Micro-diffractive nanostructures for cold-atom manipulation (and other interesting stuff)

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The basic idea

- Incoming laser light
- Structured surface
- Output optical field
- Cold atoms
Subwavelength Structures
FIB Fabrication
Arrays of Holes in Metal Films

Light transmission spectrum

Is this evidence of surface plasmons?
Decorated Slits and Holes in Subwavelength Ag Membranes
Light transmission through a slit flanked by periodic grooves

detected far-field transmission

calculated profile

Measuring the transmission profile—atomic fluorescence mapping of the field intensity
Relation between atomic fluorescence and field intensity

\[ \rho^*(\mathbf{r}) = \int d\omega L \int d\mathbf{v} \frac{\Omega_0^2(\mathbf{r})/4}{(\Delta \omega - \mathbf{k}(\mathbf{r}) \cdot \mathbf{v})^2 + \Gamma^2/4 + \Omega_0^2(\mathbf{r})/2} f(\mathbf{v}) \]

\[ \simeq \Omega_0^2(\mathbf{r}) \int_0^{+\infty} d\omega L \frac{1/4}{(\omega L - \omega_0')^2 + \Gamma^2/4} \int_0^{+\infty} f(\mathbf{v}) d\mathbf{v} \]

\[ \simeq \Omega_0^2(\mathbf{r}) \frac{\pi}{4\Gamma} \int_0^{+\infty} f(\mathbf{v}) d\mathbf{v} \]
100 nm slit flanked by 10 grooves each side

measured

calculated
How does the slit/groove structure produce the observed field distributions?
Composite Diffracted Evanescent Wave

Enhanced transmission appears not to result from Surface Plasmons... but from total evanescent surface wave diffracted by each subwavelength surface feature (aperture or groove): “composite evanescent wave”: CEW

Lezec and Thio
Optics Express, 12 3629 (2004)
Composite Evanescent Wave-I

Consider diffraction at a slit of width $d$. The field along $x$ is given by:

$$E(x, z = 0) = -\frac{E_0}{\pi} \left\{ \text{Si} \left[ k_0 \left( x + \frac{d}{2} \right) \right] - \text{Si} \left[ k_0 \left( x - \frac{d}{2} \right) \right] \right\}$$

$$\text{Si}(l) \equiv \int_0^l \frac{\sin(t)}{t} dt$$

Kowarz, Appl. Optics. 34, 3055 (1995)
The phase shift of $\pi/2$ is a signature of the CEW.

$$E(x) = \frac{E_0}{\pi} \frac{d}{x} \cos\left( k_0 x + \frac{\pi}{2} \right)$$
CEWs launched on the surface
A pi/2 phase shift between the directly transmitted wave and the CEW

We can “jog” the structures to compensate for the phase shift

\[ E(x) = \frac{E_0}{\pi \frac{d}{x}} \cos \left( k_0 x + \frac{\pi}{2} \right) \]
Jogged and unjogged slit structures

unjogged

jogged inward by $\frac{1}{4}$ period
Distribution and number of grooves controls the output optical field

We can produce a “phased array” with constructive interference in the forward direction. The result is a forward “flame”.

\[
I(\theta) = |1 + \sum_{j=-N}^{N} g(j, \alpha) e^{i(2\pi \sin(\theta) j)}|^2
\]

far-field intensity, no phase shift

\[
I(\theta) = |1 + \sum_{j=-N}^{N} g(j, \alpha) e^{i(2\pi \frac{830}{850} \sin(\theta) j + \frac{\pi}{2})}|^2
\]

far-field intensity, with phase shift
Flame divergence vs. grooves—expmt. and model for unjogged grooves

calculation

10 grooves

30 grooves

Cs flux

100 μm
Flame intensity vs. groove number for jogged and unjogged grooves

unjogged

jogged
Flame angular distributions

\[ \theta = \frac{d}{f} \]
Angular distribution of light vs. groove-slit spacing (in units of period N) for 5 grooves

Emission diagram (expanded)
Intensity angular distribution—jogged grooves output side, 3 selected distances

CDEW model measured

Emission diagram (expanded)
Intensity angular distribution—output side, unjogged red, jogged black

CDEW model:
Phase shift: $\rho_{\text{CDEW}}=\pi/2$
Index: $n_{\text{CDEW}}=850/830=1.024$
Relative field amplitude $\alpha/x=2/x$

Emission diagram (expanded)
$N = 16$ for both types of devices
Angular lobe spacing

CDEW model

Experiment
Next step: mirror MOT to get cold atoms close to surface

For a study of the mirror MOT, see:
J. Reichl et al., PRB 83, 3398 (1996)

Mirror MOT

~ $10^7$ atoms
~ 20 µK

Nanostructure support can be closer (a few 100 µm)
Compared to the fall of standard MOT:
No attenuation of density
No increase of kinetic energy
Next step: mirror MOT with the optical funnel generated by a planar nanostructured phased array.
Toward integrated structures: cold atom sources and transport on a chip
Interaction atomes neutres-lumière

Champs proches optiques : confinement sub-longueur d’onde de la lumière.

interaction dipolaire

Diffraction and confinement

optique atomique cohérente : diffraction

nanolithographie
Coupled resonant rings:
symmetric/antisymmetric modes
Funnel effect: optical potential above the rings
Réseau à onde évanescente stationnaire

\[ V(x, z) = V_0 e^{-2\kappa_0 z} \left( 1 + \varepsilon \cos(2k_{surf}x) \right) \]

Autre approche : potentiel nanostructuré

Réseau à onde évanescente nanostructurée :

Diffraction de l’onde évanescente :

\[ E(\mathbf{l}, z) = \sum_m E_m e^{\frac{\kappa_m z}{L}} e^{i\mathbf{k}_m \cdot \mathbf{l}} \]

\[ Q_m = m \frac{2\pi}{L} e_x \]

\[ \kappa_m^2 = k_m^2 - k_0^2 \]

\[ k_m = k_{surf} + Q_m \]

D. van Labeke & D. Barchiesi
A. Roberts & J.E. Murphy (1996)
Periodicity controllable through angle of optical coupling-1

50 nm above surface

250 nm above surface
Periodicity controllable through angle of optical coupling.

50 nm above surface

250 nm above surface
Experimental parameters

\[ \lambda_{dB} = 5 \text{ nm} \]
\[ L_x = L_y = 250 \text{ nm} \]
\[ \theta_{\text{diff}} = 20 \text{ mrad} \]
\[ e = 100 \text{ nm} \]
\[ \varphi = 40^\circ \]
\[ \theta = 55^\circ \]
\[ n = 2.1 \text{ (TiO}_2\text{)} \]
\[ z_r = 250 \text{ nm} \]
Tales from the future—nanophotonics, addressable atom manipulation with optical arrays
Electro-optic Devices

\[ \varepsilon_o/\varepsilon = 1/n^2(E) = 1/n_o^2 + rE + sE^2 \]

n at E = 0

linear electro-optic coefficient (Pockels coefficient)

quadratic electro-optic coefficient (Kerr coefficient)

\[ n = (\varepsilon / \varepsilon_o)^{1/2} \]

\[ n(E) = n_o - \frac{1}{2} r n_o^3 E - \frac{1}{2} s n_o^3 E^2 \]
Electro-optic Devices

- The refractive index, $n$, is a function of the applied field, $E$

$$n = n_0 - \Delta n$$

- Can be used to create electrically tunable devices
  - Phase modulator
  - Variable retarder
  - Irradiance modulator
  - Optical switch
Pockels Effect
\[ \Delta n = \frac{1}{2} r n_0^3 E \]

E=10V/200nm \rightarrow E=0.5 \times 10^8 \text{ V/m}

\[
\text{BaTiO}_3: \quad n_0=2.4 \quad r_{42}=1300 \text{ pm/V}
\]

\[ \Delta n=0.45 \quad (20\%) \]
Electro-Optic Beaming Control with variable index of refraction

Variable Depth Focusing
Electro-Optic Beaming Control

Change $n$ from 0.8 to 1.2

Steering
Future: arrays of optical traps loaded with one or more atoms

Summary—evolution of conception

Yesterday:

Today:

Tomorrow: