Optical Trapping and Manipulation of Nanoparticles

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Outline

- Optical trapping background
- Trapping applications and accomplishments
- Extension to nanoparticles

Radiation Pressure

- 1600's Kepler: Comet tails point away from sun
- 1873 Maxwell: theory of radiation pressure
- 1933 Frisch: light deflects atoms
- 1970 Ashkin: Bell labs trapping experiments, optical tweezers
- 1997 Nobel Prize - Chu, Phillips, Cohen-Tannoudji (cool & trap)
- 2001 Nobel Prize - Cornell, Ketterle, Weiman (BEC)

Optical Tweezers

- 1970 Ashkin: optical trapping of particles
- 1986 Ashkin: optical tweezer trapping of dielectric spheres
- 1986 Chu: optical tweezer trapping of atoms
- 1987 Ashkin: optical tweezer trapping of viruses and bacteria

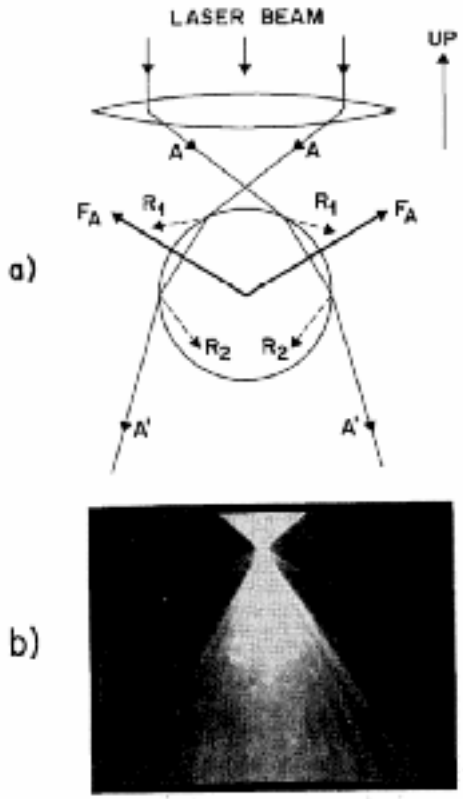
Ashkin Tweezer Trap

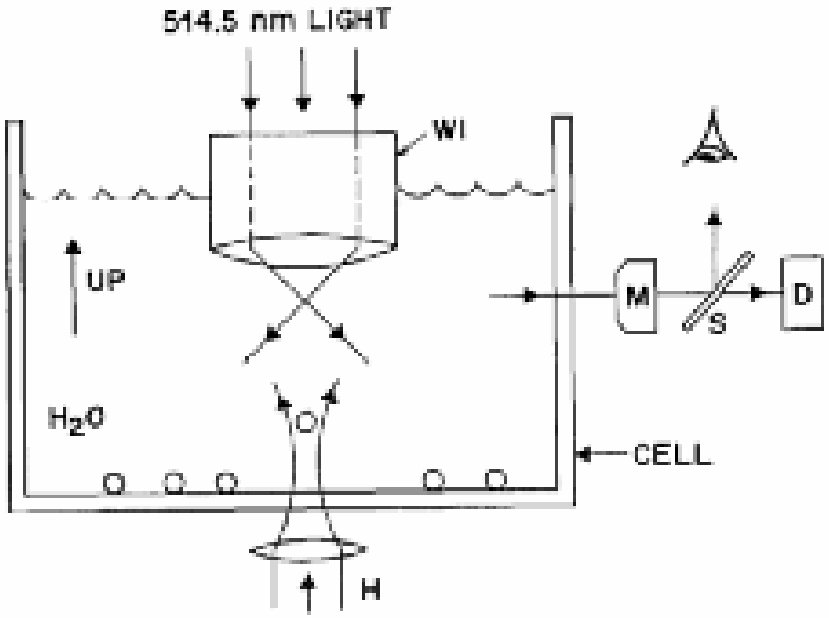
Observation of a single-beam gradient force optical trap for dielectric particles

A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and Steven Chu

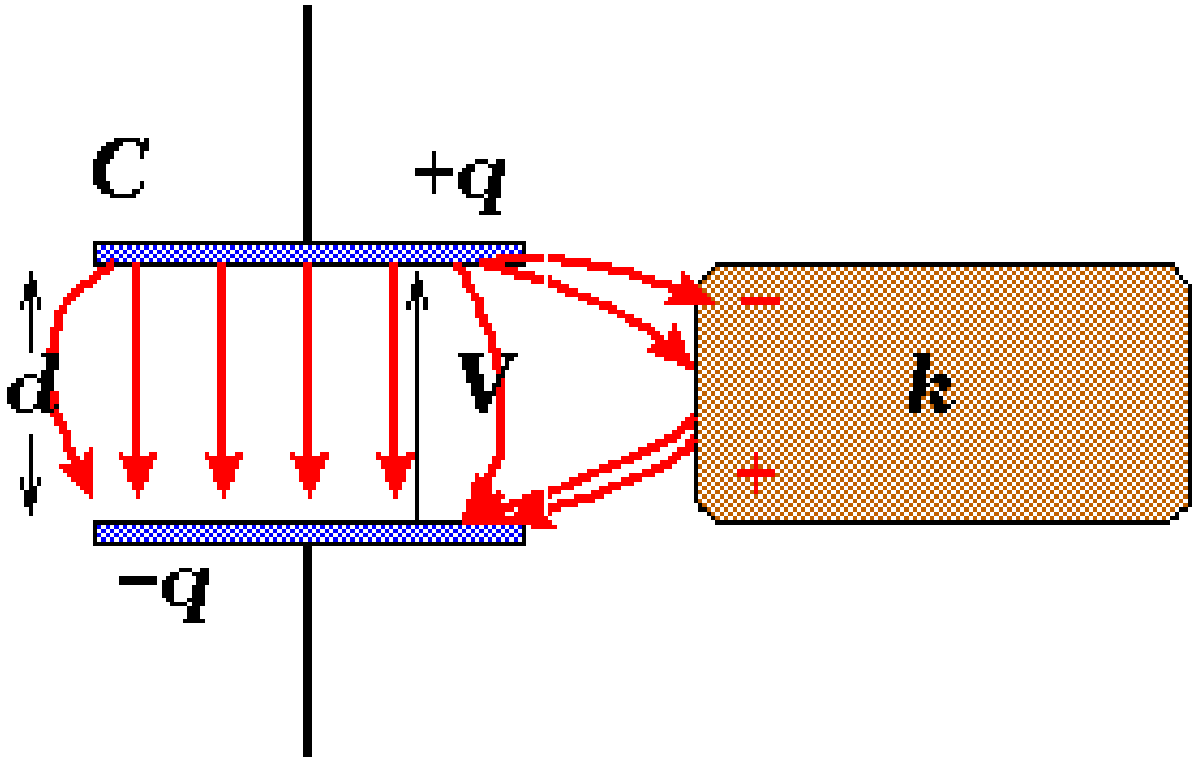
AT&T Bell Laboratories, Holmdel, New Jersey 07733

Received December 23, 1985; accepted March 4, 1986





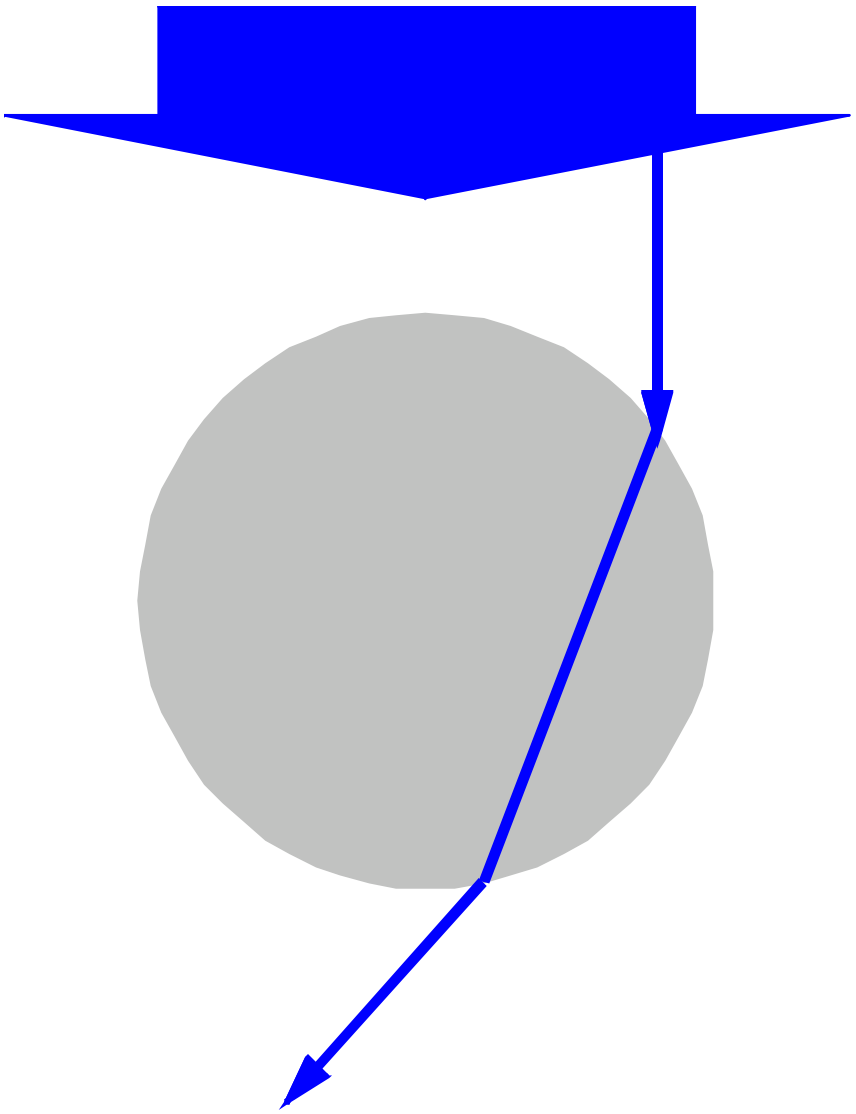
Electric Force on Dielectric



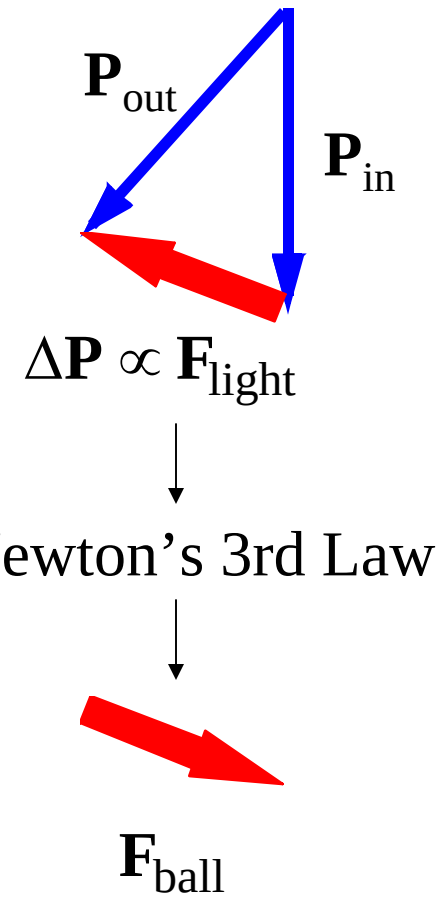
- Fringe fields pull dielectric in
- System lowers energy U = **-p•E**

http://dept.physics.upenn.edu/courses/gladney/phys151/lectures/lecture_feb_03_2003.shtml

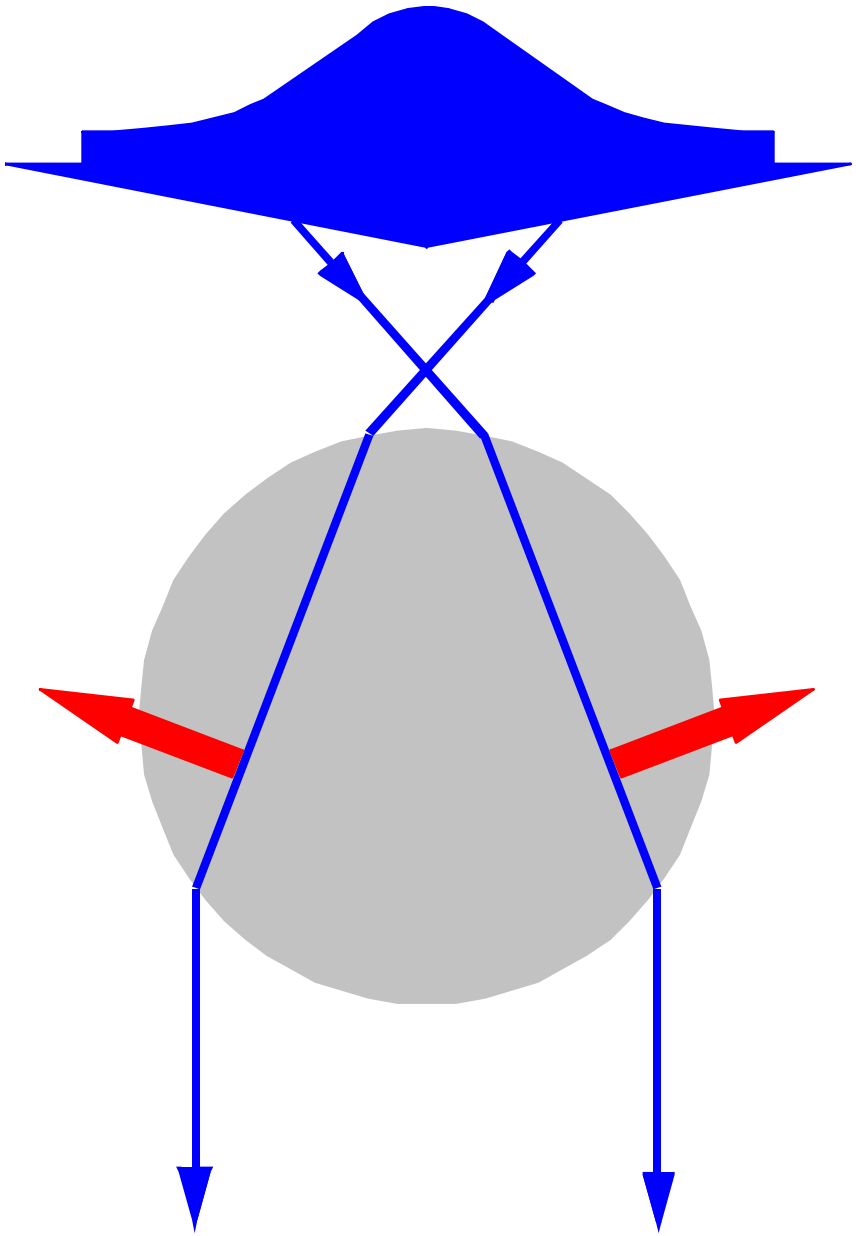
Ray Optics Radiation Pressure (Mie)



Light-Matter
momentum exchange

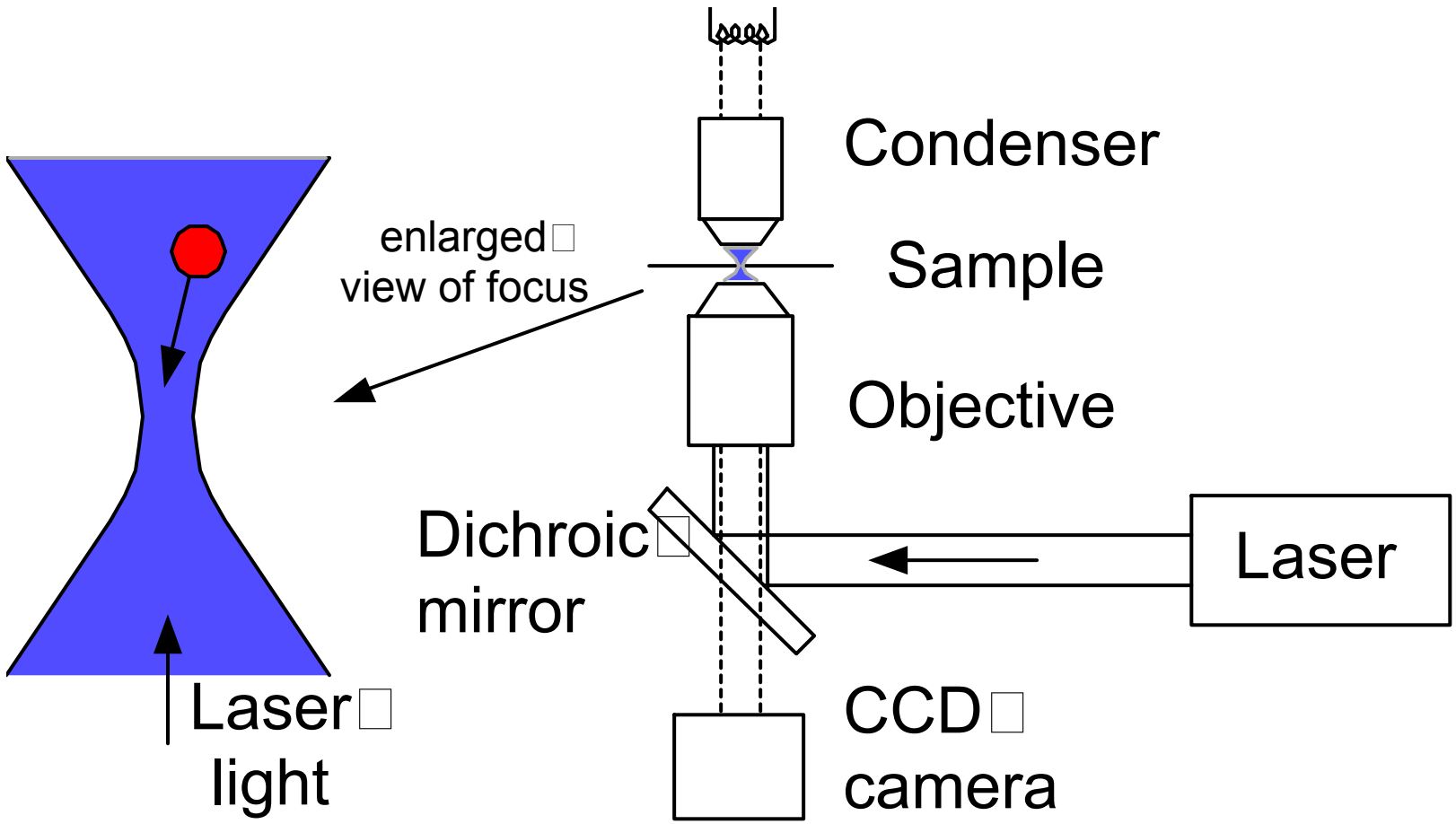


Radiation Pressure near Focus



- Scattering force down
- Backward gradient force
- Net force up toward focus
- Optical Tweezers trap

Optical Tweezer Experiment

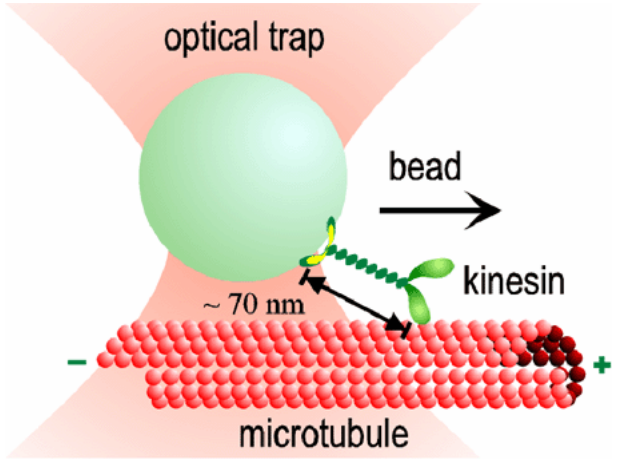


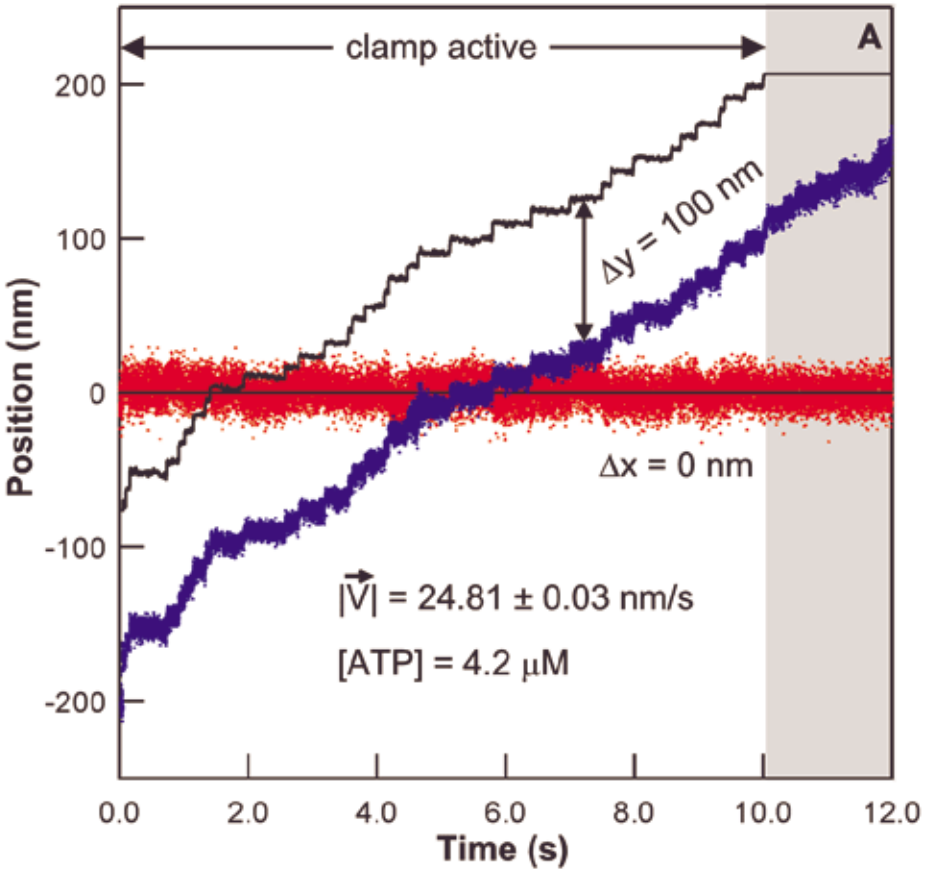
Trapped Microspheres

Tweezer Applications

- Particle manipulation, alignment, rotation
- Biological samples: DNA, molecular motors
- Fabrication
  - Assemble structures, devices
- Microfluidics
  - Flow control, sorting
- Nanometrology
  - Measure forces, displacements, topology
  - Assemble test structures, metrological standards

Kinesin motor motion

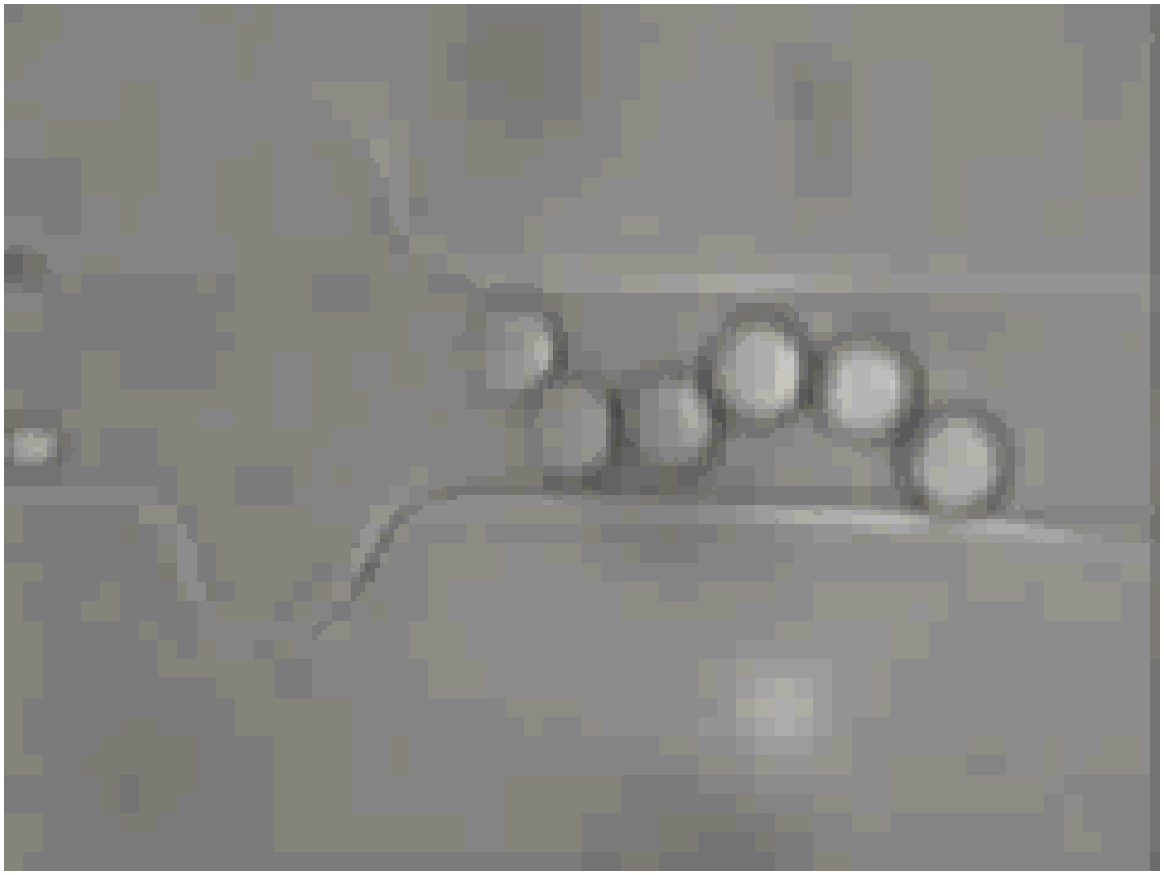




Lang, M.J., Asbury, C.L., Shaevitz, J.W., Block, S.M. An Automated Two-Dimensional Optical Force Clamp for Single Molecule Studies. ***Biophys. J.*** 83, 491 (2002).

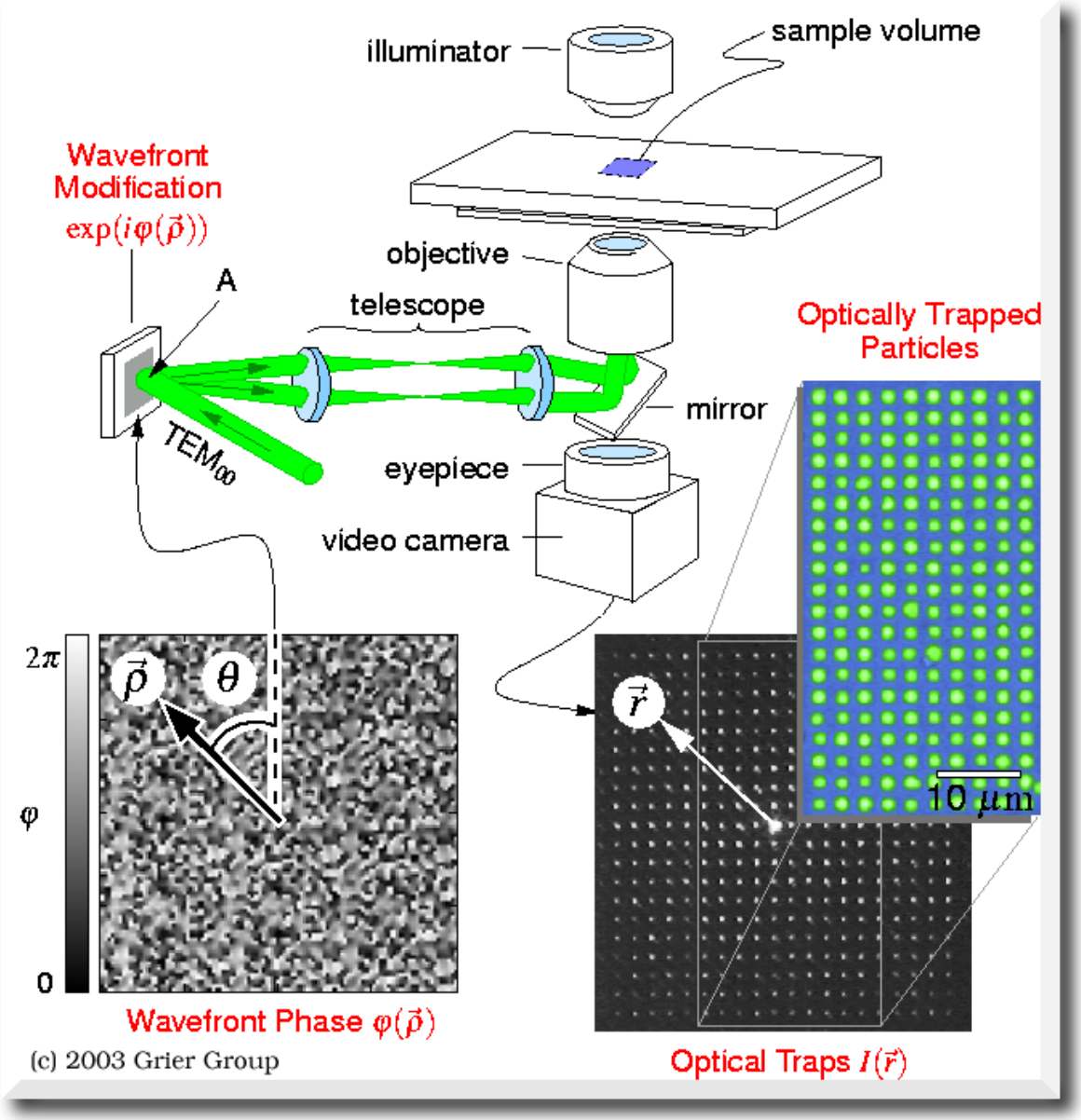
http://www.stanford.edu/group/blocklab/kinesin.html

Tweezer Pump (scanning trap)



A. Terray, J. Oakey, D.W.M. Marr, " Microfluidic Control Using Colloidal Devices ", *Science*, ***296***, 1841 (2002).

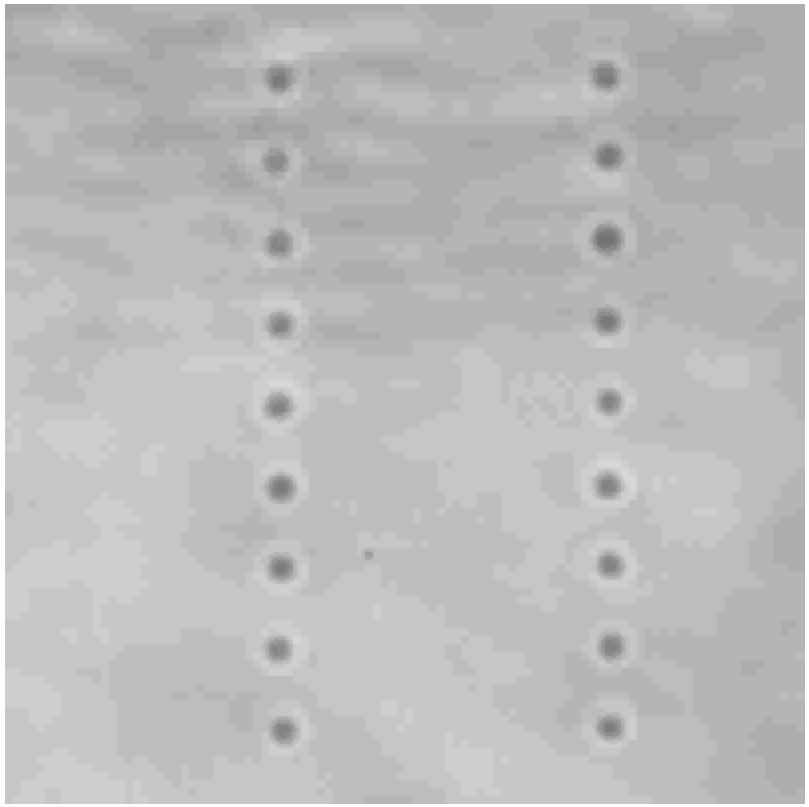
Holographic Optical Tweezers



E. R. Dufresne and D. G. Grier, "Optical tweezer arrays and optical substrates created with diffractive optical elements," *Rev. Sci. Instr.* **69**, 1974 (1998).

http://physics.nyu.edu/grierlab/dynamic5b/

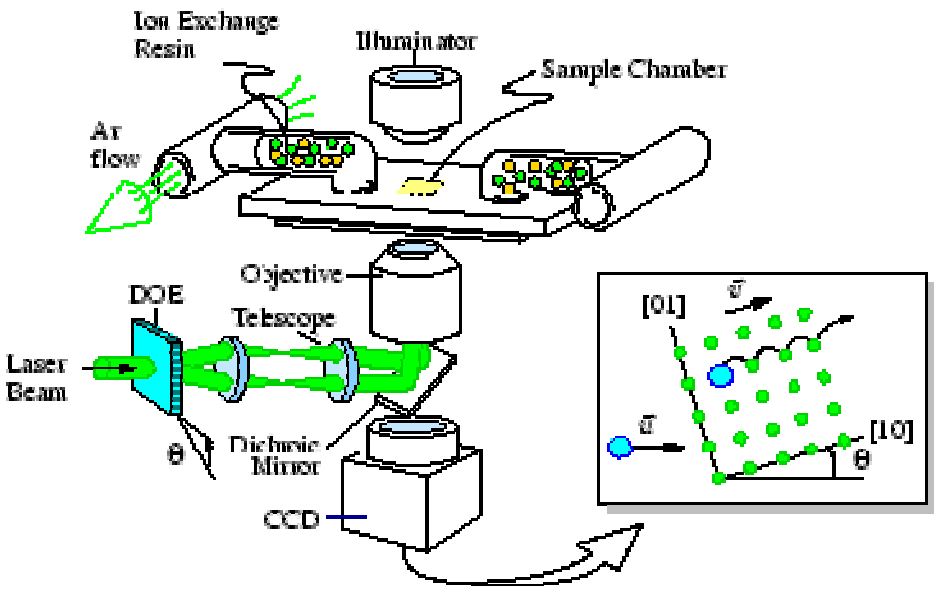
Assembly of 3D Structures

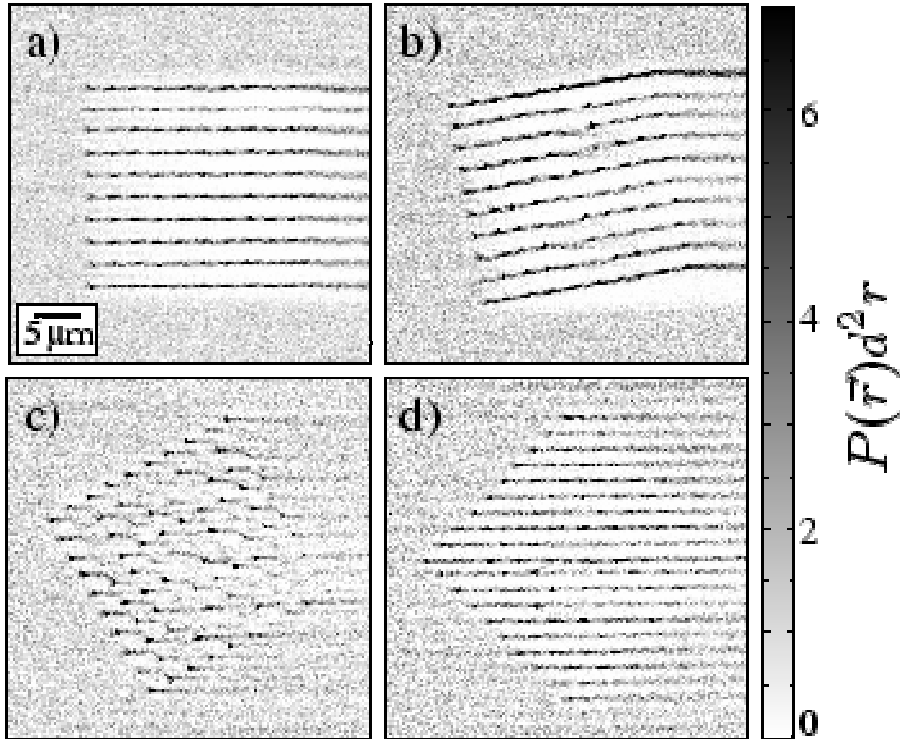


G. Sinclair, P. Jordan, J. Courtial, M. Padgett, J. Cooper and Z. J. Laczik, *Assembly of 3-dimensional structures using programmable holographic optical tweezers*, Opt. Express **12**, 5475 (2004)

http://www.physics.gla.ac.uk/Optics/projects/tweezers/

Particle Sorting with Tweezer Arrays

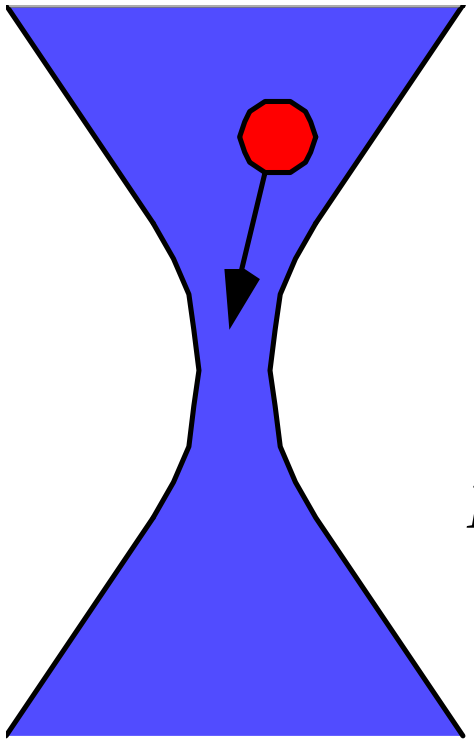




Kinetically locked-in colloidal transport in an array of optical tweezers , P. T. Korda, M. B. Taylor and D. G. Grier, *Phys. Rev. Lett.* **89** , 128301 (2002).

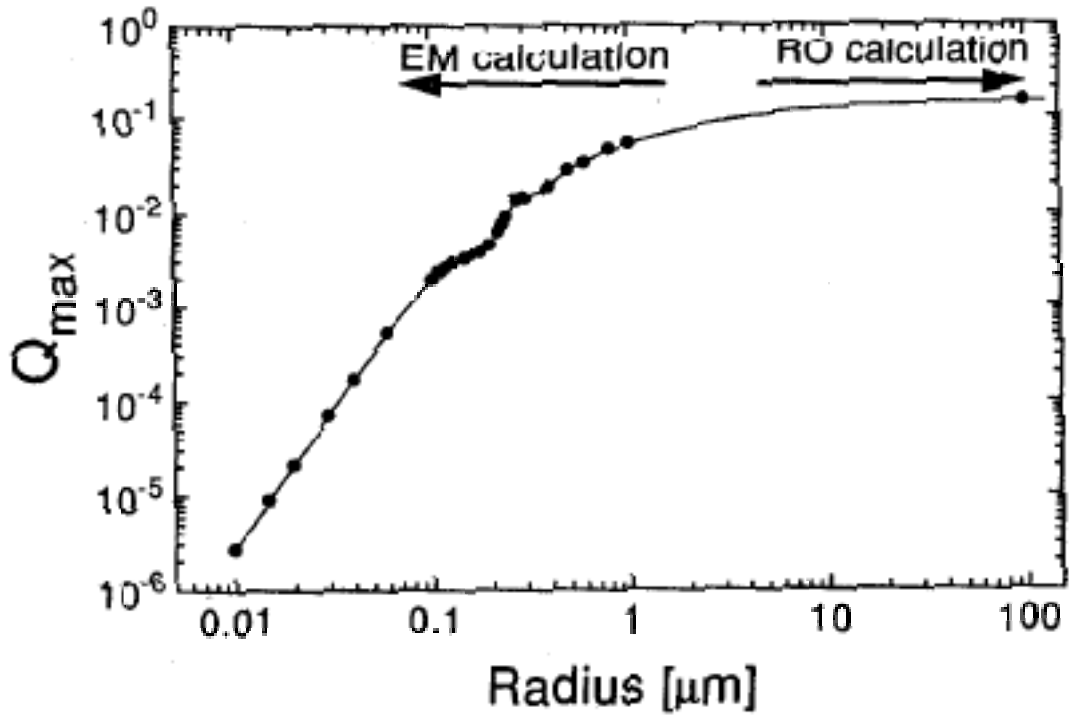
http://physics.nyu.edu/grierlab/pachinko6b/

Rayleigh (a<<λ) Trapping



$\vec{\mathbf{p}} = \alpha \vec{\mathbf{E}}$	induced polarization
$U = -\vec{\mathbf{p}} \bullet \vec{\mathbf{E}}$	energy of interaction
$\vec{\mathbf{F}}_{grad} = -\nabla U$	force toward high intensity
$\vec{\mathbf{F}}_{grad} = \mathrm{Re}(\alpha)\nabla E^2$	in phase ($I \propto E^2$)
$F_{scat,abs} \propto \mathrm{Im}(\alpha) I$	out of phase
$\alpha = a^3 \dfrac{\varepsilon - 1}{\varepsilon + 2}$	polarizability (complex)

Trapping efficiency

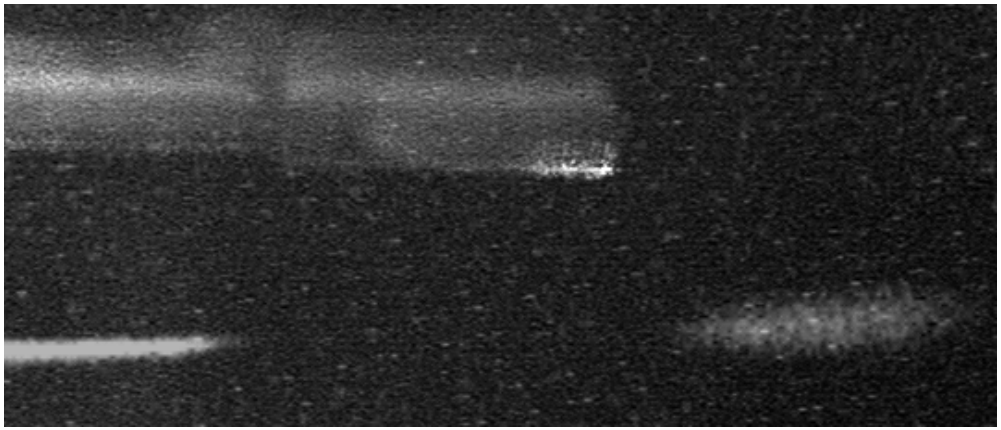


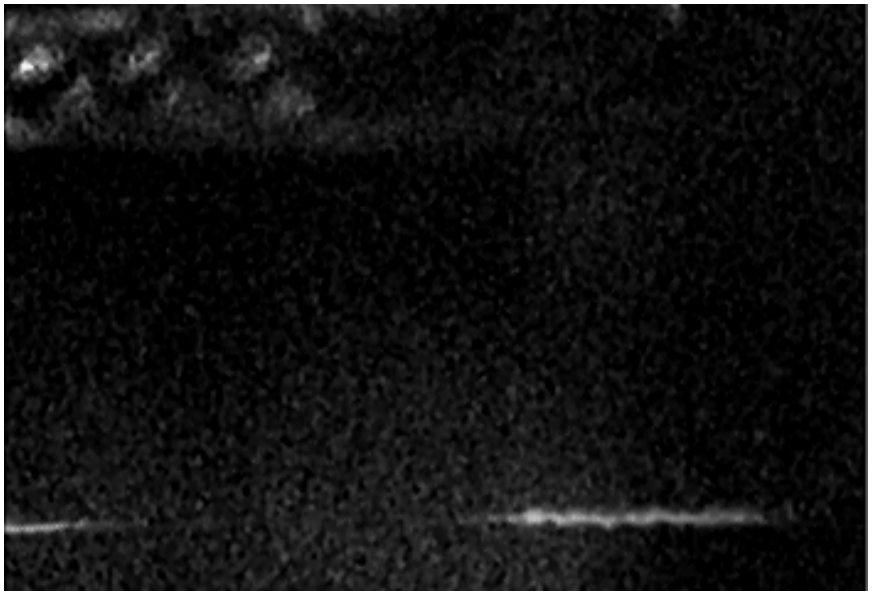
$$F_{grad} \propto a^3$$

w = 0.4μm, λ = 1.06 μm

Wright and Sonek, Appl. Phys. Lett., **63**, 715 (1993).

Trapped Rubidium Atoms

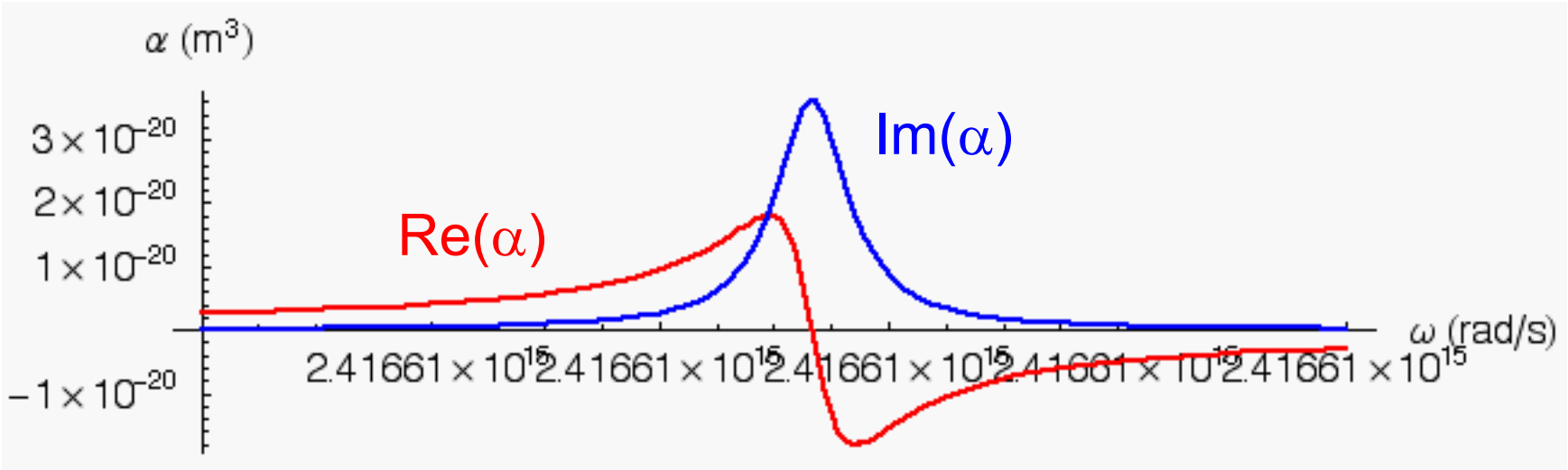




Spectral Response Trapping

Use spectral response to enhance optical force

- Atoms



Spectral Response Trapping

Use spectral response to enhance optical force

- Atoms
- Molecules
- Metallic particles - plasmon resonant particles (PRP) (Gold)
- Shape dependent plasma resonances
- Metal-dielectric nanoshells
- Quantum dots
- Fluorescent probes
- Carbon nanotubes

Plasmon Resonant Particles

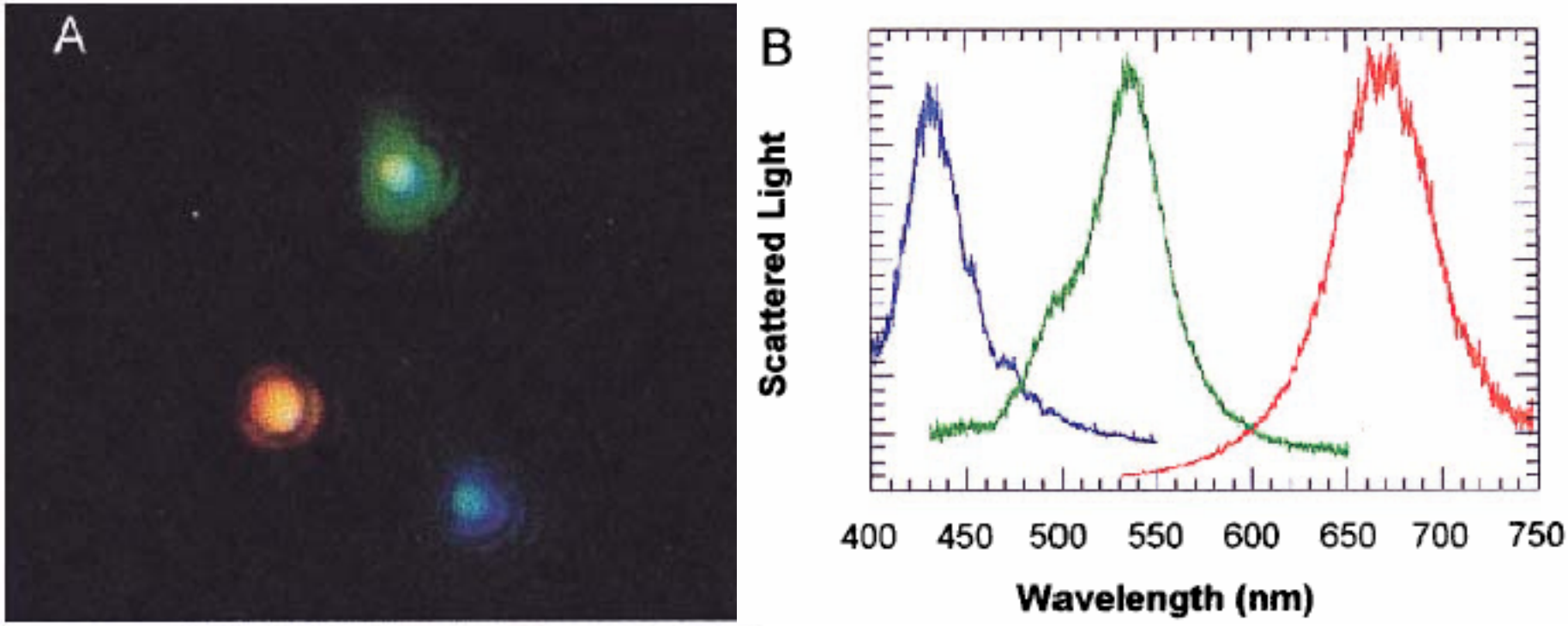
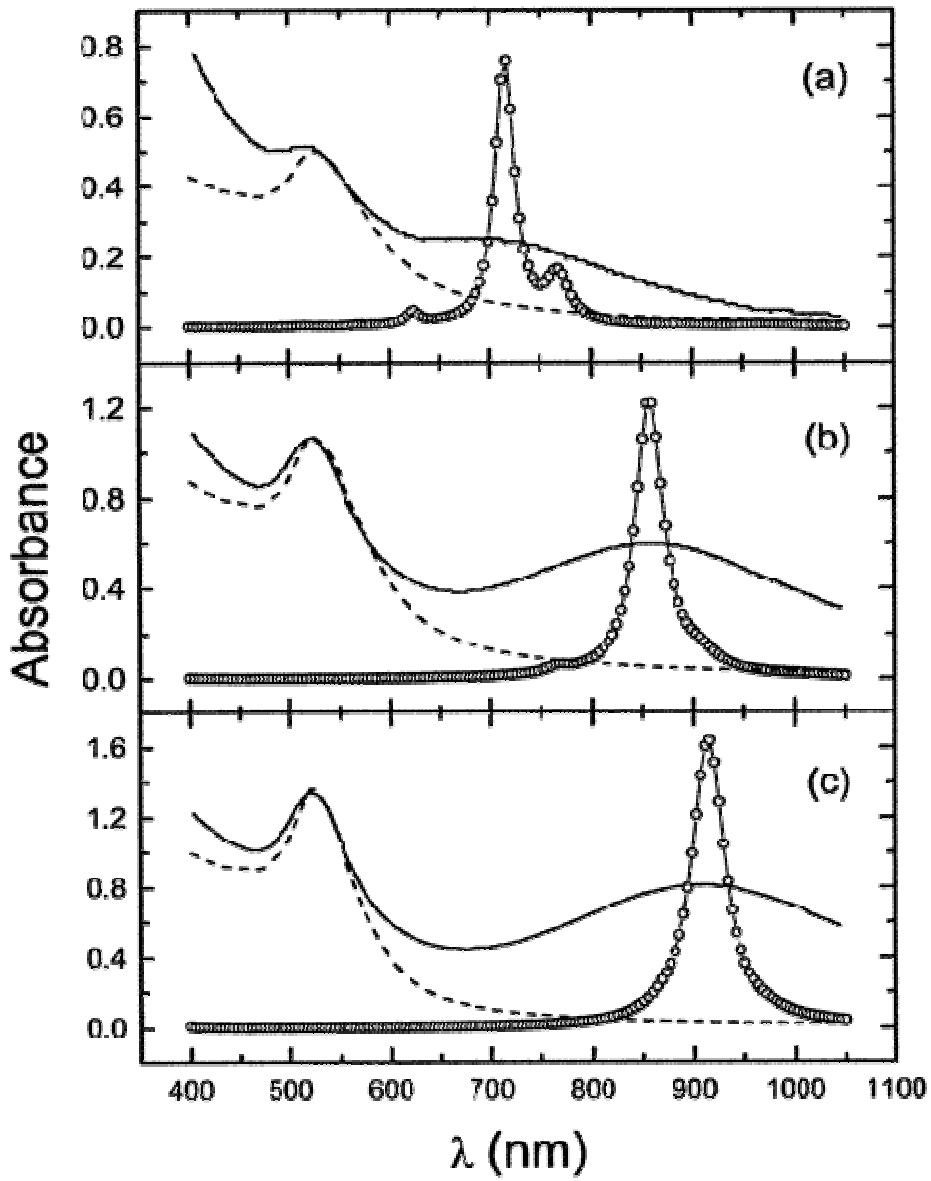


Fig. 1. (A) A color photograph of three PRPs illuminated with white light. The particles were chosen so that their plasmon resonance peak wavelengths would be red, green, and blue, respectively. The distance between the red and green particles is ≈4 μm. The weaker intensity of the blue PRP can be qualitatively seen by the overexposure of the film for the green and red images. (B) Spectral curves: the relative intensity of scattered light as a function of wavelength for the three particles shown in A. The two PRPs whose peak wavelengths are shifted by ≈100 nm have ≈10% overlap of intensity at the peak of their respective plasmon resonances. The full width at half height of the PRP with peak centered at ≈440 nm is ≈40 nm.

Schultz et al., PNAS, **97**, 996-1001 (2000).

Nanoshell Spectra



Comparison between the calculated (circles) and experimentally measured (solid line) absorbance for three different gold nanoshells. Panel a is a nanoshell of dimension (4.1, 5.1) nm, panel b is for a nanoshell of dimension (8.6, 9.9) nm, and panel c is for a nanoshell of dimension (13.1, 14.9) nm. The dashed line is the absorbance of solid gold colloidal spheres that are also present in the solution. The parameters used in the TDLDA calculations are $\varepsilon_C = 5.4$, $\varepsilon_E = 1.78$, and $\varepsilon_J = 8$.

Prodan, Nordlander, and Halas, Nano Letters, **3**, 1411, (2003).

Optical Tweezers Summary

- Optical manipulation on micro & nano-scale
- Assemble, operate, & test micro & nano devices
- Trap arrays, sorting particles
- Extension to nanoparticles via spectral enhancement