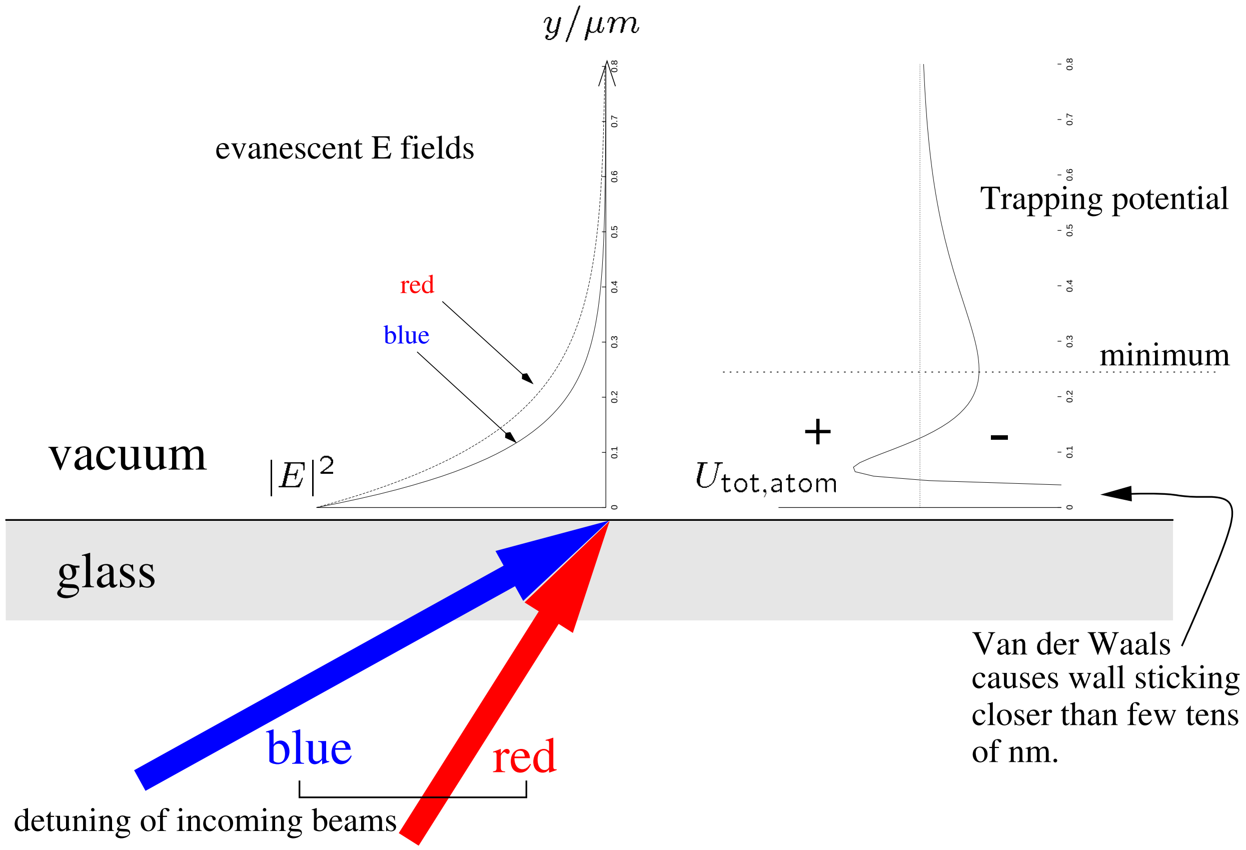
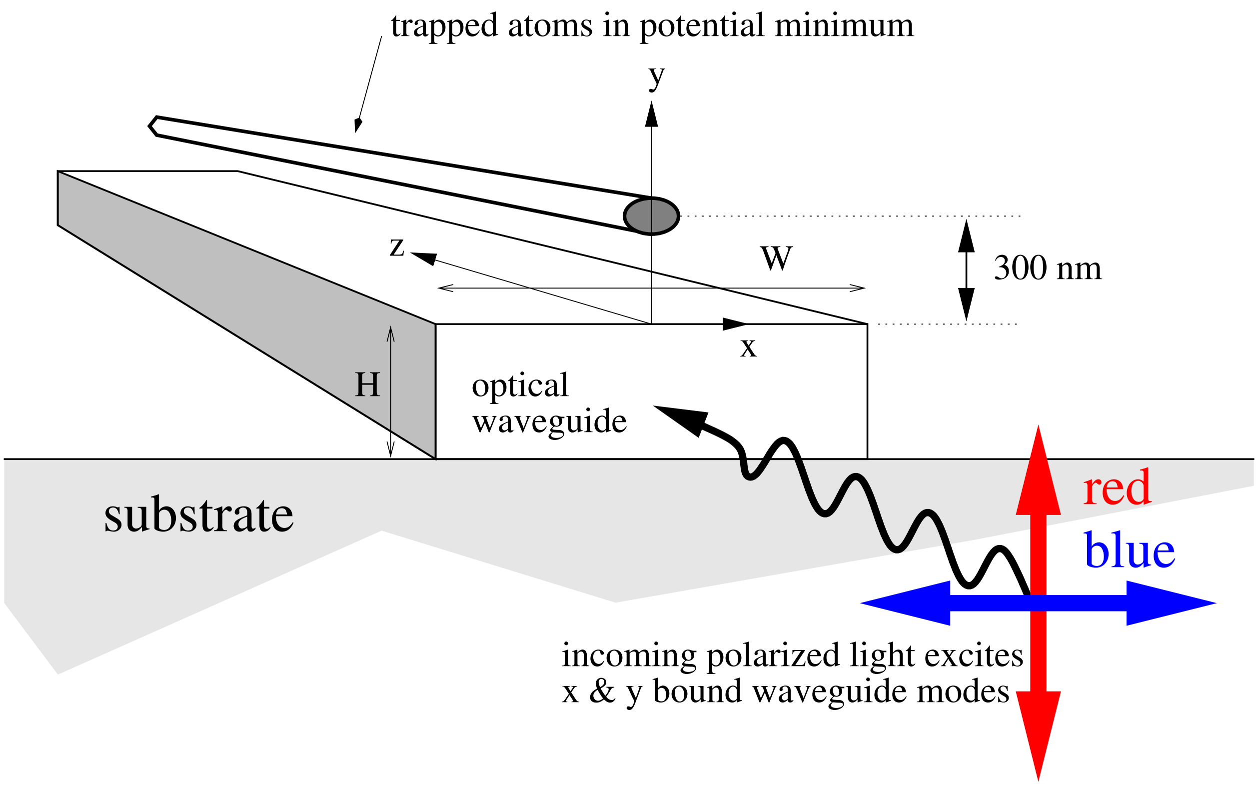
Background: Planar Atom Traps



- Evanescent light fields outside a glass prism have been used to trap alkali atoms in a plane (Ovchinnikov *et al.*)
- Atom finds red-detuned intensity attractive, blue-detuned repulsive (detuning δ from an atomic transition ω_o). Use incoming beam angles to choose longer decay length for red than blue $\Rightarrow$ $U_{\mathrm{tot,atom}}$ has minimum
- Would like to trap in a second axis: make a linear atom "pipe" (1D trap). Many attempts using eg inside hollow optical fibers (severe pumping limitations). Possible solution: trap *outside* an optical waveguide.

Concept: Trap Above Waveguide



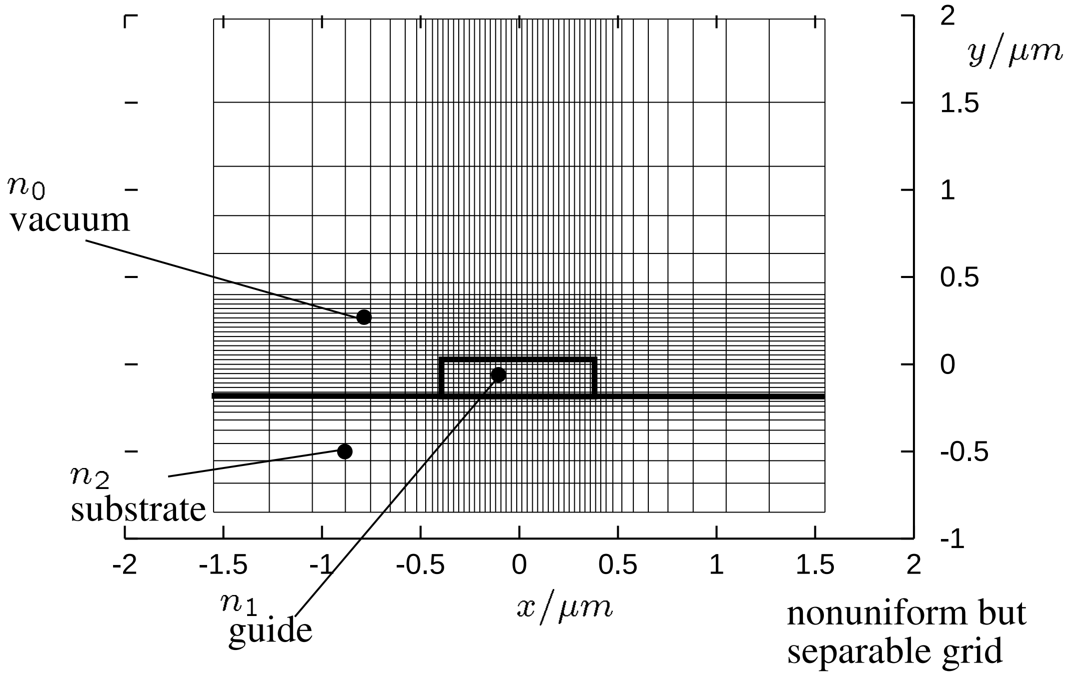
- Submicron waveguide has just 2 bound modes with chiefly horizontal (E^x_{11} : faster evanescent decay in y) and chiefly vertical (E^y_{11} : slower decay) polarizations. Choose intensity ratio to trap in y (trapping in x occurs simply due to field shapes)

- Advantages: confinement in x and y, atoms easily loaded and detected since accessible, guides easily patterned on substrate, atoms can follow bending guides.

- How to calculate trap depth U_{max}? No analytic expressions for fields $\Rightarrow$ Solve for bound modes numerically, and use E fields to find spatial potential (Γ = spontaneous linewidth):

$$U_{\mathsf{tot,atom}}(\mathbf{r}) = \frac{\hbar\Gamma}{8} \cdot \frac{\Gamma}{\delta} \cdot \frac{(|E_{\mathsf{blue}}(\mathbf{r})|^2 - |E_{\mathsf{red}}(\mathbf{r})|^2)}{Z_0 I_{\mathsf{sat}}}$$

Calculating Dielectric Bound Modes: Finite Elements (FE)

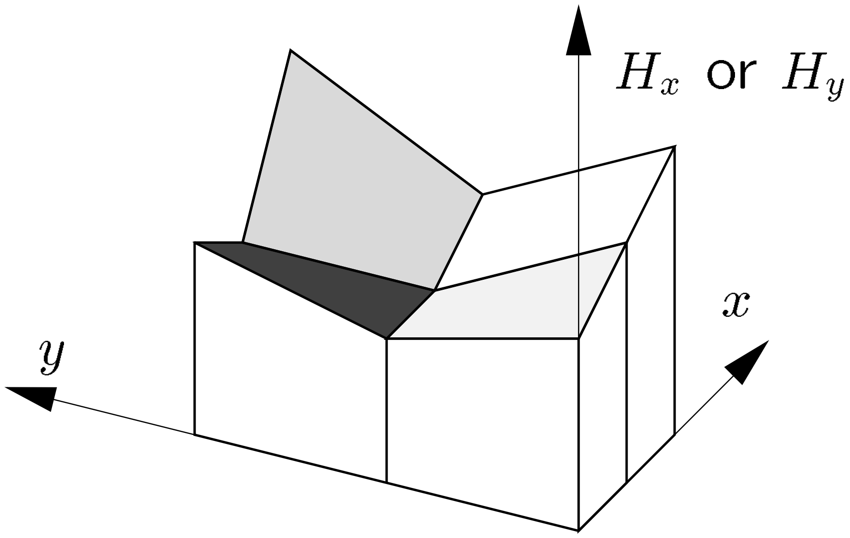


- Assume $e^{ik_z z - i\omega t}$ propagation.
- Cover the xy plane with $\sim 5 \times 10^3$ rectangular elements, with higher density in regions of rapid field change. Choose a large enough box size so fields are very small at system edges. Represent the transverse fields H_x, H_y as the sum of basis functions weighted by their values on the element corners $\Rightarrow$ finite # of degrees of freedom
- Source-free Maxwell Equations using only these 2 fields:

$$(\mathcal{L}_1 + k_z^2 \mathcal{L}_2)(H_x, H_y) = 0$$

Evaluating overlap integrals of basis functions, following Fernandez & Lu (1993), this becomes a matrix equation...

A magnetic field component represented by patchwork of rectangular (lowest-order, ie, 'bilinear') basis functions:



- Generalized sparse eigenequation:

$$A\mathbf{x} = k_z^2 \cdot B\mathbf{x}$$

  B : symmetric
  A : non-symmetric due to line-integral terms at dielectric boundaries (nonstandard for FE algorithms)

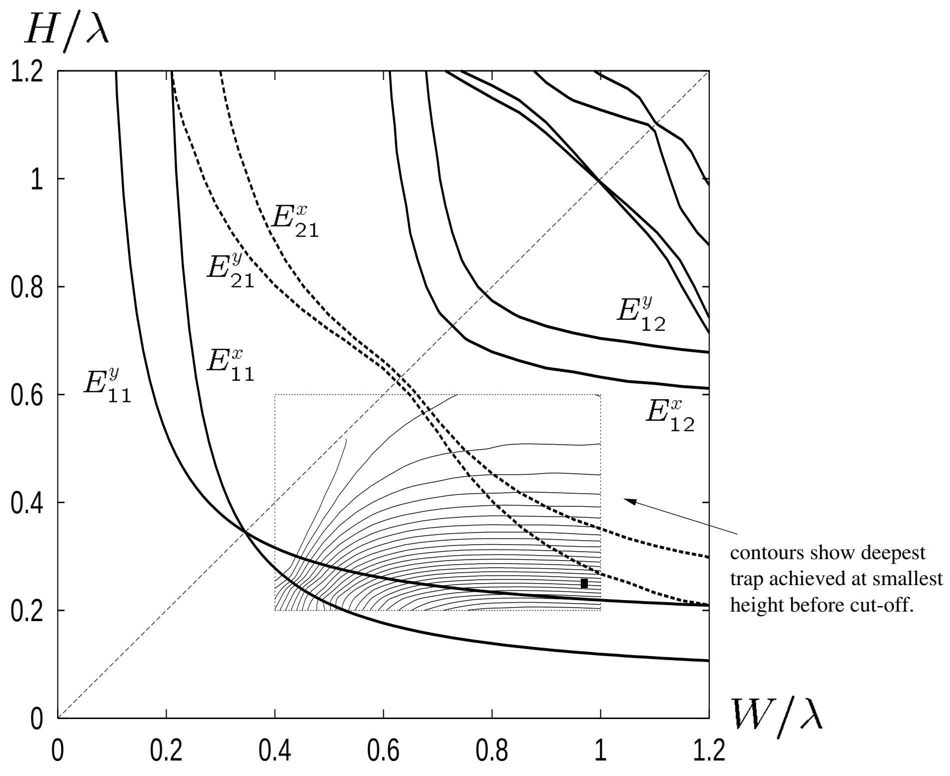
- Eigenvectors give you $H_x, H_y \rightarrow$ get H_z and $\mathbf{E}$ vector by differentiation.

- Advantages: simple to code, lowest order, using only 2 fields means a small number of degrees of freedom and no possibility of "spurious modes".

- Disadvantages: non-symmetric (harder numerically), can't represent H_z and $\mathbf{E}$ (the field we want) very well $\Rightarrow$ no high accuracy or convergence rate. Higher order elements would be needed, and some way of including the weak infinite *singularities* present in the true fields at the guide corners.

Results: Trap Depth

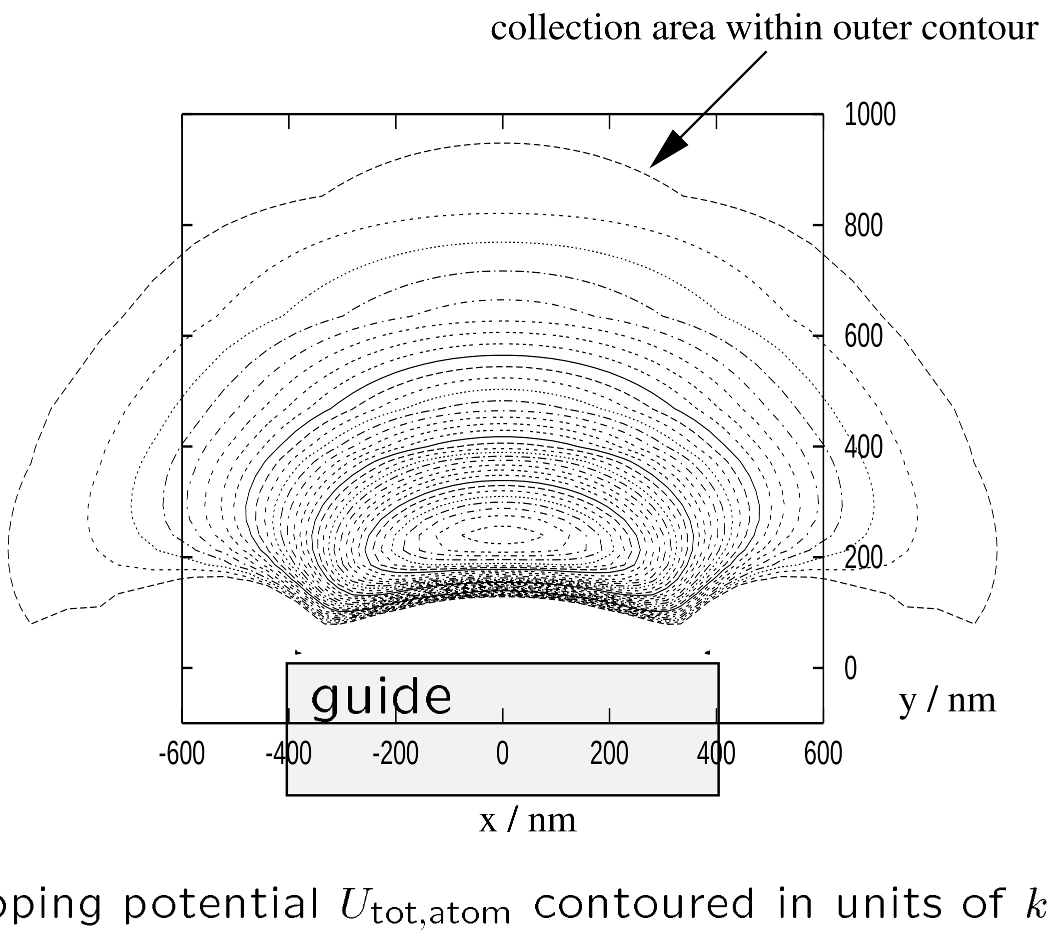
- System: Cs atom $D2$ line ($6S_{3/2} \to 6P_{3/2}$, $\lambda = 0.852\mu m$), has linewidth $\Gamma \approx$ 5Mhz. We calculate for the case $m_F = 0$ (other m_F states feel in addition an effective magnetic field, therefore slightly differing trap depths).
- Detune by $\delta = 30$ THz (far detuned limit), fix total laser power carried by guide at 10mW. Solving for the fields for all possible guide dimensions (W, H), using the optimal red/blue intensity ratio at each, allows us to maximize the trap depth $U_{\max}$ (rectangular marker shows a good choice of W, H):



TRAP DEPTH CONTOURS SHOWN ON CUT-OFF DIAGRAM OF OPTICAL MODES

Results: Trap Potential

- We find optimal size $W = 0.83\mu m$, $H = 0.21\mu m$. This large aspect ratio gives us a large difference in decay lengths, and a deep trapping potential $\sim$ 40 times the typical MOT temperature of $T_{\text{MOT}} \approx 3\mu K$, as well as nearly a square micron of collection area:



Trapping potential $U_{\text{tot,atom}}$ contoured in units of kT_{MOT}

Conclusions

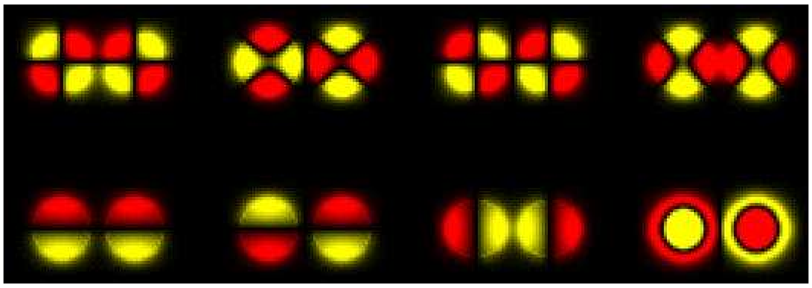
- Created a non-uniform Finite Element code for solving the full vector bound EM modes of arbitrarily-shaped dielectric waveguides (uniform in the z axis).

- Accurately modelled atom trapping potential in promising new geometry, found a highly feasible trap without very stringent requirements on design parameters (W, H, intensity ratio, etc.)

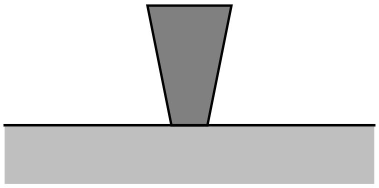
- Trap is very deep even when far detuned, giving us long coherence times ($\delta \sim 30$ THz gives $\tau_{\mathrm{coh}} \sim 30$ ms).

- Applications: atom transport across substrate (incoherent, coherent with arbitrary bending angles), lithography, potential for *atomically single-mode* pipes $\rightarrow$ interferometry, ring gyroscopes.

- Applications of code: modelling coupled guides, novel guide shapes...



...calculation of coupled circular waveguide bound modes



...fabrication proposal to reduce substrate coupling