resonance

\[
\omega + 4 \omega_{\text{rec}}
\]

\[\omega\]

Laser beam

Time of flight

Bragg scattering as 4WM

\[|2\hbar k\rangle\]

\[|0\hbar k\rangle\]

\[\Omega: \text{Two-photon Rabi-frequency}\]

\[\Gamma: \text{Bragg linewidth}\]

For \(\Gamma \gg \Omega\): linear gain!
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Slow group velocity

\[ v_g = \frac{c}{\frac{d}{d\omega} (n(\omega) \omega)} \]

\[ \approx \frac{c}{\frac{dn}{d\omega}} \]

\[ = \frac{\lambda}{dn} \Gamma_{\text{Bragg}} \propto \frac{\Gamma_{\text{Bragg}}}{\ln(G)} \]
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**Slow group velocities**

\[
\Omega < \Gamma; \\
\text{Delay } \approx 20 \mu \text{sec} \\
\text{Size } \approx 20 \mu \text{m} \\
\text{Group velocity } \approx 1 \text{m/sec}
\]

Gain for matter?

Can’t create atoms like photons

reservoir

N_{in} \quad N_{in} \rightarrow N_{out} > N_{in}

mechanism: light scattering

Matter wave amplification

input atoms

BEC
Matter wave amplification

Pump light

BEC

input atoms

Total gain

Gain: 30
Phase coherence

\[ \phi_{\text{out}} = \phi_{\text{in}} ? \]

Interference experiment

Ramsey interferometer

- Pulse 1: generate seed pulse
- Pulse 3: generate reference pulse

\[
\begin{align*}
\text{N/N}_0 & = f(\text{Phase}/\pi) \\
\text{N} & = \text{Number of atoms} \\
\text{N}_0 & = \text{Number of atoms at equilibrium} \\
\text{Phase} & = \phi
\end{align*}
\]
Weak signal in one arm

Phase-coherent amplification

Pulse 1: generate seed pulse
Pulse 2: amplify
Pulse 3: generate reference pulse
**Active atom interferometer**

Two-pulse interferometer with phase-coherent amplification in one arm

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**Atom laser vs. Amplifier?**

Compare: injection locked lasers

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Related work at University of Tokyo
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Quantum gases in lattices

perfect lattice in 1D, 2D, 3D
@T ~ 0K
few two-level atoms per lattice cite

Solid state physics
Cold collisions
Quantum optics
Mott Insulator transition

"Little do we reliably know about the Mott transition, and we are far from a complete understanding of the Metal-insulator transition due to electron-electron interactions."


Questions:
- Groundstate?
- Phasediagram?
- Dimensional crossover?
- Elementary excitations?
- Dynamics?

\[
|\psi_{\text{out}}\rangle = \left[\frac{1}{\sqrt{2}} (|\psi_3\rangle + |\psi_4\rangle)\right]^N
\]

Nonclassical states

|\psi_{\text{in}}\rangle = |\psi_1\rangle^N

No interaction

50/50 beamsplitter

Repulsive interaction

\[
|\psi_{\text{out}}\rangle = |\psi_3\rangle^{N/2} + |\psi_4\rangle^{N/2}
\]

Attractive interaction

\[
|\psi_{\text{out}}\rangle = \frac{1}{\sqrt{2}} (|\psi_3\rangle^N + |\psi_4\rangle^N)
\]

Fisher et al., PRB, 40 546 (1989)
Tunable atom-atom interaction

Feshbach resonances:
Change molecular potential by external fields

Dipole dipole interaction

vectorial potential in the polarized case:

\[ V(r, \alpha) = \frac{\mu_0 \mu^2}{4\pi} \frac{1 - 3\cos^2 \alpha}{r^3} \]

\[ \sigma \sim \mu^4 \quad \text{e.g.} \quad \text{Cr (}\mu = 6 \, \mu_\text{B}) \]

Rydberg atoms
Molecules

stability and shape of the condensate?
Elementary excitations
Spinor physics
Super solids?
Dipole blockade
Quantum gates
### Conclusion:

**Light waves meet matter waves**

- **Lithography:** sub 100 nm structures
  - structured doping

- **Integrated atom optics**

- **Optical properties of cold matter**
  - $v_g = 1 \text{ m/s}$

- **Matter wave amplification:**
  - active atom interferometer

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### The Team @ KN

- **Lithography:**
  - B. Brezger
  - Th. Schulze
  - D. Jürgens
  - M. Oberthaler
  - T. Mütther

- **Cold Cr atoms:**
  - J. Stuhler
  - P.O. Schmidt
  - S. Hensler
  - J. Werner

- **Integrated atom optics**
  - D. Schneble
  - Th. Anker
  - M. Hasuo

- **LS Mlynek, University of Konstanz**
**The team @ MIT**

- **Light scattering from BECs**
  - S. Inouye
  - A. Görlitz
  - D. Stamper-Kurn
  - T. Gustavson
  - S. Gupta
  - A. Chikkatur
  - D.E. Pritchard
  - W. Ketterle

- **BEC group @ MIT**

**Now in...**

- **More performance...**
  - A. Görlitz
  - Y. Ovchinnikov
  - J. Schoser
  - R. Löw
  - A. Grabowski
  - A. Batär
  - P. Schmidt
  - S. Hensler
  - J. Werner

- **5. Physikalisches Institut**
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  - S. Kroboth