Optical trapping on waveguides

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COMSOL
CONFERENCE
2015 GRENOBLE

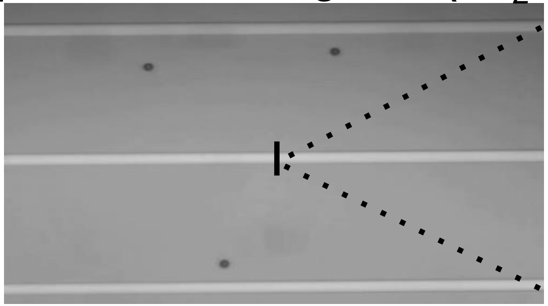
Outline

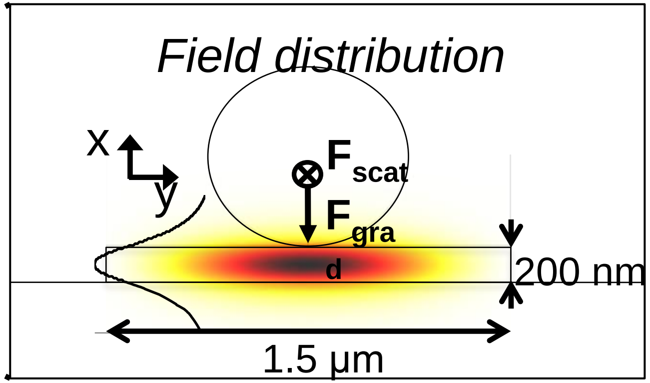
- Principles of waveguide propulsion
- Simulation of optical forces: Maxwell stress tensor vs. pressure
- Squeezing of red blood cells on a waveguide
- Trapping in a waveguide gap: Interference & levitation
- Phase-change due to trapped particle: S-parameters
- Summary

Waveguide propulsion

- Transparent microparticles are attracted by strong field gradient (evanescent field).
- Radiation pressure propels particles along the waveguide.

Top view of waveguide (Ta_2O_5)





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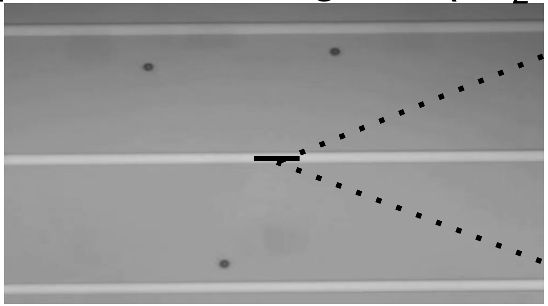
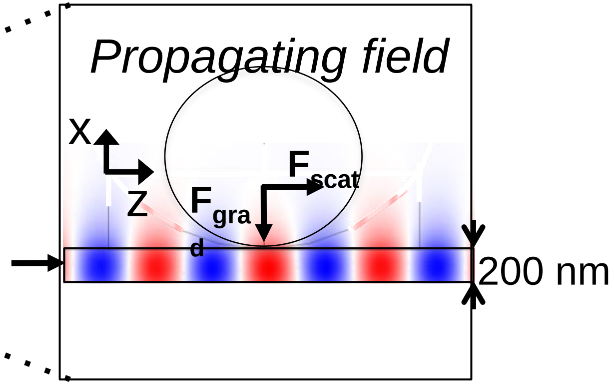
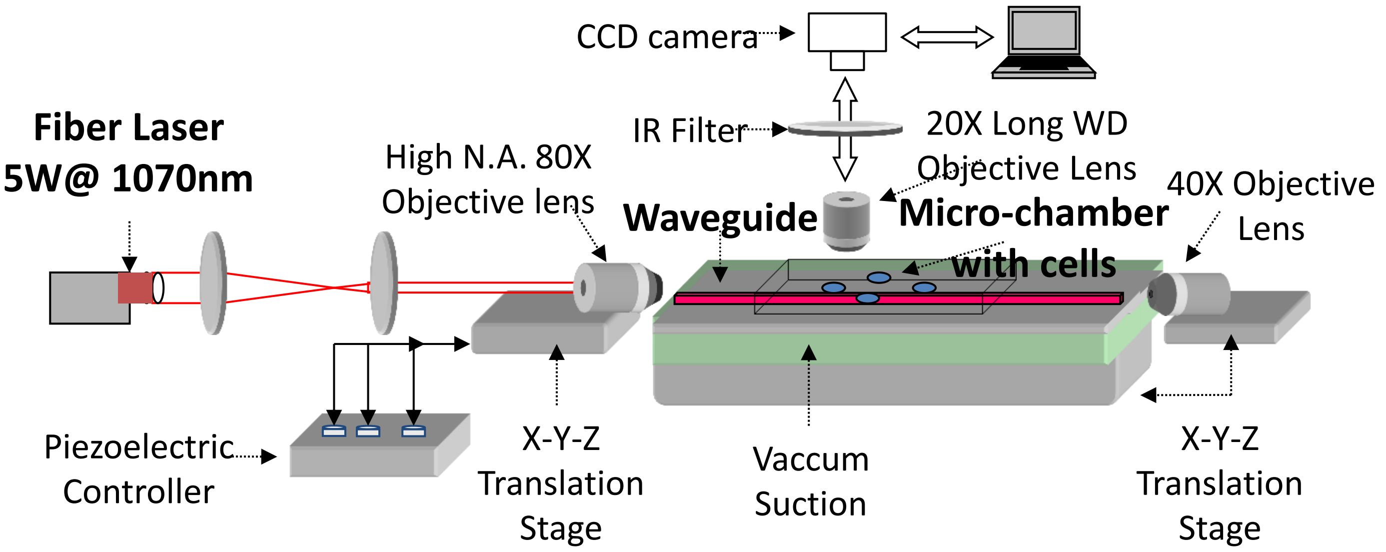




Waveguide propulsion– experimental setup

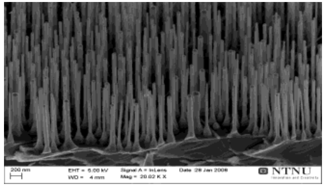


Waveguide propulsion – on straight waveguide

- Waveguides made of Ta_2O_5 (n = 2.1)
- Red blood cells: 6 µm/s (in sucrose), Polystyrene microparticles: 50 µm/s, Nanowires: > 500 µm/s !

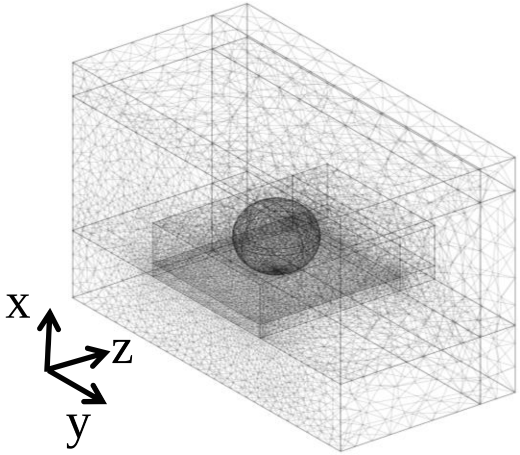
Waveguide propulsion of red blood cells

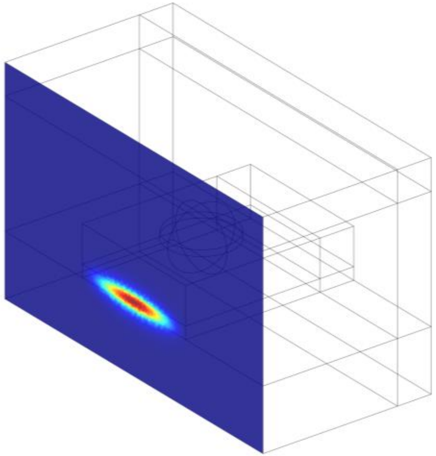
Waveguide propulsion of nanowires



Photon. Tech. Letters, 21, 1408, (2009)
Optics Express,18, 21053, (2010)
Optics Letters, 36, 3347–3349 (2011)

Simulation of optical forces with Comsol





- Define geometry
- Define mesh
- Set boundary conditions
- Find waveguide mode
- Propagate through geometry

- Find forces by integrating Maxwell's Stress Tensor over the surface of the particle
- Memory-intensive, using e.g. 8x128 GB on a cluster

Simulation of optical forces with Comsol

- Forces by integrating Maxwell's stress tensor (**MST**) over surface of particle:

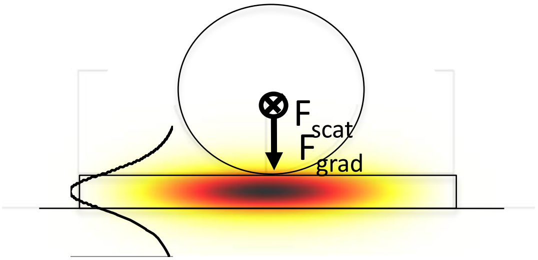
$$\vec{\mathcal{F}} = \oint_S \overleftrightarrow{\mathcal{T}} \cdot \hat{n}\, da, \qquad \mathcal{T}_{ij} = \varepsilon_0 \varepsilon_r \left(\mathcal{E}_i \mathcal{E}_j - \frac{1}{2} \delta_{ij} \mathcal{E}^2 \right) + \frac{1}{\mu_0} \left(\mathcal{B}_i \mathcal{B}_j - \frac{1}{2} \delta_{ij} \mathcal{B}^2 \right)$$

  - Comsol: emw.unTx, unTy & unTz

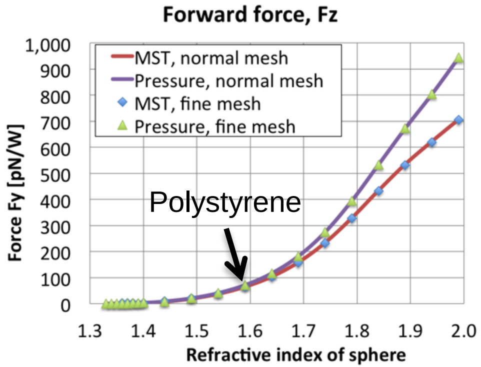
- Optical pressure given by field (ref. Brevik & Kluge, *JOSA B,* 1999): can also be integrated over surface to give force:

$$\sigma^{AM} = \frac{1}{4} \varepsilon_0 n_w^2 \left(\frac{n_c^2}{n_w^2} - 1 \right) \left[E_t^2 + \frac{n_c^2}{n_w^2} E_r^2 \right]_{a-},$$

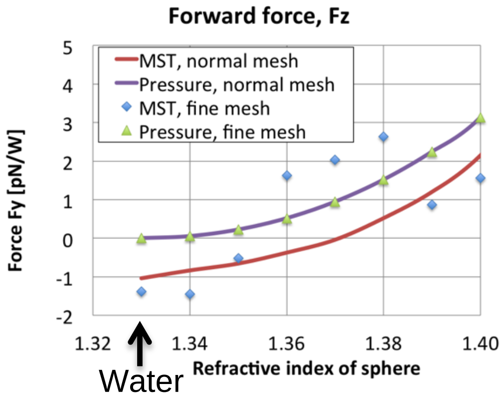
$$F_x = \oint_S \sigma^{AM} n_x\, da$$

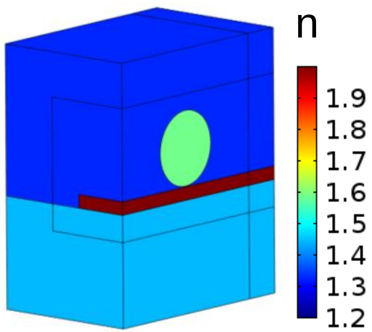


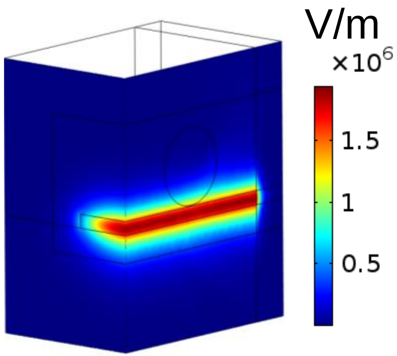
Simulation of optical forces with Comsol
Force from MST vs. from optical pressure



Zoom







Thus:

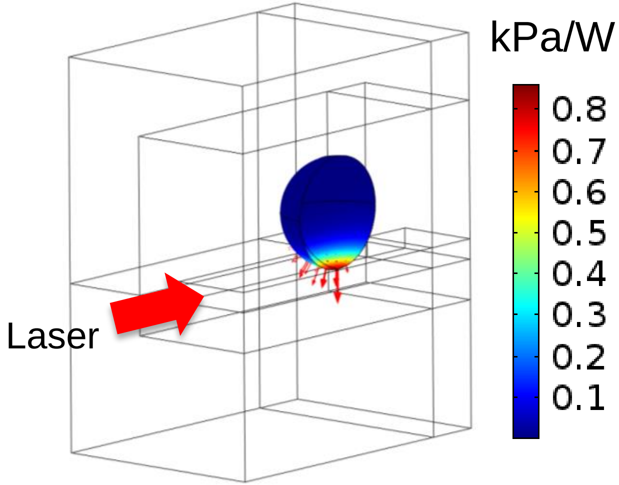
- MST gives error for small index difference
- And for high???

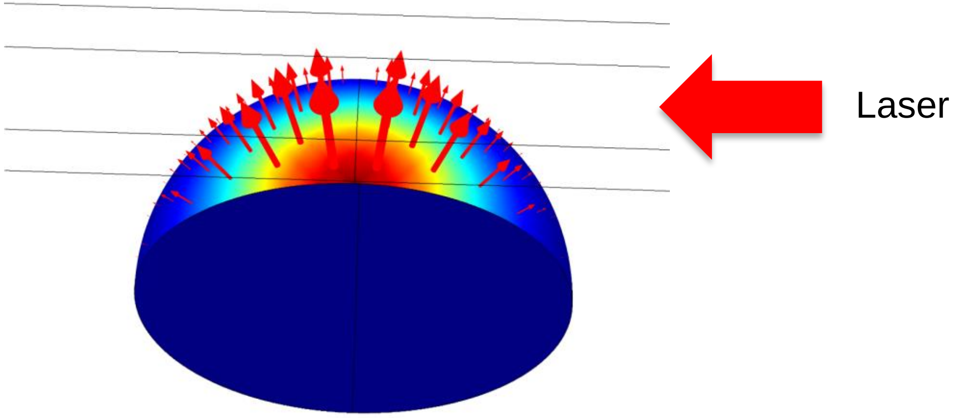
Cause of error:

- Triangular mesh on spherical surface?
- MST subtracting large numbers?
- Error in Comsol for MST?

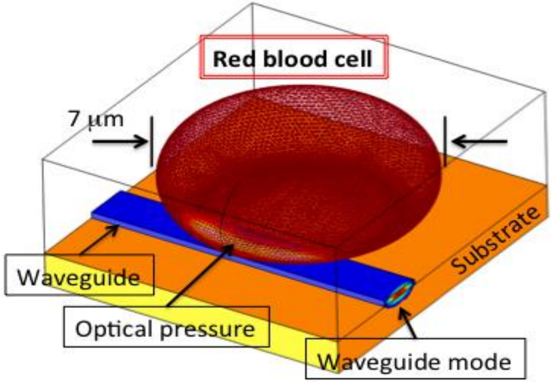
Optical pressure

- Can be found from:
  - The field using the expression of Brevik & Kluge, σ^{AM}
  - Difference in diagonal radial components of MST on the two sides of a surface





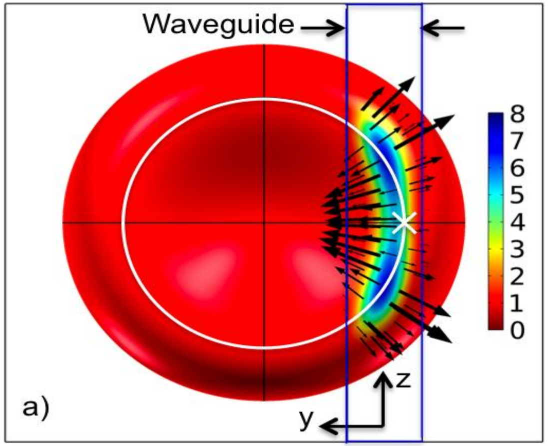
Forces & pressure on red blood cells (RBC)

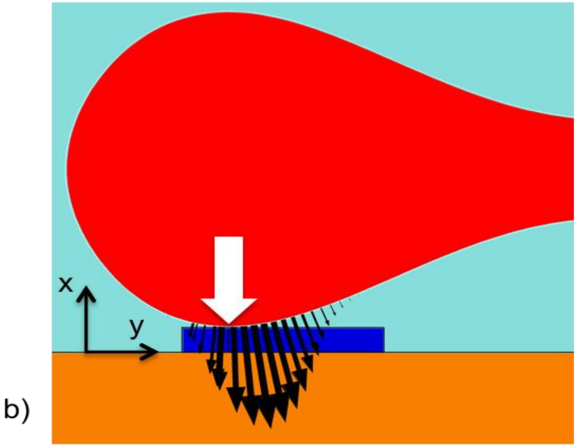


Pressure (Pa) and direction

a) From bottom, through w.g.

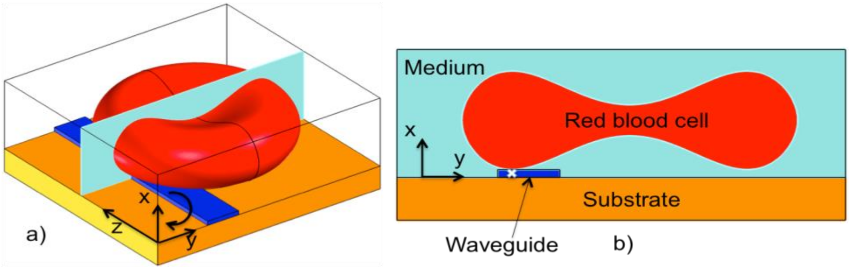
b) Cross-section

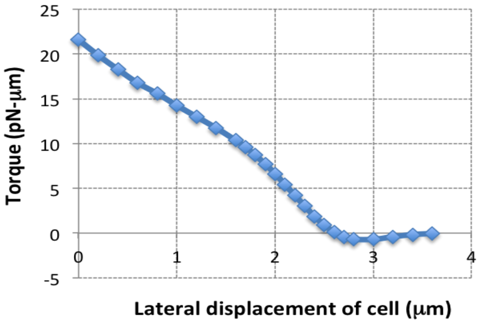


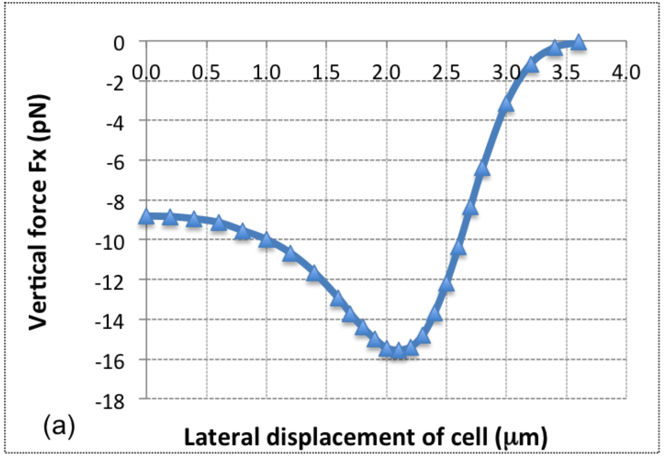


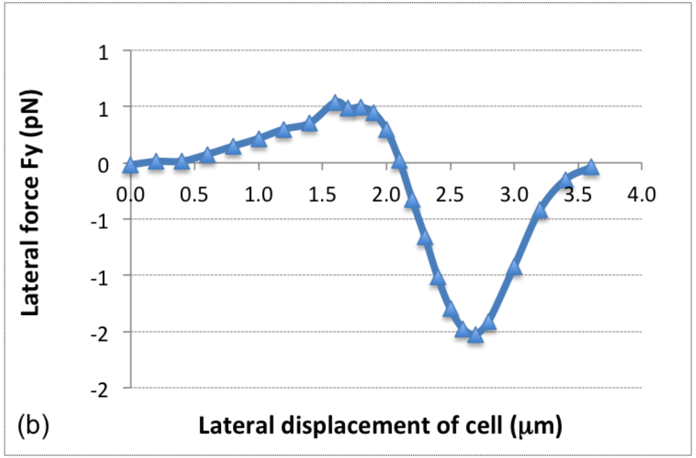
Analyst, 2015,**140**, 223-229

Force & torque on RBC



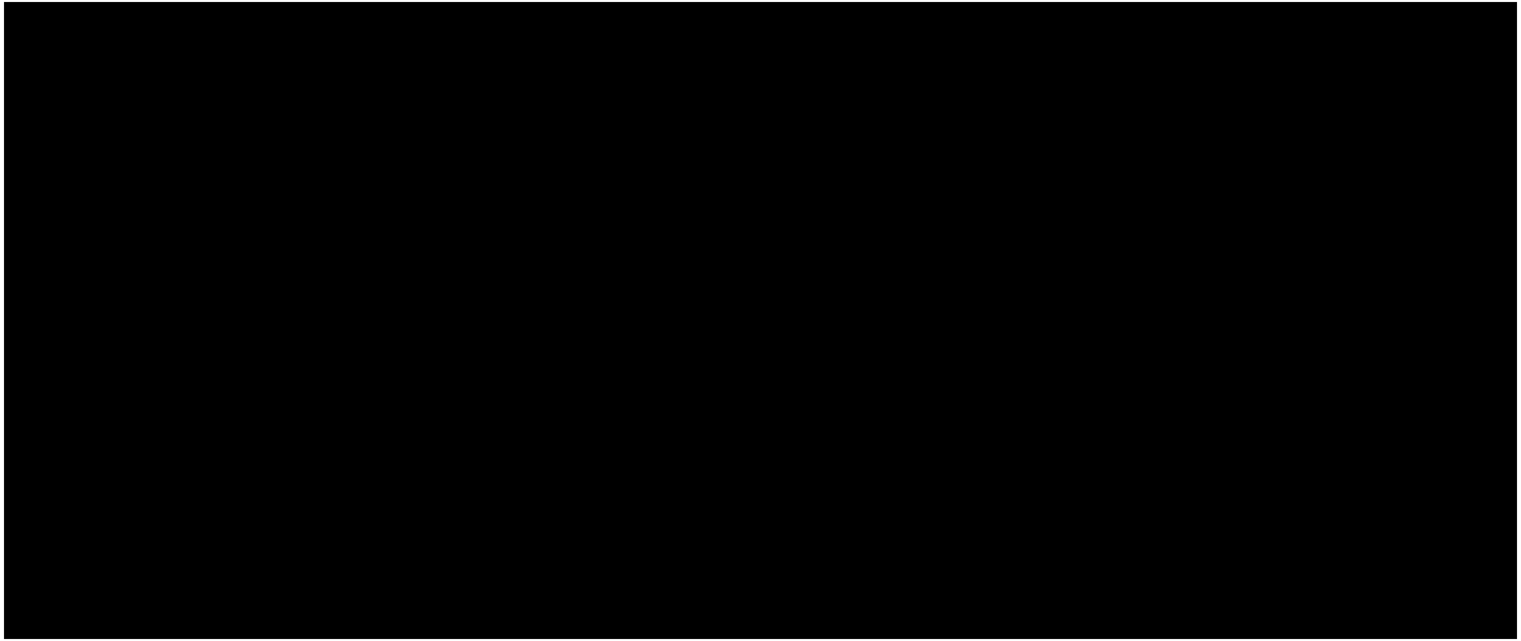






Analyst, 2015,**140**, 223-229

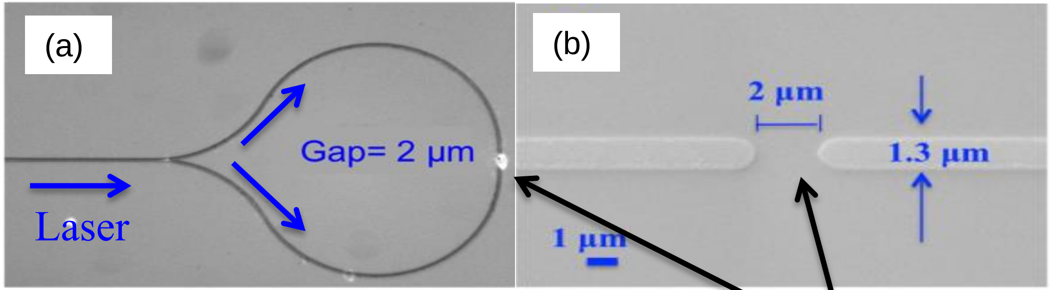
Squeezing of red blood cells on tapered waveguide



Analyst, 2015,**140**, 223-229

Loop with a gap: *Transport & stable trapping*

- On a waveguide, particles are continuously propelled forward
- Alternative: loop with intentional gap on the far side
- Particle is stably trapped in the gap by the counter-propagating fields



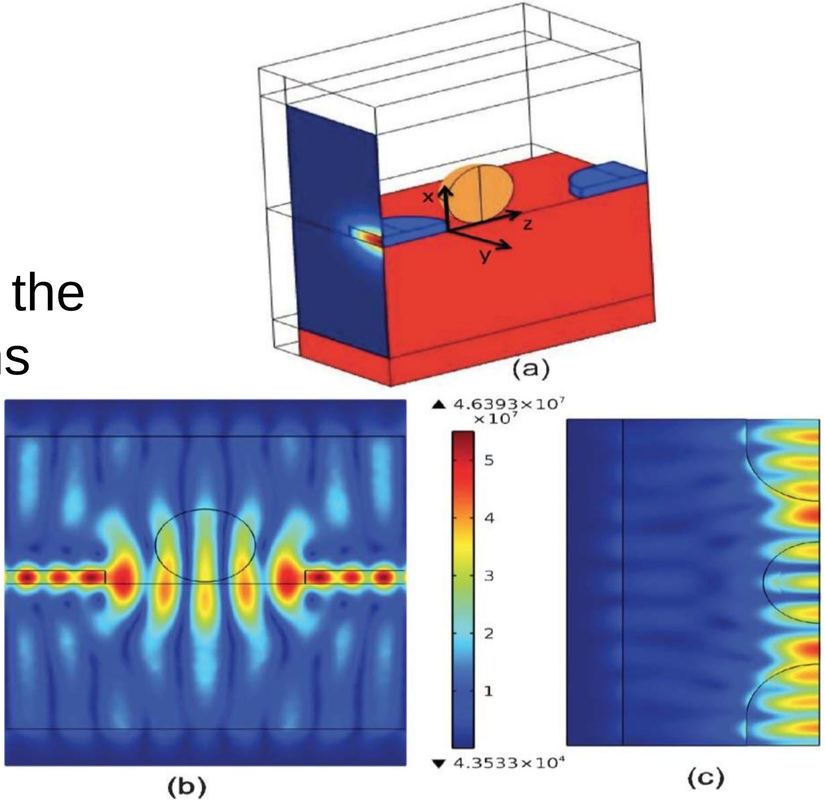
Waveguide loop with a 2µm gap

Lab Chip, 12(18), 3436-40, 2012

Trapping in waveguide gap: Simulation of 2μm gap

- Symmetric about centre of waveguide
  - ➢ Simulate half the problem
- Interference fringes caused by the two counter-propagating beams

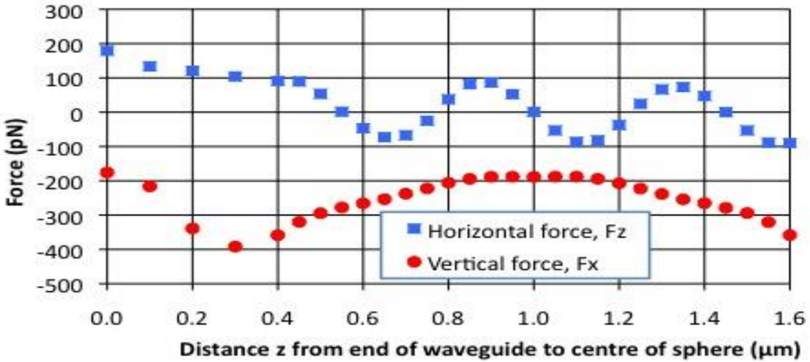
a) 3D-model
b) Field, side-view
c) Field, top-view



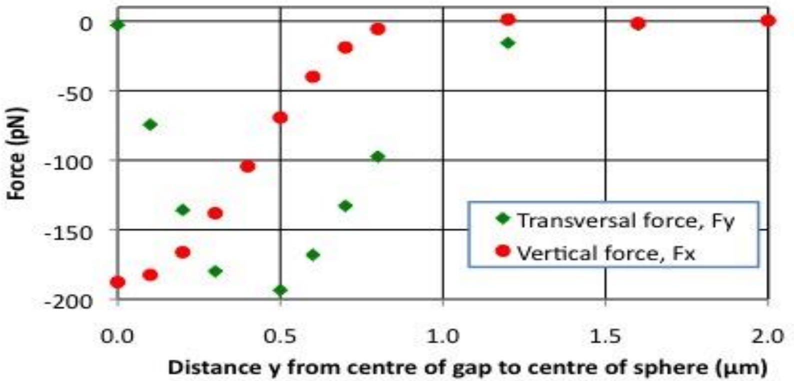
Lab Chip, 12(18), 3436-40, 2012

Trapping in waveguide gap: Simulation of 2μm gap

Horizontal and vertical forces as **sphere is moved across gap**:

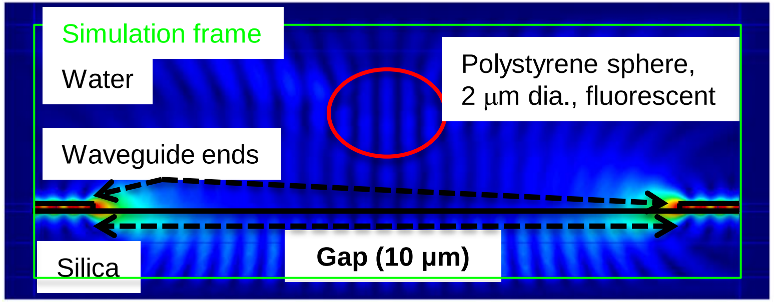


Transversal and vertical forces as **sphere is moved sideways** out of the gap:



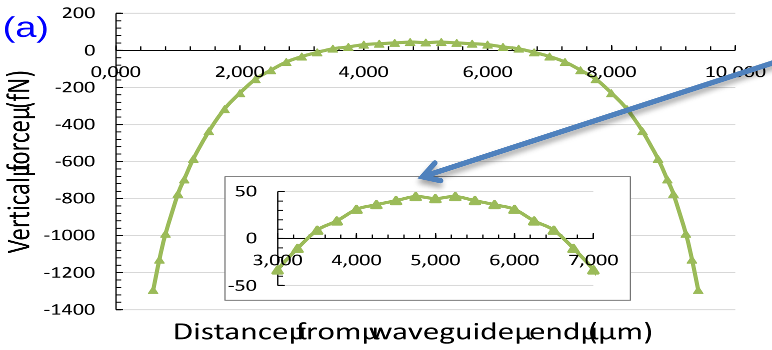
Lab Chip, 12(18), 3436-40, 2012

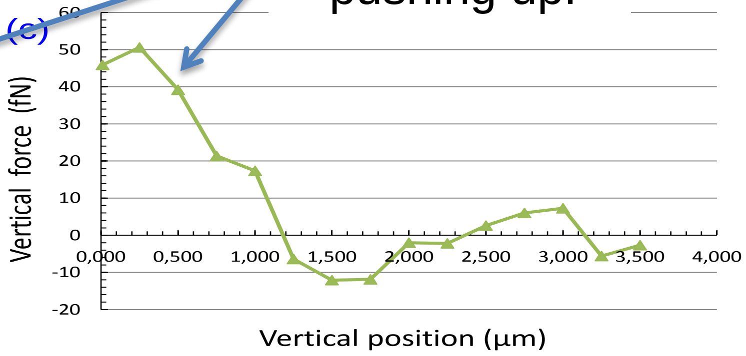
Trapping in waveguide gap: *Optical levitation?*



- 2μm gap = tight trapping
- 10μm gap = **levitation**?

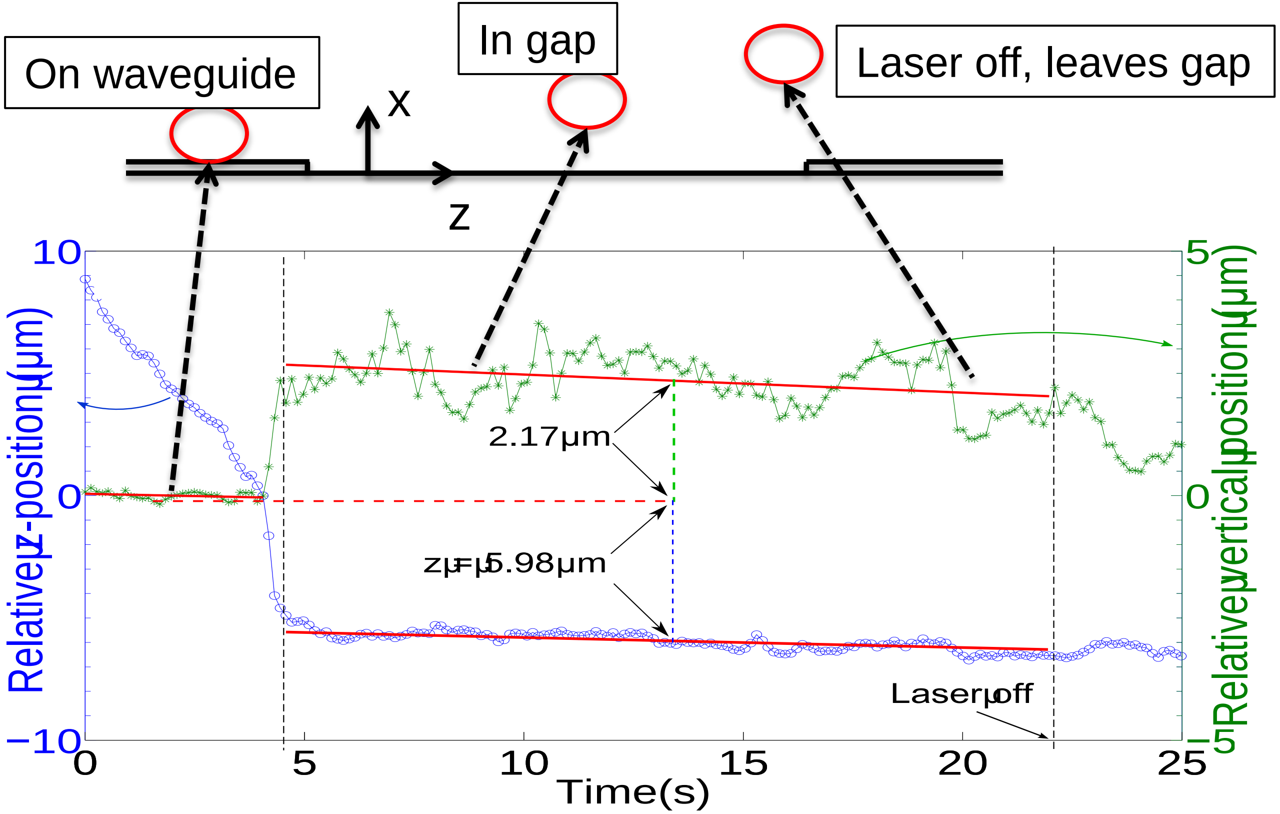
Positive values
= pushing up!





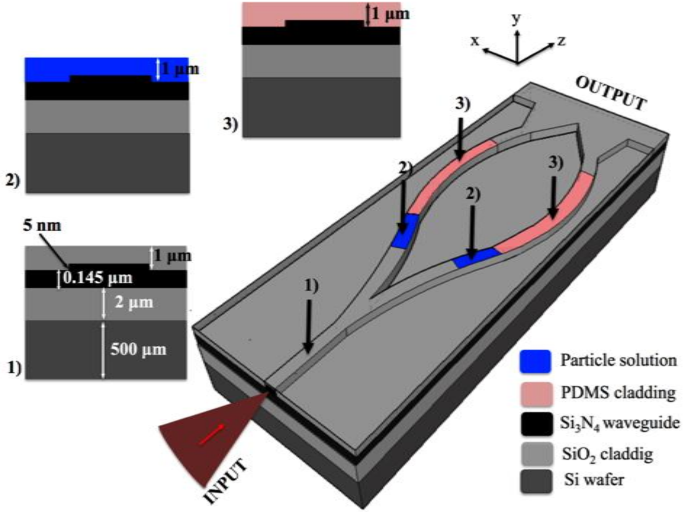
Optics Express, 6601-6612 (2015)

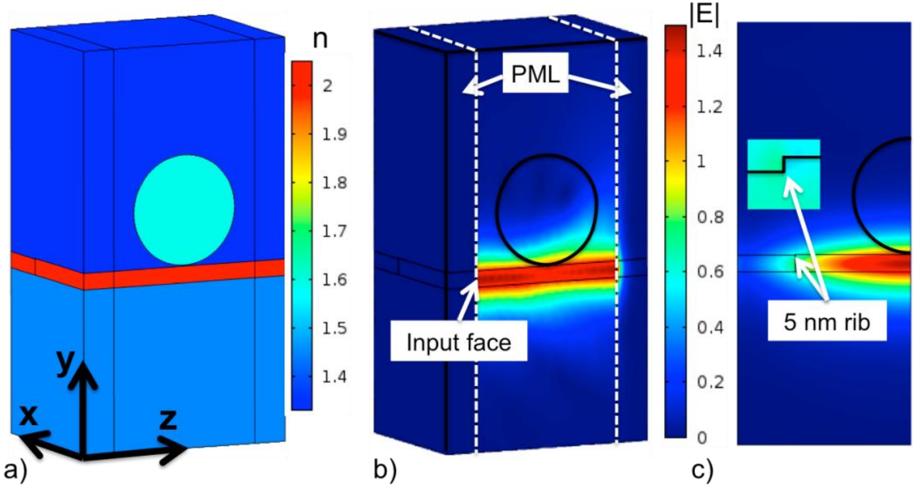
Trapping in waveguide gap: *Optical levitation!*



Optics Express, 6601-6612 (2015)

On-chip phase measurement





Measurement set-up:
Waveguide Young interferometer

Lab Chip, 2015,**15**, 3918-3924

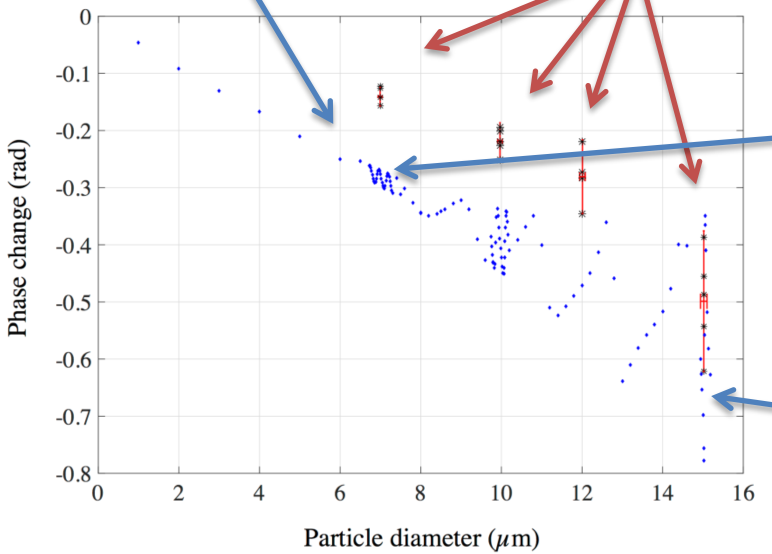
Simulation using PMLs, input and output ports.
Phase and transmission found from S-parameters.

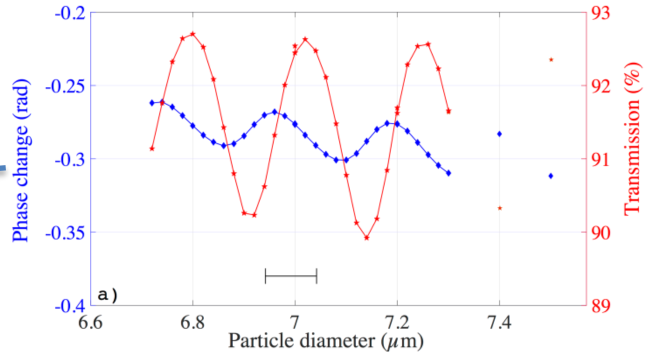
On-chip phase measurement

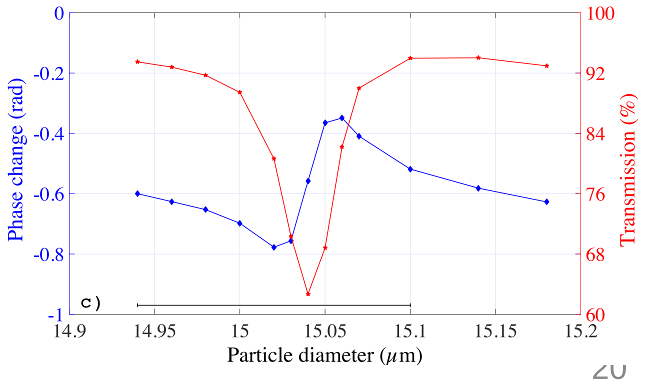
Simulated

Measured

Resonances!
(not measured)







Lab Chip, 2015,**15**, 3918-3924

Summary

- Comsol works fine to find the field around nano- and microparticles on waveguides
  - But memory-hungry: Up to 1TB RAM
- Optical forces: Problem with Maxwell's stress tensor
- Optical pressure: Can be combined with mechanical model?
- Interference and resonances require tight sampling
- Critical to avoid reflection from PML at end of waveguide
- Use PML with slit port excitation for counter-propagating beams

Thanks to:

- Balpreet Singh Ahluwalia, Per Jakobsen, Pål Løvhaugen, Firehun Tsige Dullo and Øystein Helle
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- Cell work: Thomas Huser (Bielefeld), Ana Oteiza and Peter McCourt (UiT)
- Funding: Research Council of Norway
- Computer resources: Notur - The Norwegian metacenter for computational science

THANK YOU!

Squeezing of red blood cells on narrow waveguide

- RBCs are squeezing on waveguides < 6µm wide
- RBC regains shape when laser is switched-off
- No permanent loss of RBC elasticity was observed