The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

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Introduction to Optofluidics

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Extended optical micromanipulation with test objects of special shape

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Introduction to optofluidics
Trieste, 2009

Extended optical micromanipulation with microstructures of special shape

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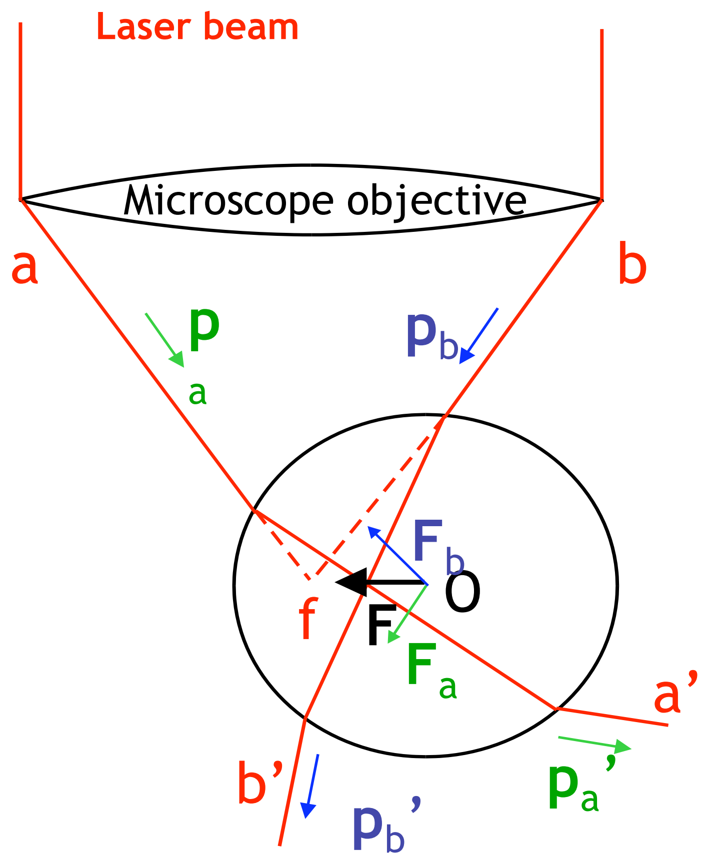
Topics

- Structure building by photopolymerization
- Extended manipulation possibilities
- Rotation and torque measurement in optical tweezers
- Light generated and light driven optomechanical devices

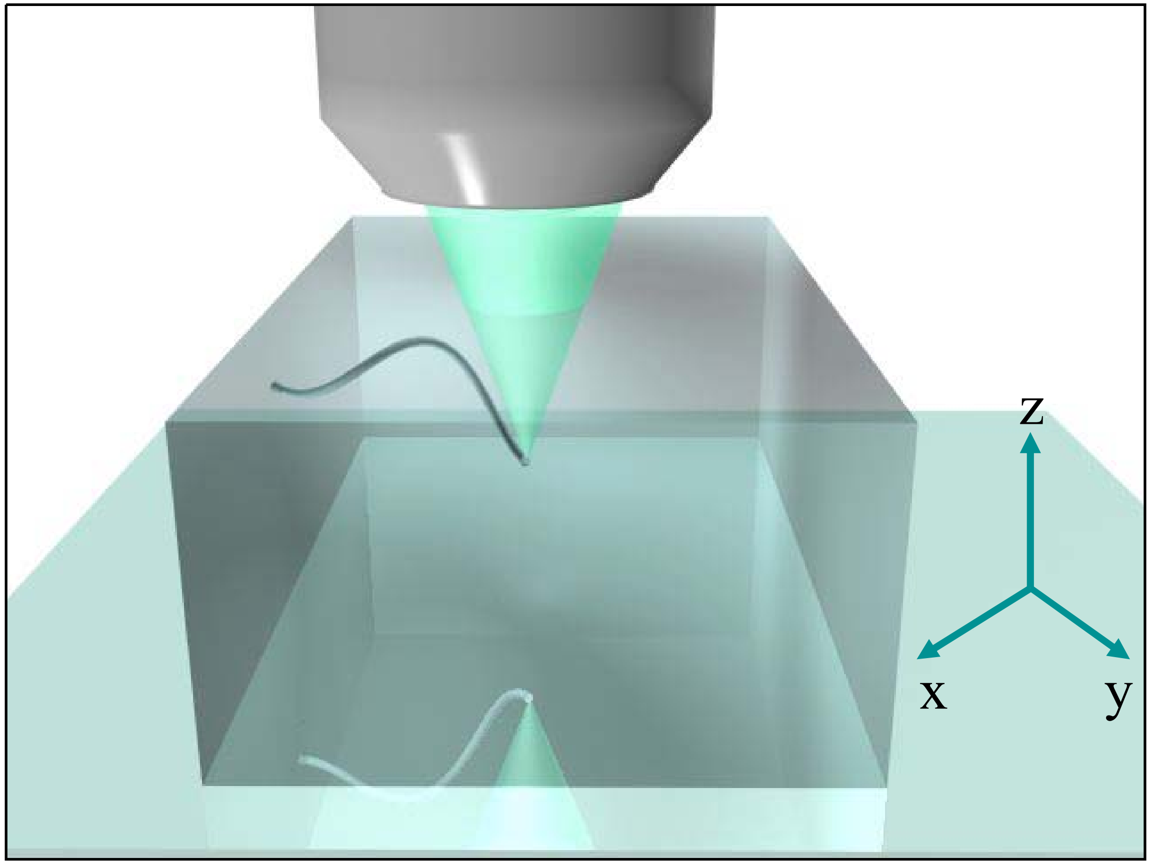
Optical tweezers



Trap non spherical objects

Gives additional control

Produce particles of arbitrary shape by two-photon photopolymerization



Produce particles of arbitrary shape by two-photon photopolymerization

The chemical process:

Start: $I \rightarrow 2R\cdot$

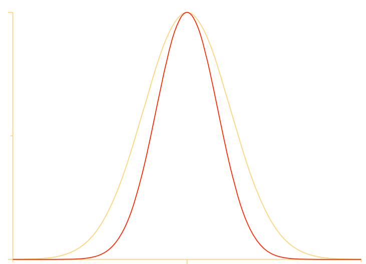
$R\cdot + M \rightarrow R{-}M\cdot$

Growth: $R{-}M_n\cdot + M \rightarrow R{-}M_{n+1}\cdot$

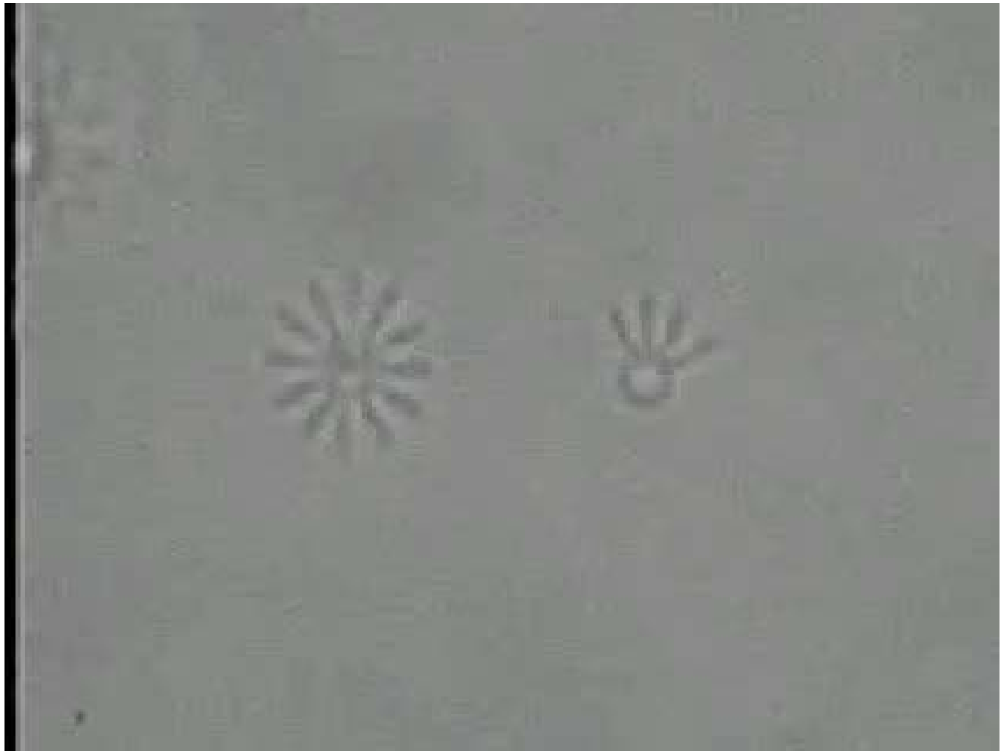
Stop: $2\,\cdot R{-}M_n \rightarrow R{-}M_{2n}{-}R$

Two photon processes scale by the <u>square of the intensity</u> $\Rightarrow$ <u>better spatial resolution</u>

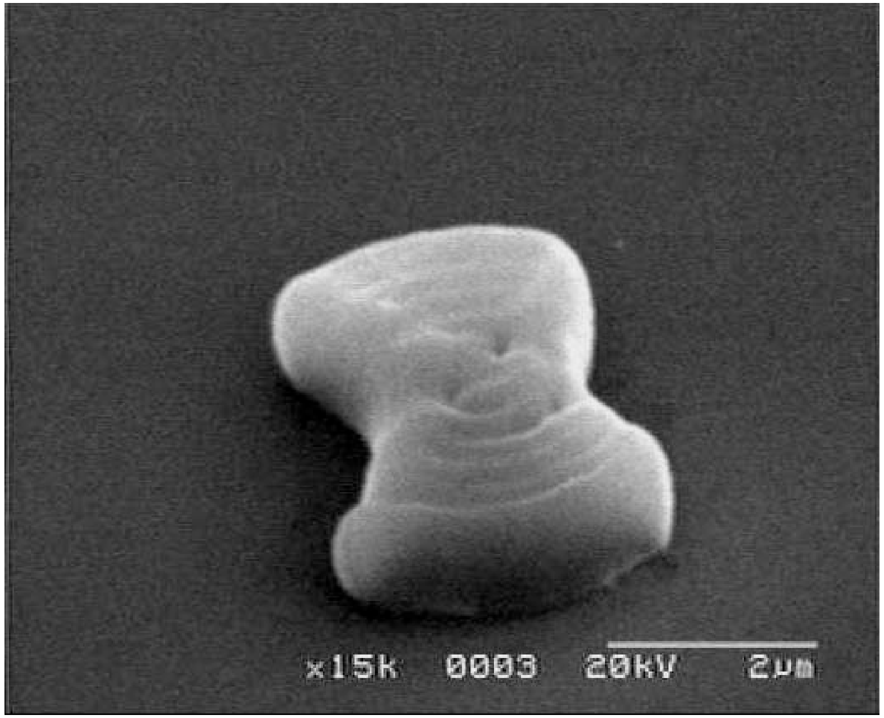
This brings smaller half width for a gaussian beam thus better spatial resolution



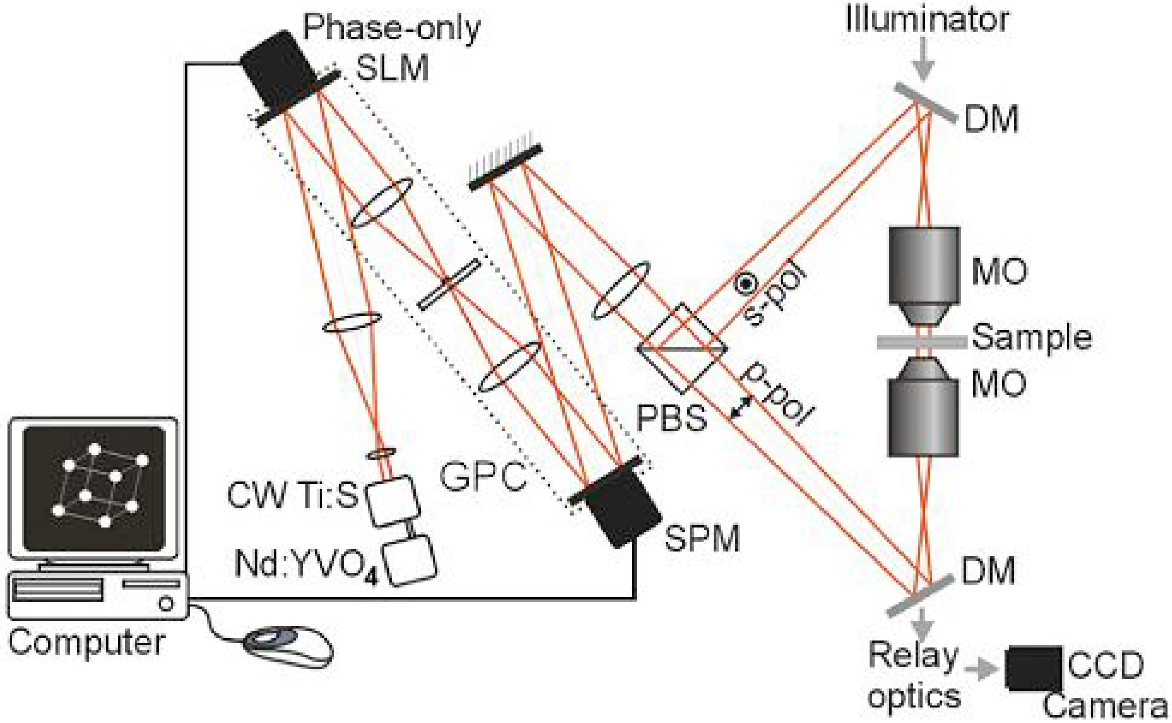
Produce particles of arbitrary shape by two-photon photopolymerization



Special structures for structure building by optical manipulation

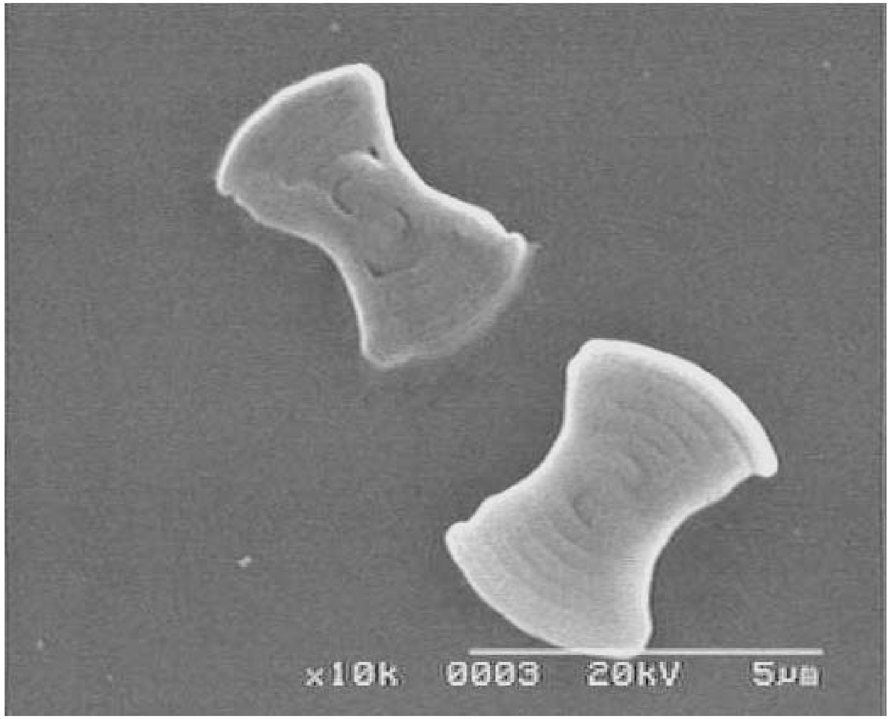


Multiple trap system of J. Glückstad



Jesper Glückstad, RISO

Special structures for structure building by optical manipulation



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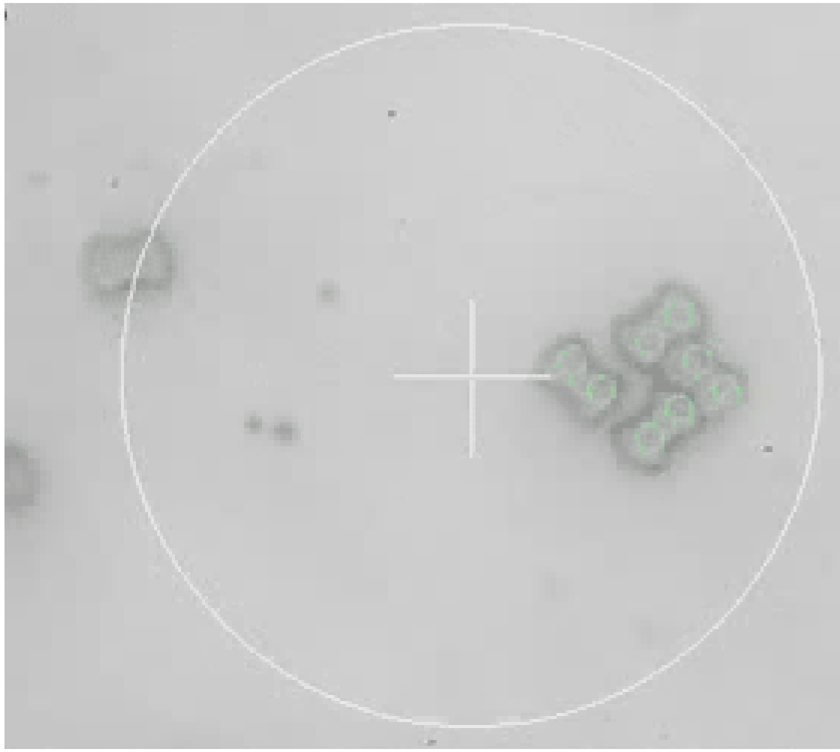
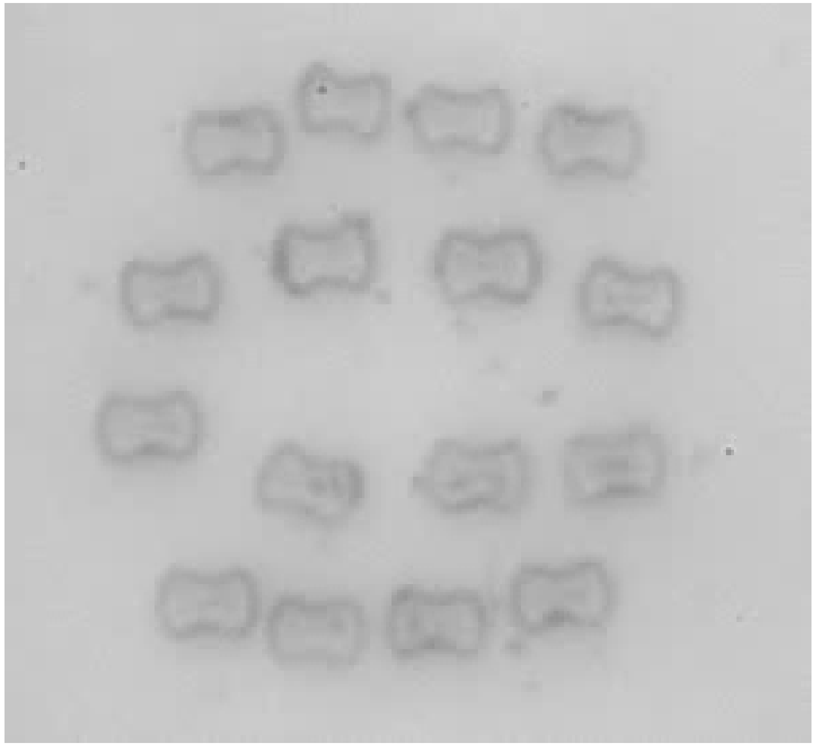


Collaboration with the Jesper Glückstad group at RISO

Special structures for structure building by optical manipulation



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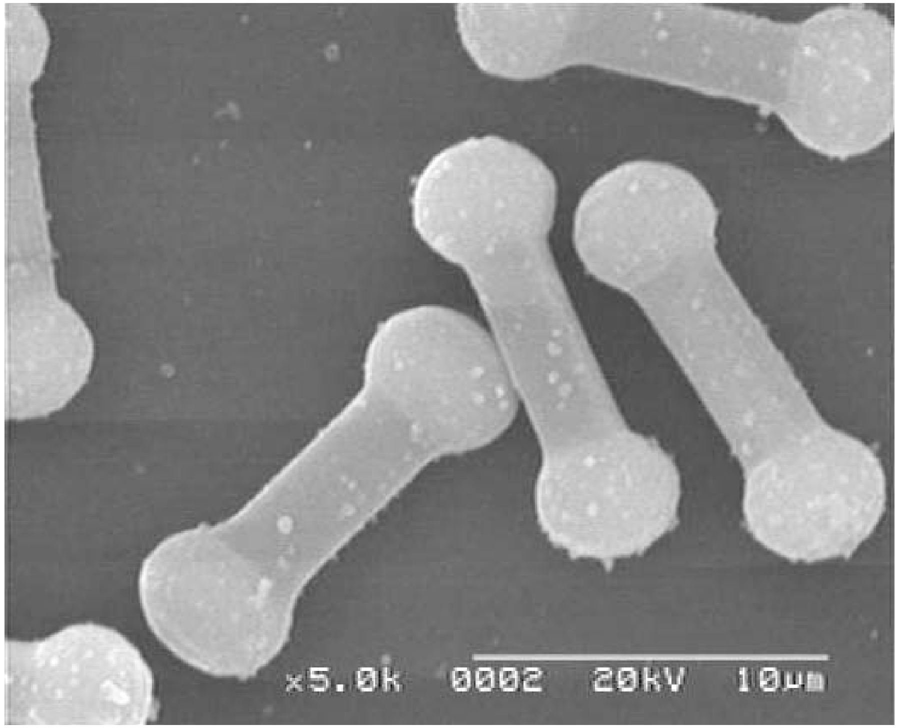
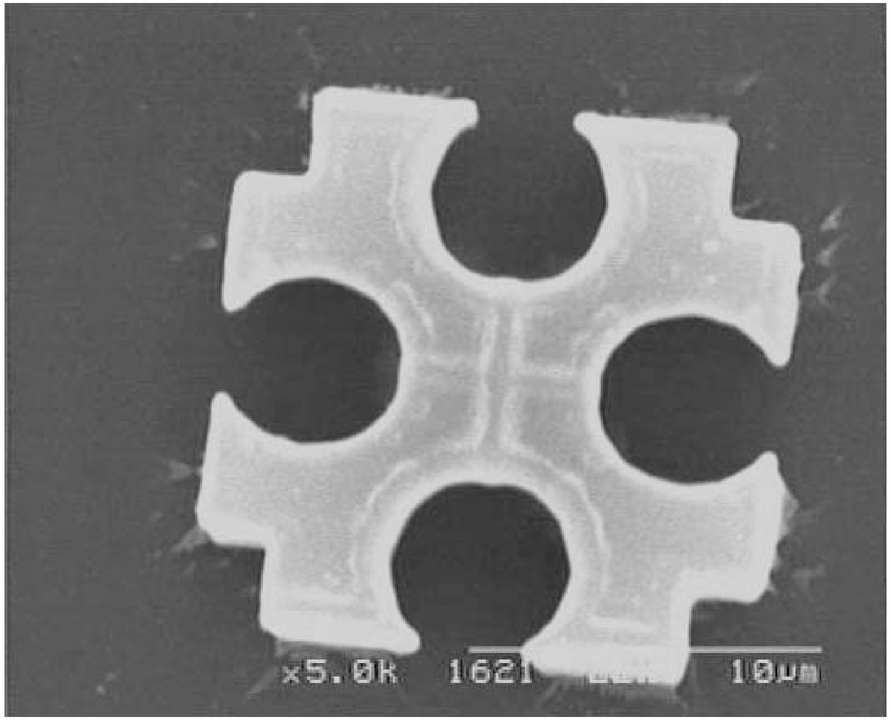
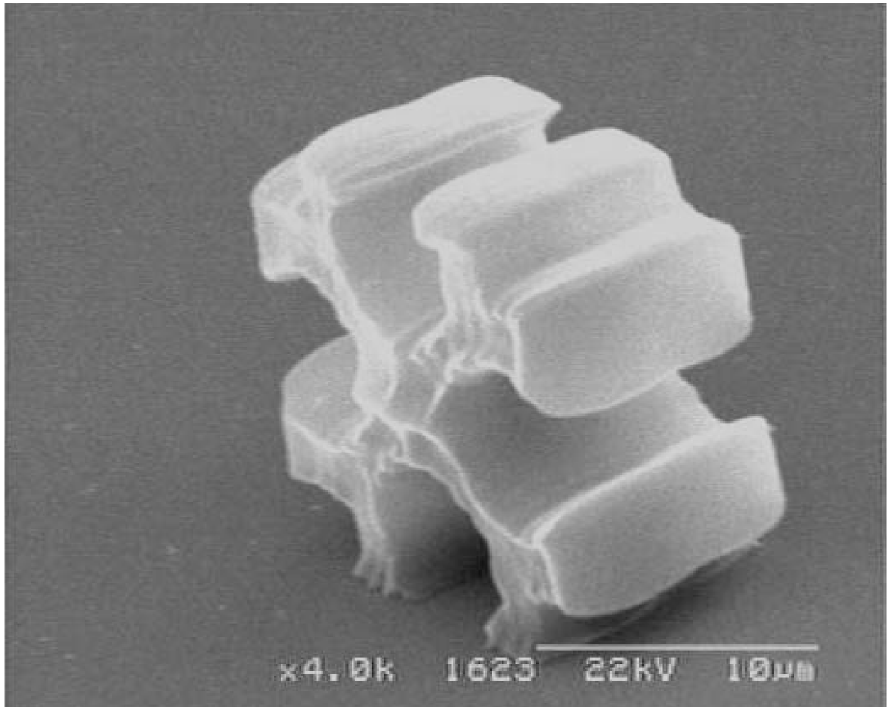


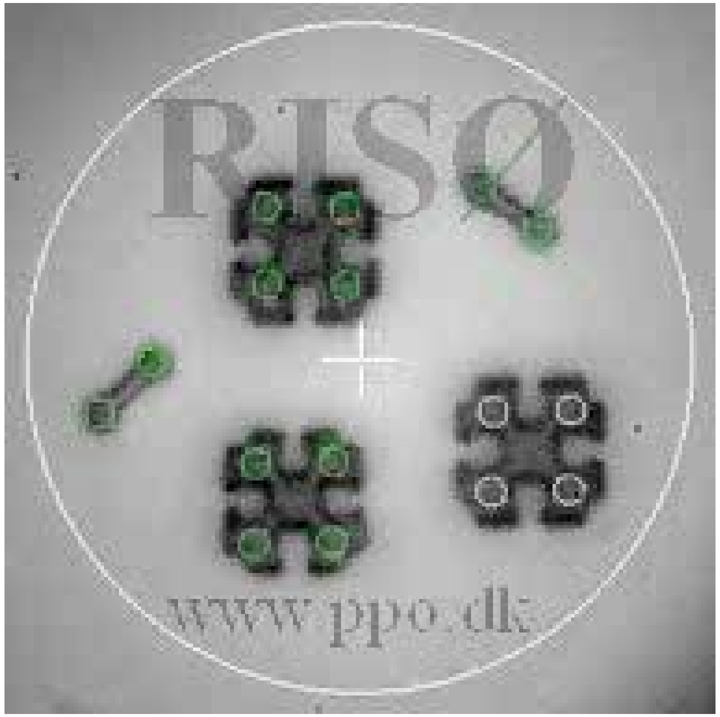
Special structures for structure building by optical manipulation



Special structures for structure building by optical manipulation



Special structures for structure building by optical manipulation

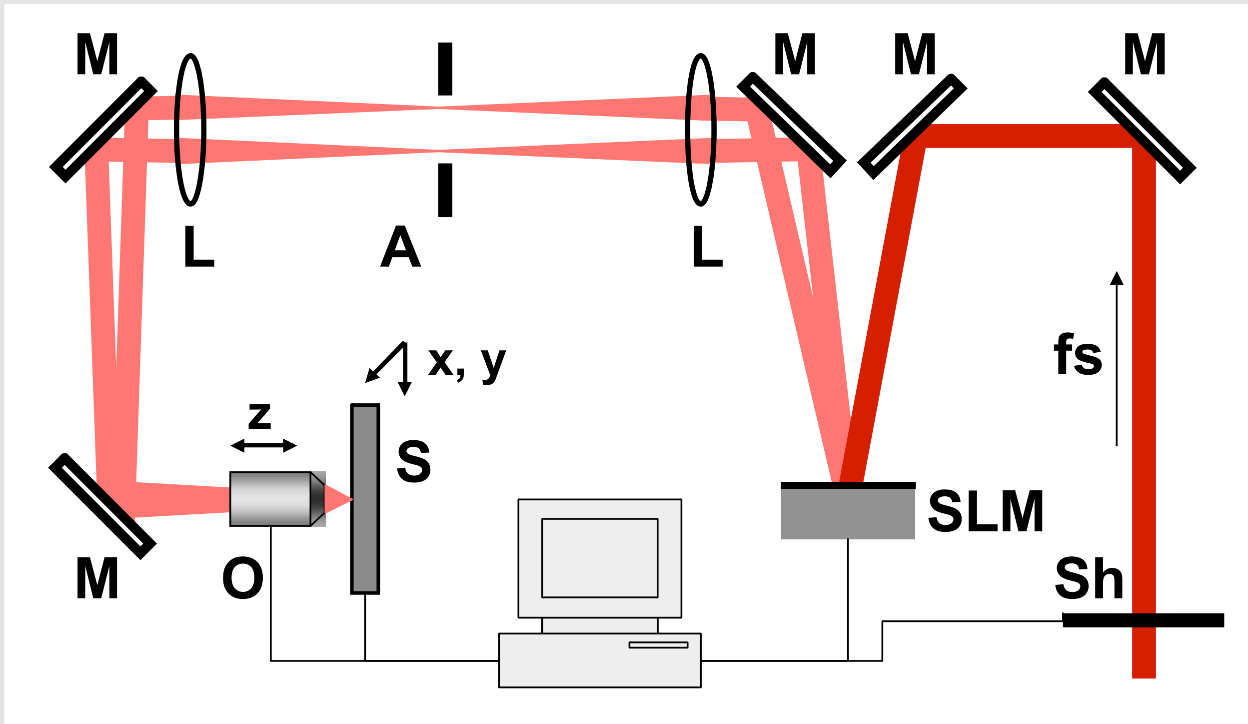


Collaboration with the Jesper Glückstad group at RISO

Photopolymerisation with SLM

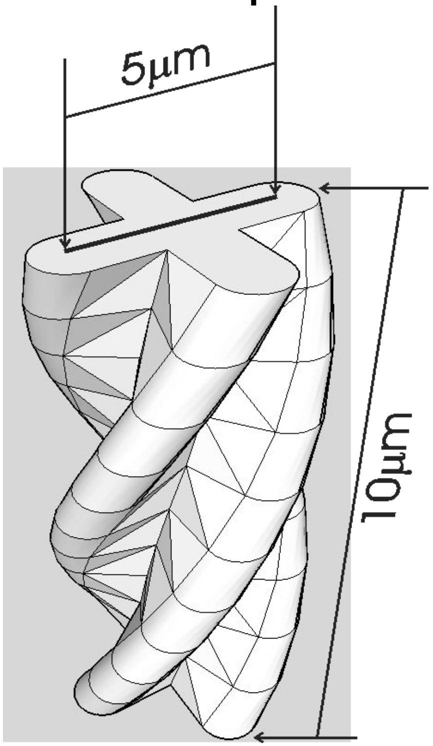
Optical layout 2

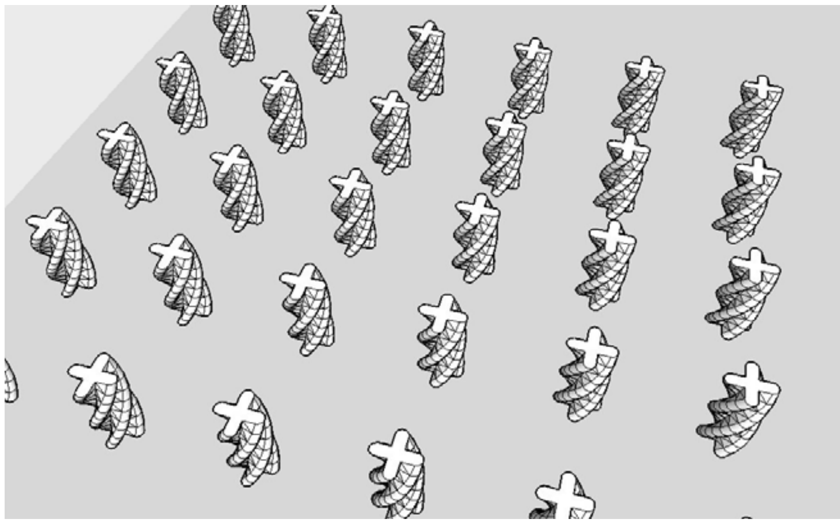
SLM 1 : 1 optics



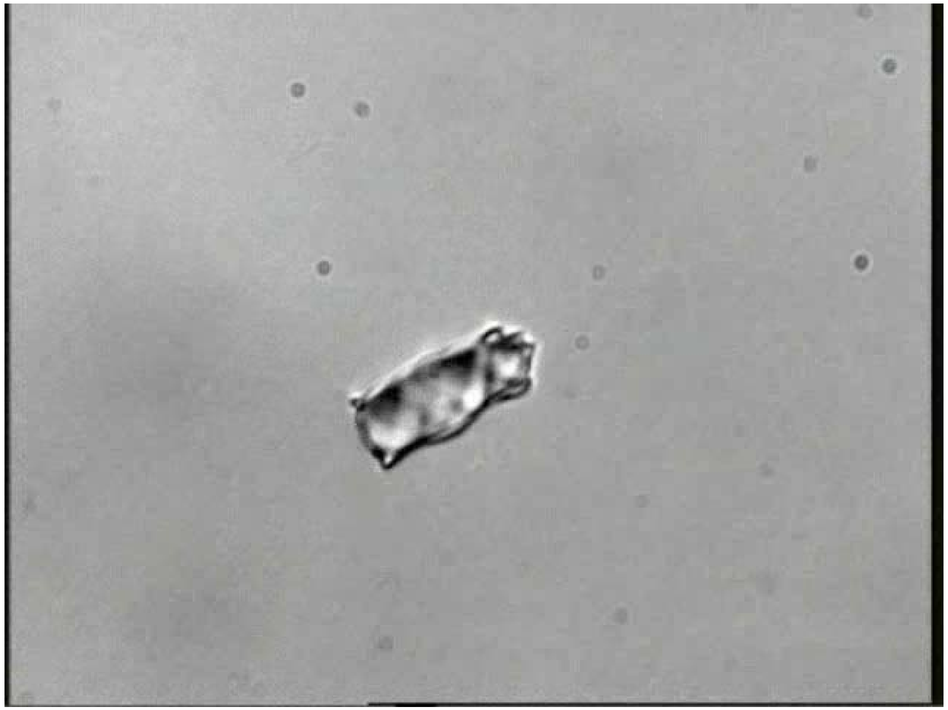
Test structures

To demonstrate the **applicability of SLMs** in photopolymerisation we produced **helical-shaped** objects to be manipulated later with **optical tweezer**





Rotating a holographically-made helical column by laser tweezers



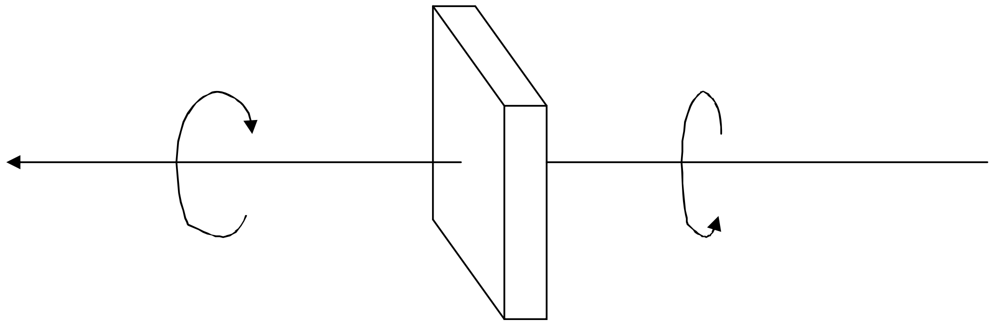
Rotation in optical tweezers

- Angular momentum carried by light
  - Rotate birefringent particles

- Helical scattering
  - Propeller

Polarised light acting on birefringent particle

Electric field strength: $\vec{E} = E_0 e^{i\omega t}\cos\phi\,\vec{x} + iE_0 e^{i\omega t}\sin\phi\,\vec{y}$ **(ϕ: ellipticity)**

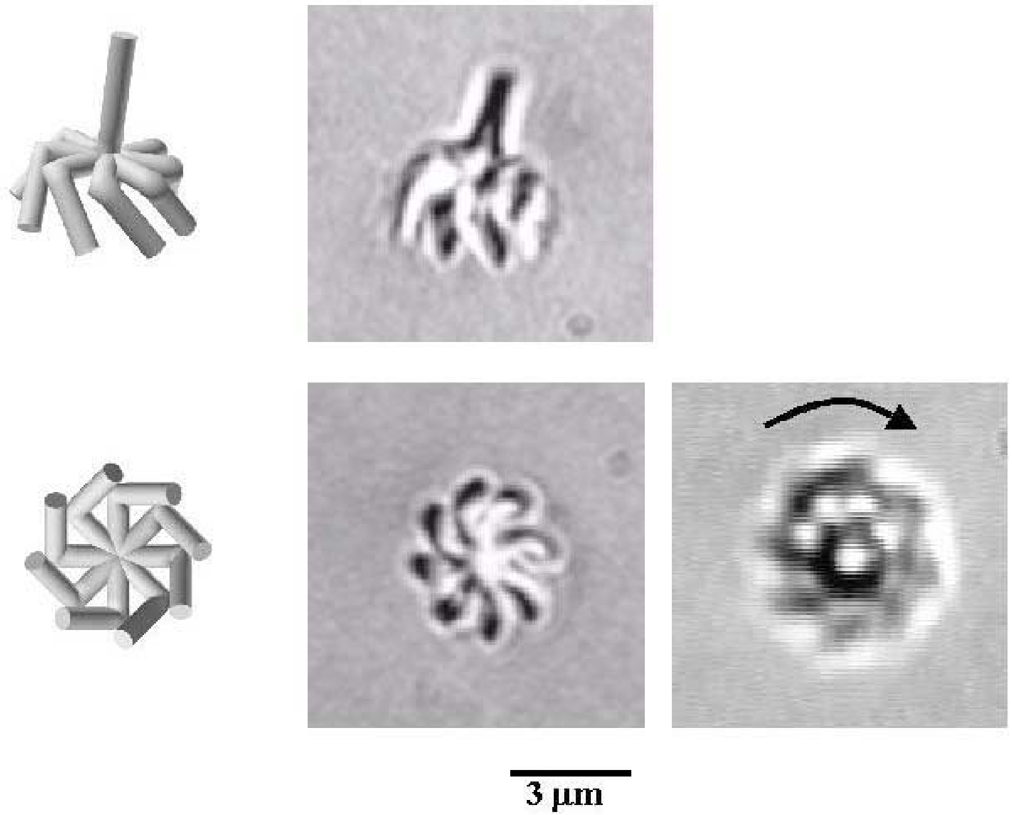


torque on unit surface of a birefringent material of thickness d:

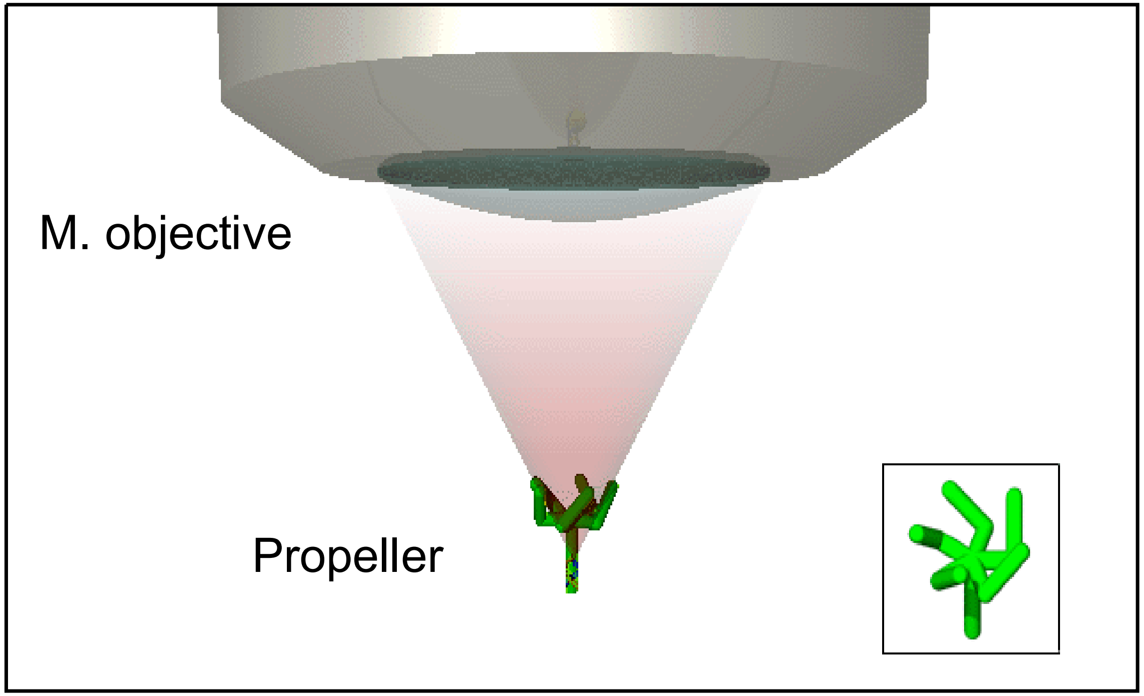
$$\vec{m} = \frac{\varepsilon}{2\omega}E_0^2 \sin[kd(n_o - n_e)]\cos 2\phi \sin 2\theta +$$

$$+\frac{\varepsilon}{2\omega}E_0^2\{1-\cos[kd(n_o - n_e)]\}\sin 2\phi$$

Light driven propeller

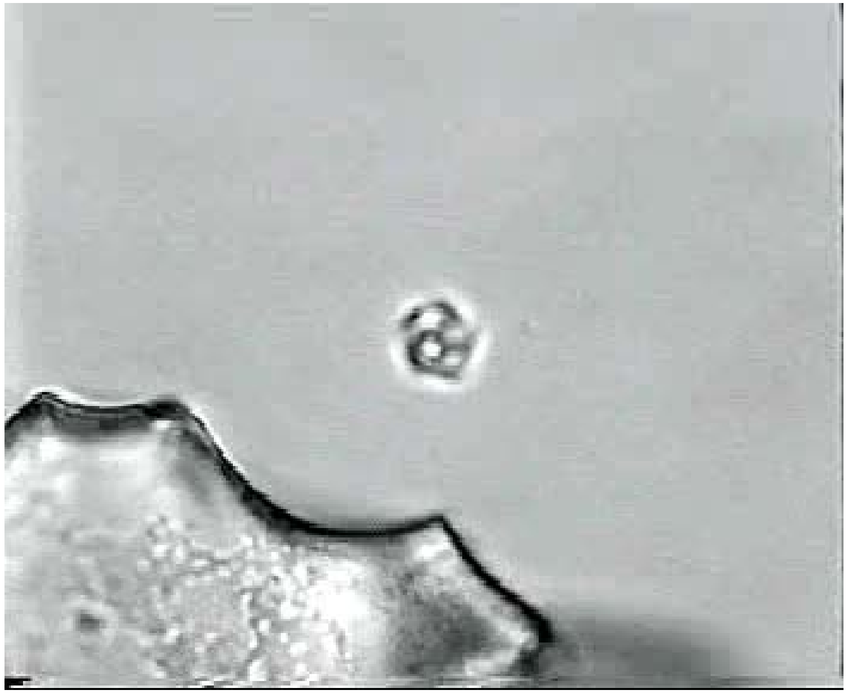


Light driven propeller

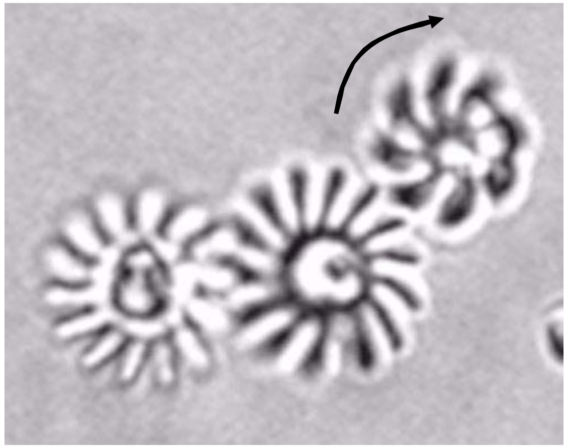


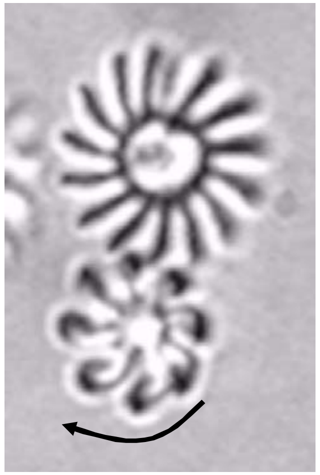
Galajda and Ormos, Appl. Phys. Lett. (2001)

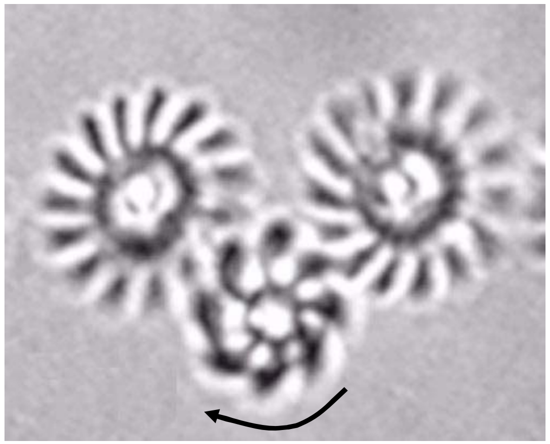
Light driven propeller



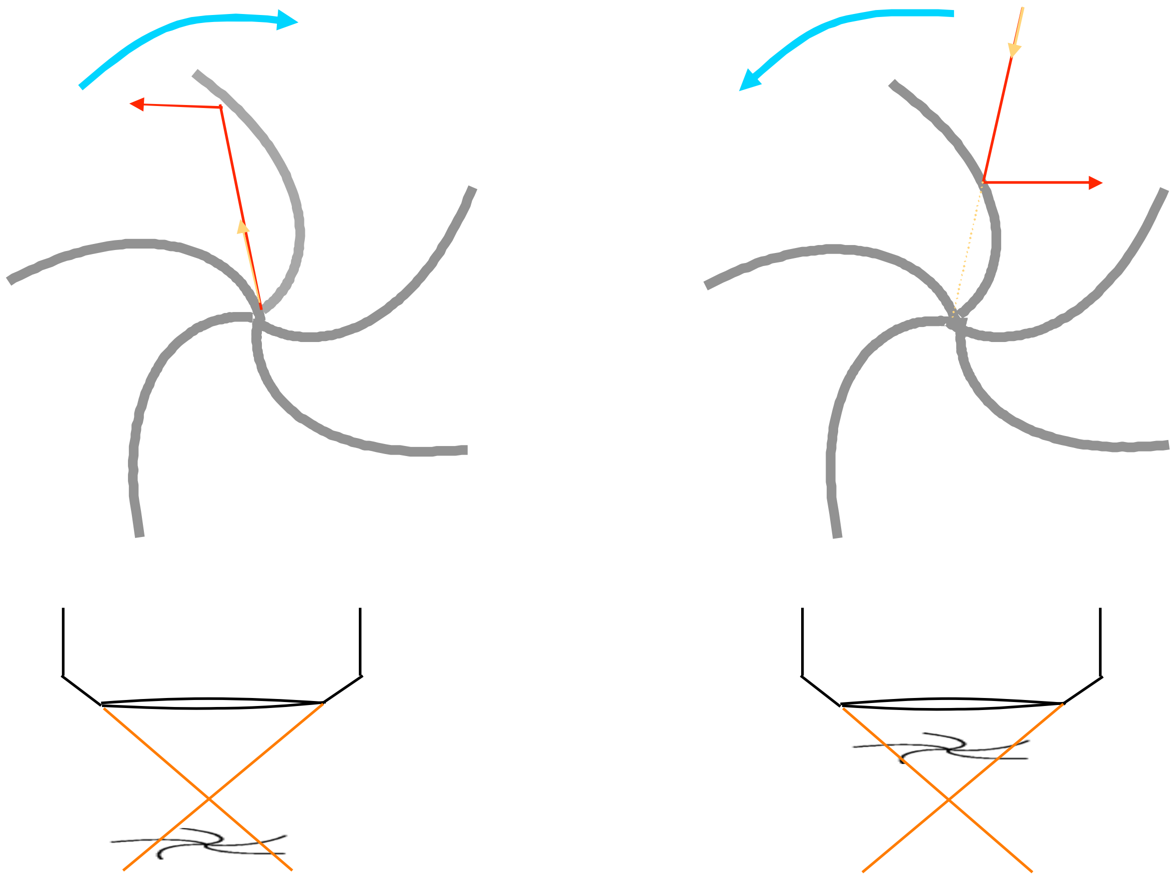
Complex optomechanical machines







Study of light induced rotation:
controlling the direction



Galajda and Ormos, Appl. Phys. Lett. (2002)

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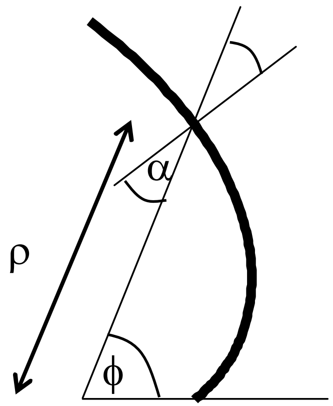
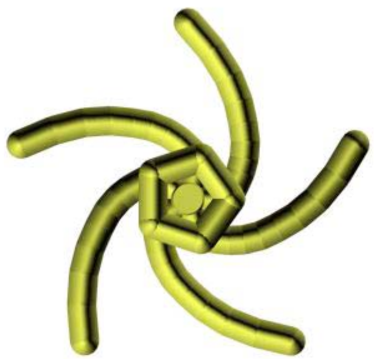


Equation of a logarithmic spiral in a polar coordinate system:

$$\rho = a \cdot e^{k\Phi} \qquad k = ctg\alpha$$



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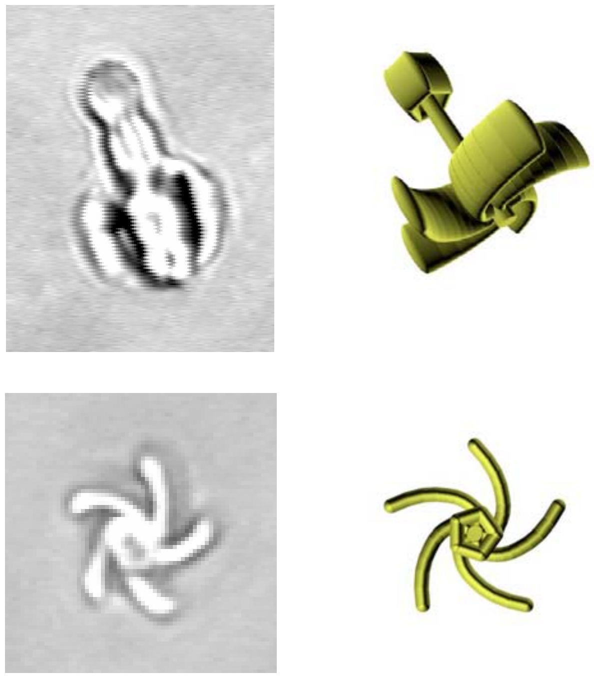
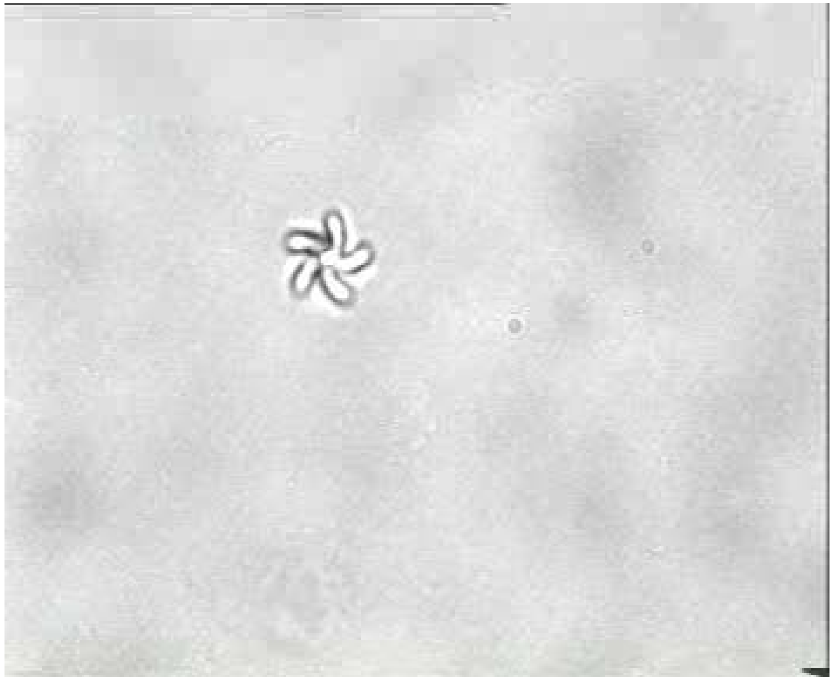
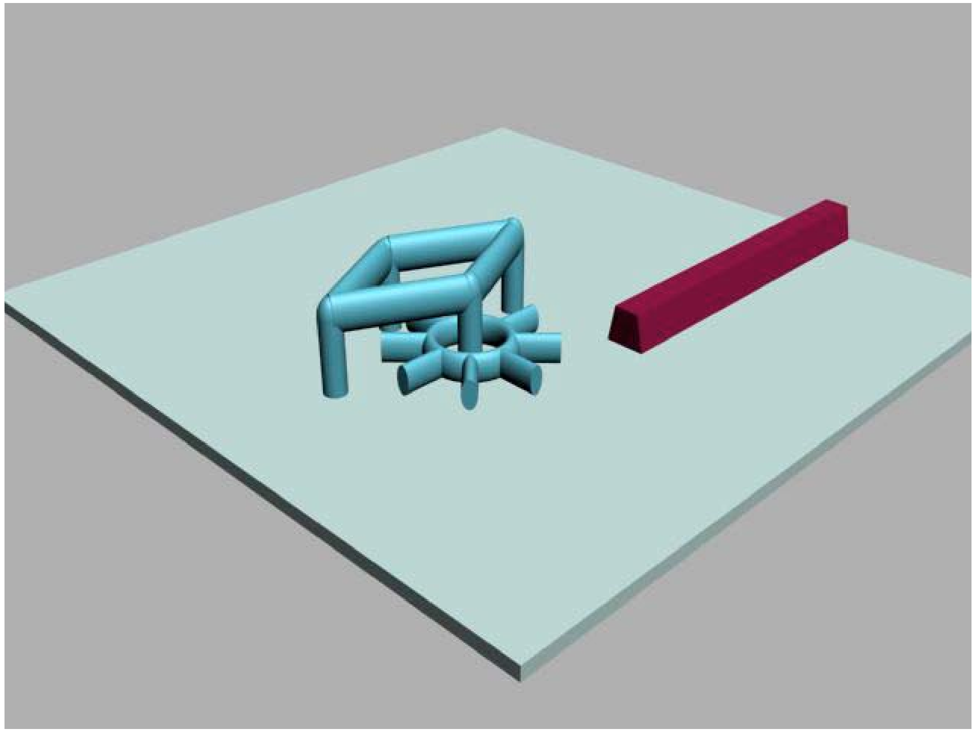


Reverse rotational direction

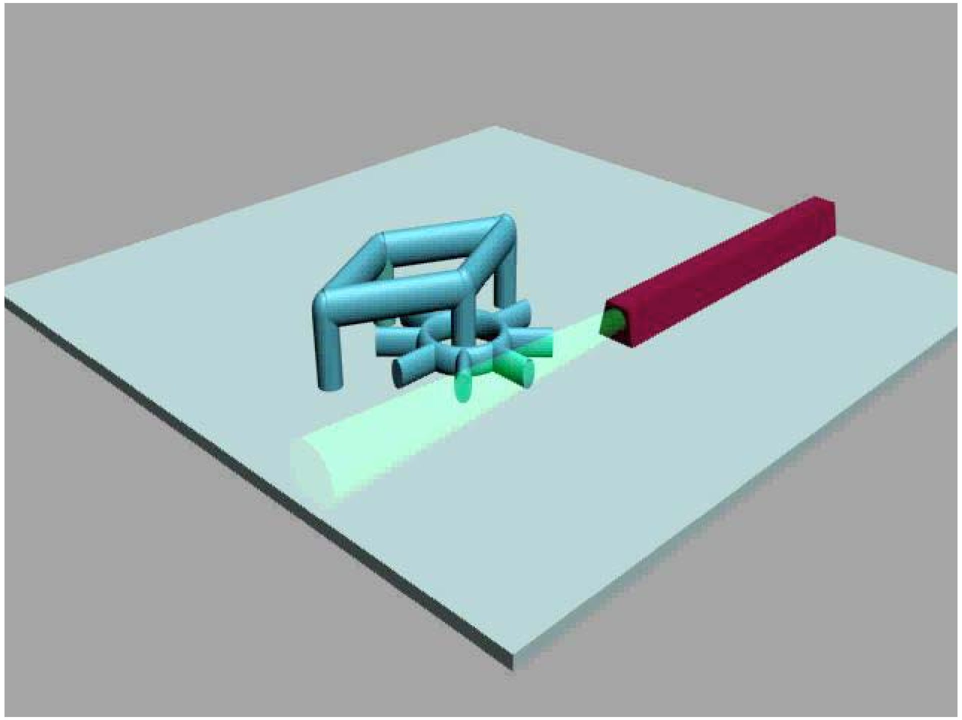


Integrated optical motor



Kelemen et al. , Appl. Opt (2006)

Integrated optical motor



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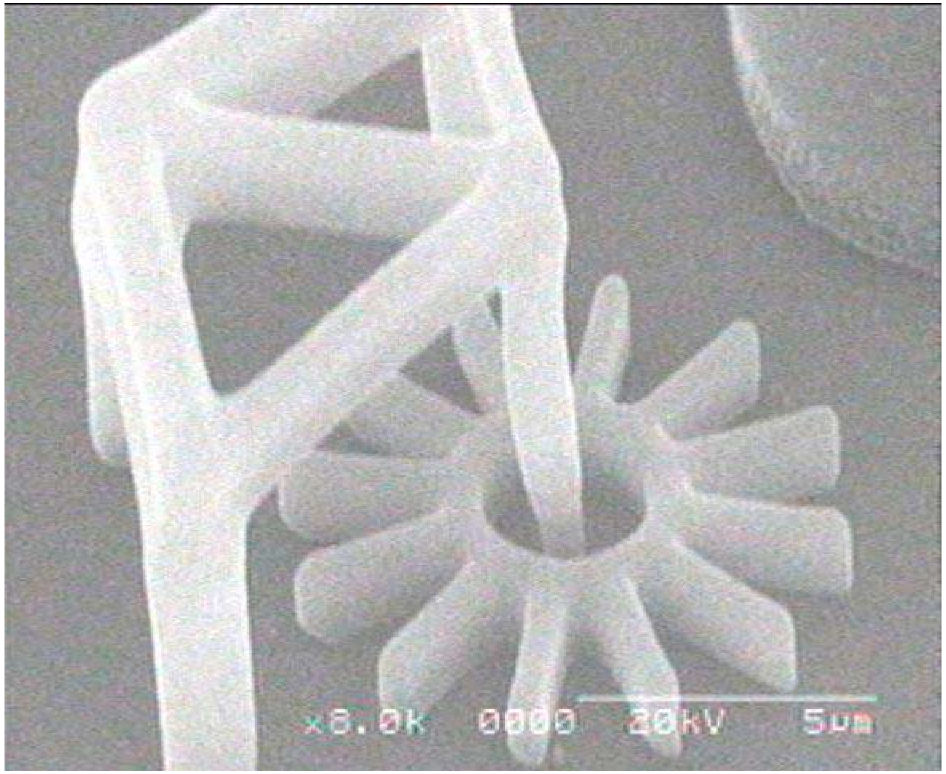

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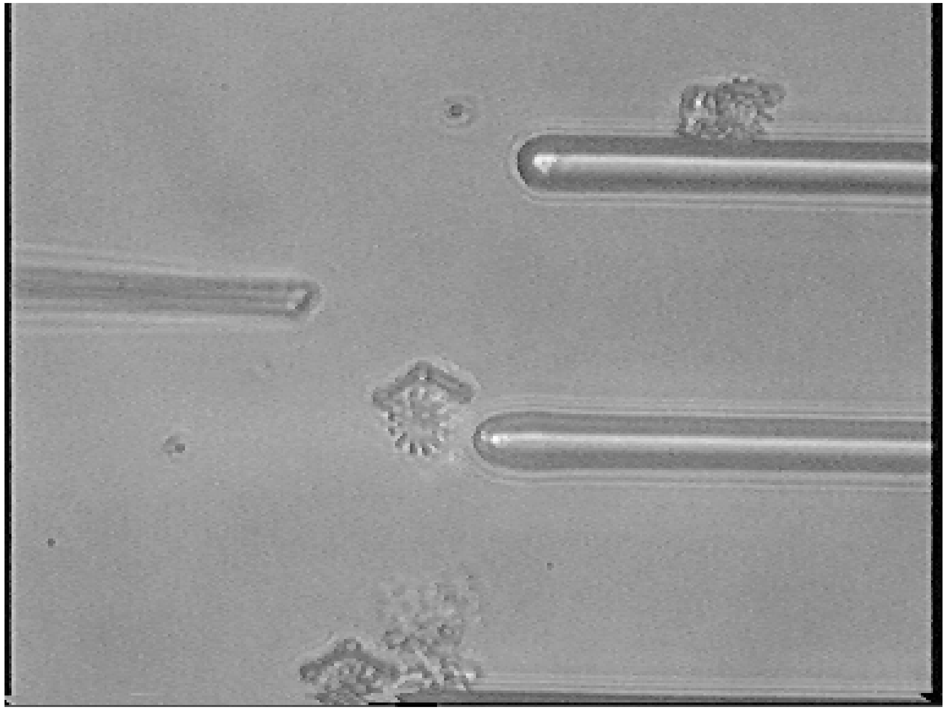
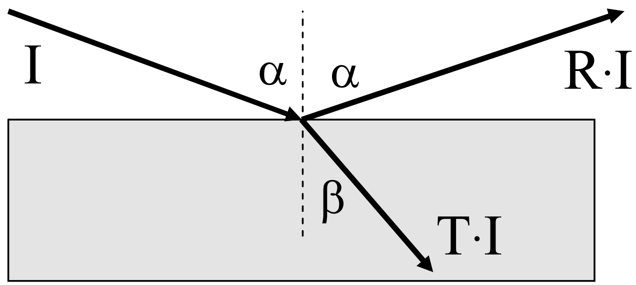


Torque: 10^{-19}-10^{-18} Nm @ 10 mW

Trap non spherical objects

Orientation of a flat particle in an optical trap



Fresnel-formulae:

1. The polarization and incidence planes are perpendicular:

$$R_\perp = \frac{\sin^2(\alpha-\beta)}{\sin^2(\alpha+\beta)}, \qquad T_\perp = \frac{\sin 2\alpha \sin 2\beta}{\sin^2(\alpha+\beta)}$$

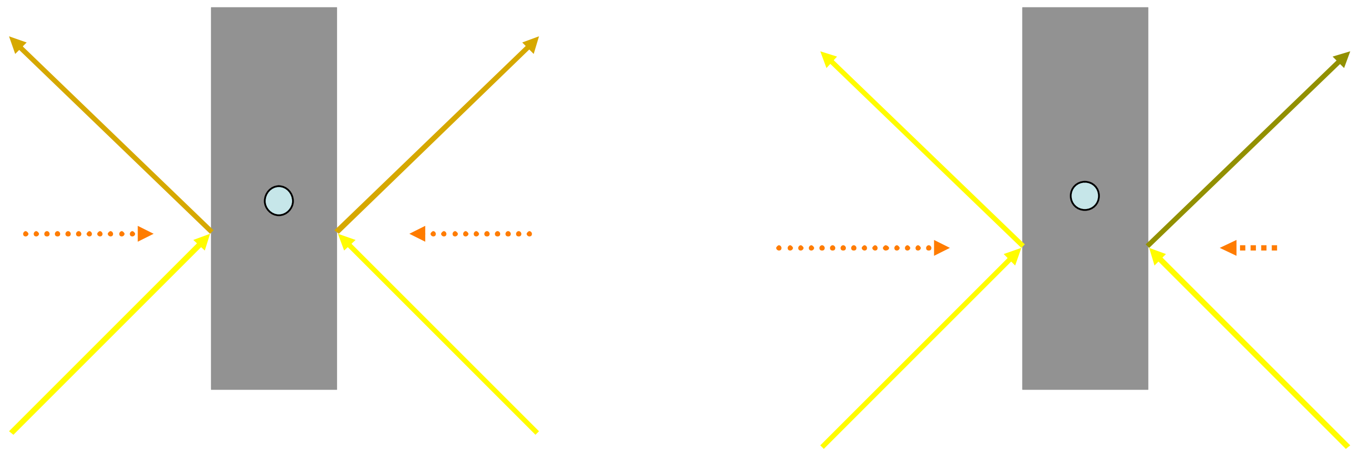
2. The polarization and incidence planes are parallel

$$R_{\parallel} = \frac{tg^2(\alpha-\beta)}{tg^2(\alpha+\beta)}, \qquad T_{\parallel} = \frac{\sin 2\alpha \sin 2\beta}{\sin^2(\alpha+\beta)\cos^2(\alpha-\beta)}$$

3. General case (φ is the angle between polarization and incidence plane):

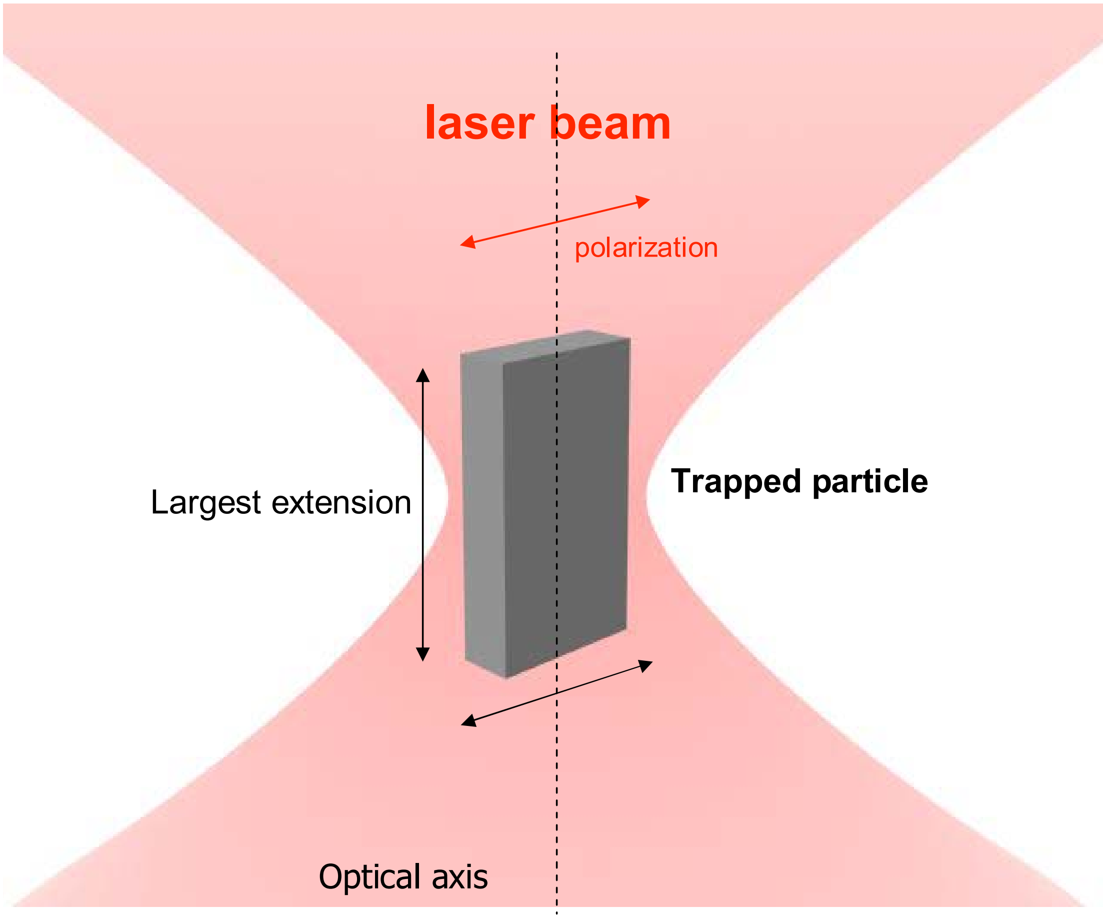
$$R = R_{\parallel}\cos^2\varphi + R_\perp \sin^2\varphi, \qquad T = T_{\parallel}\cos^2\varphi + T_\perp \sin^2\varphi$$

Torque of liearly polarized light

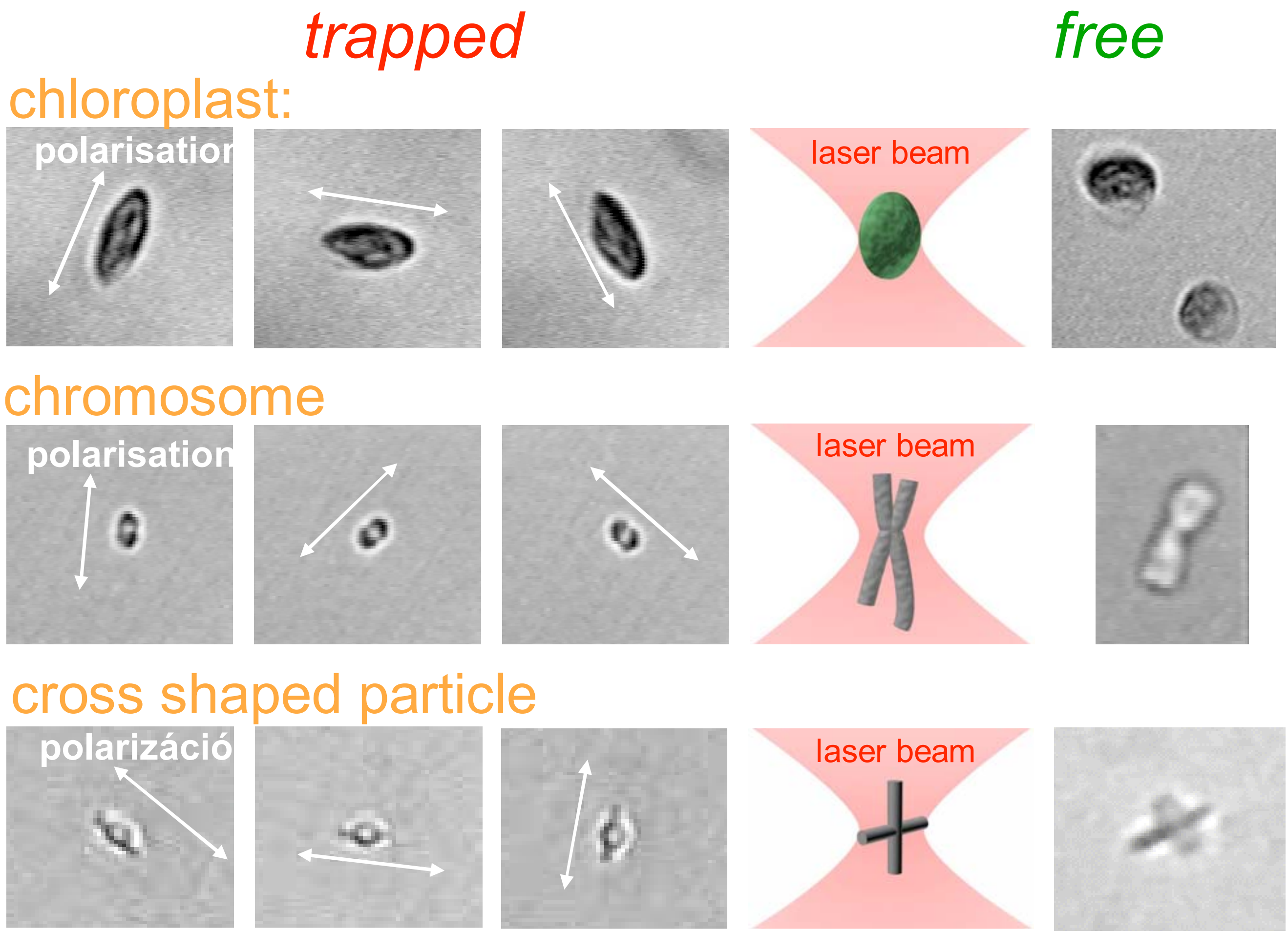


Polarization dependent light refraction (described by the Fresnel-formulae)

Orientation of a flat particle in trap formed by polarized light

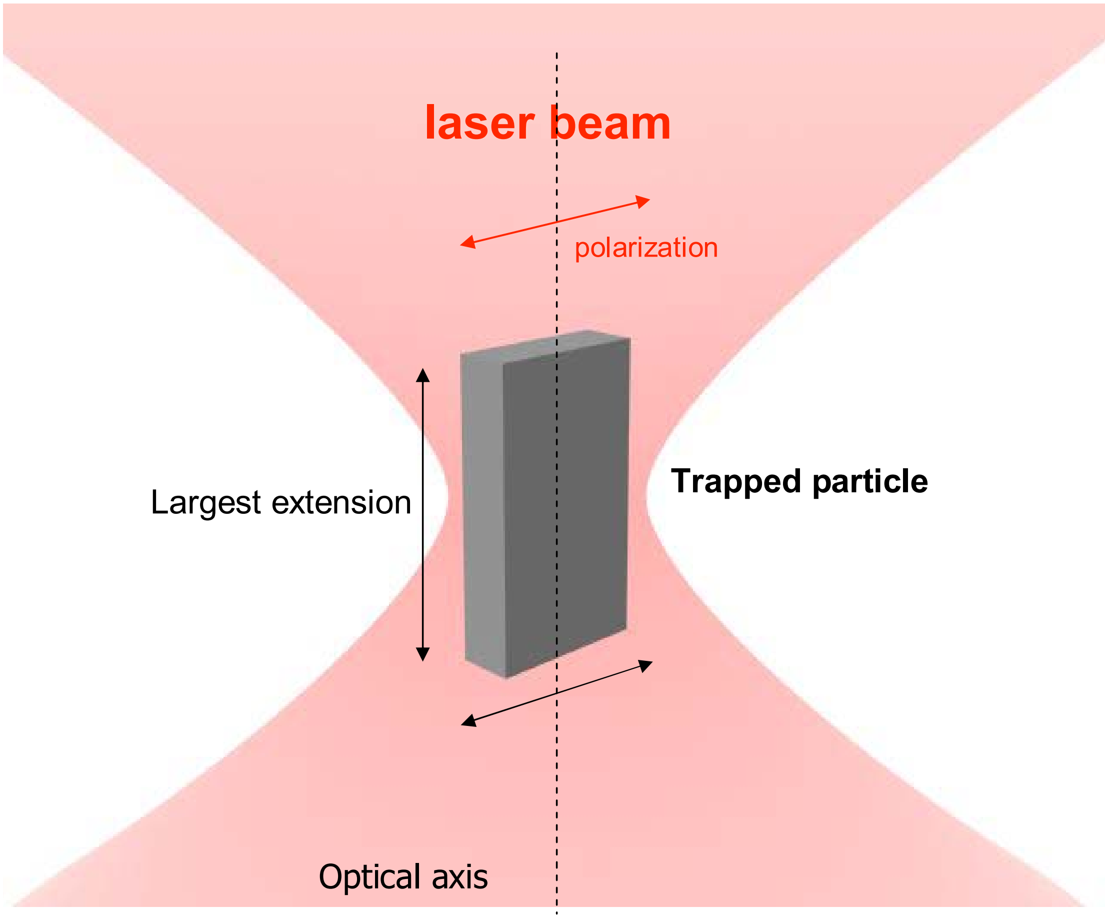


Orientation of different particles in laser tweezers

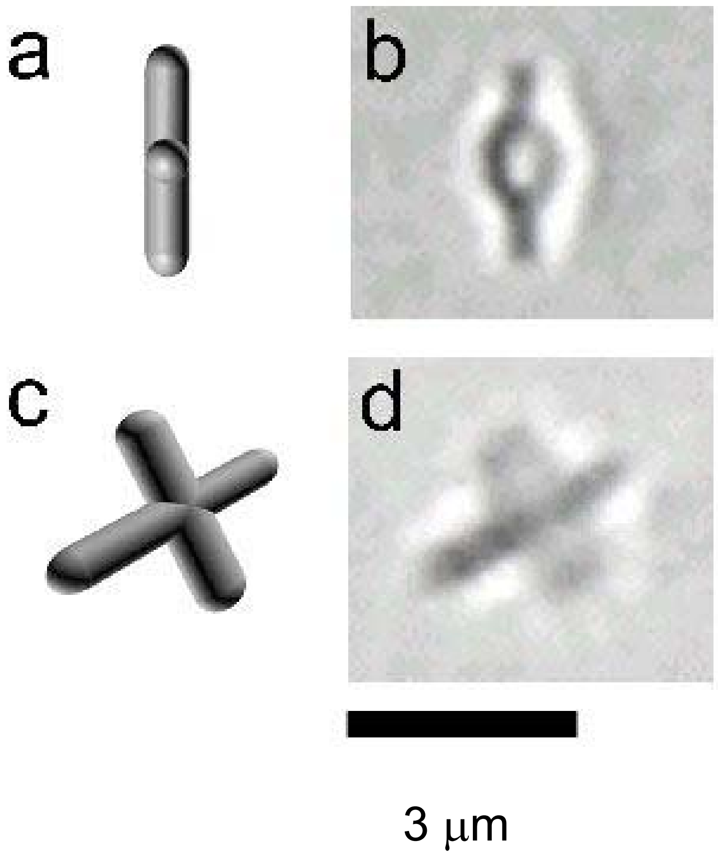


Garab, et al. Eur.Biophys. J. 2005

Orientation of a flat particle in trap formed by polarized light



Rotor to characterize the system



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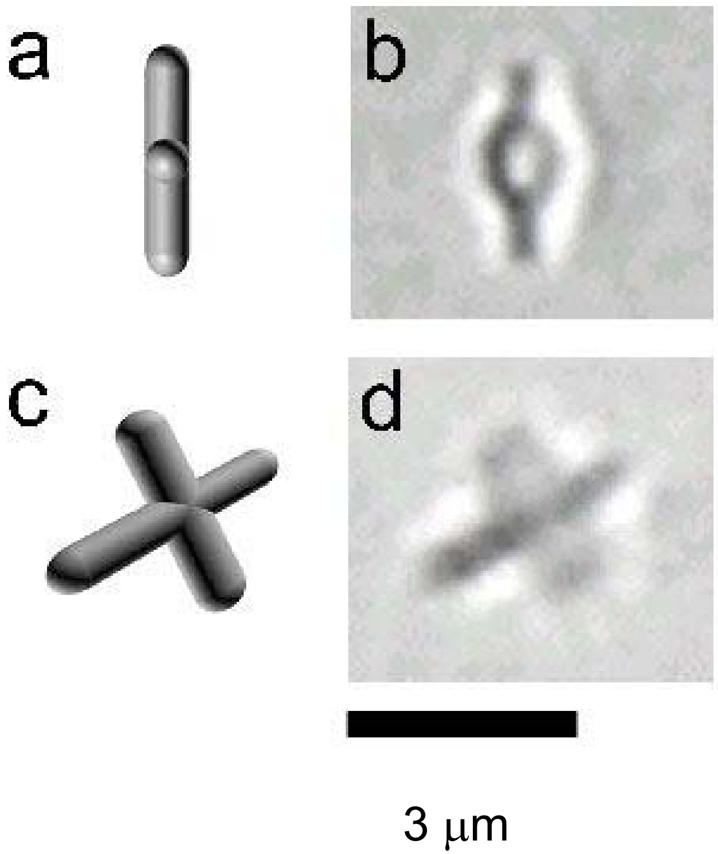
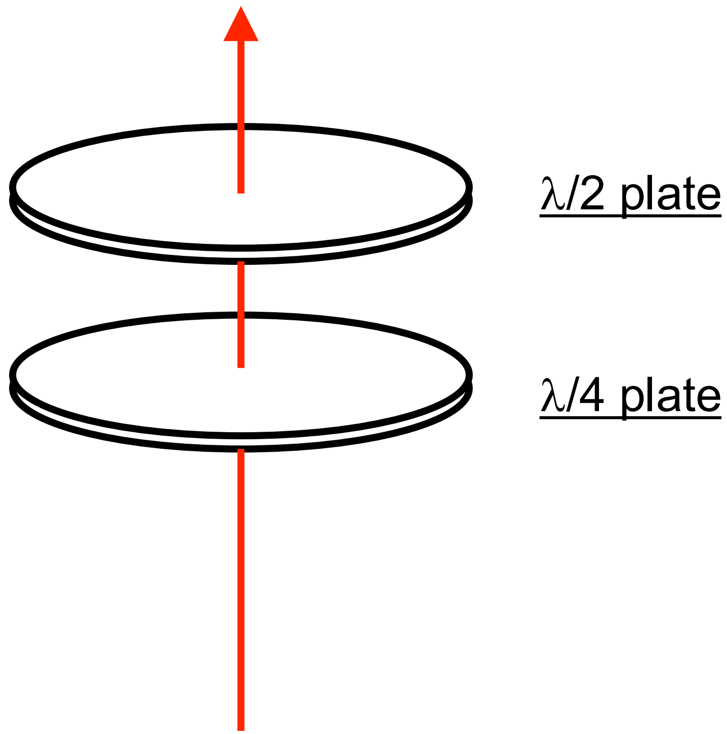
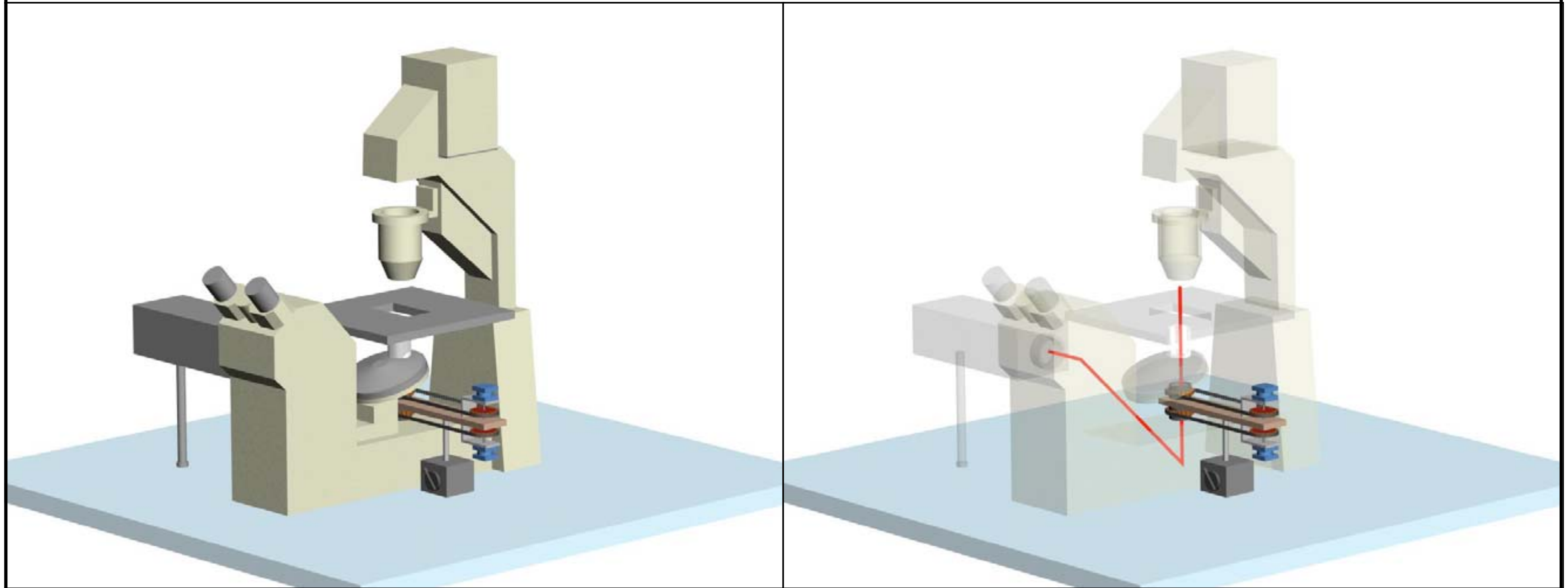


Laser beam adjustment

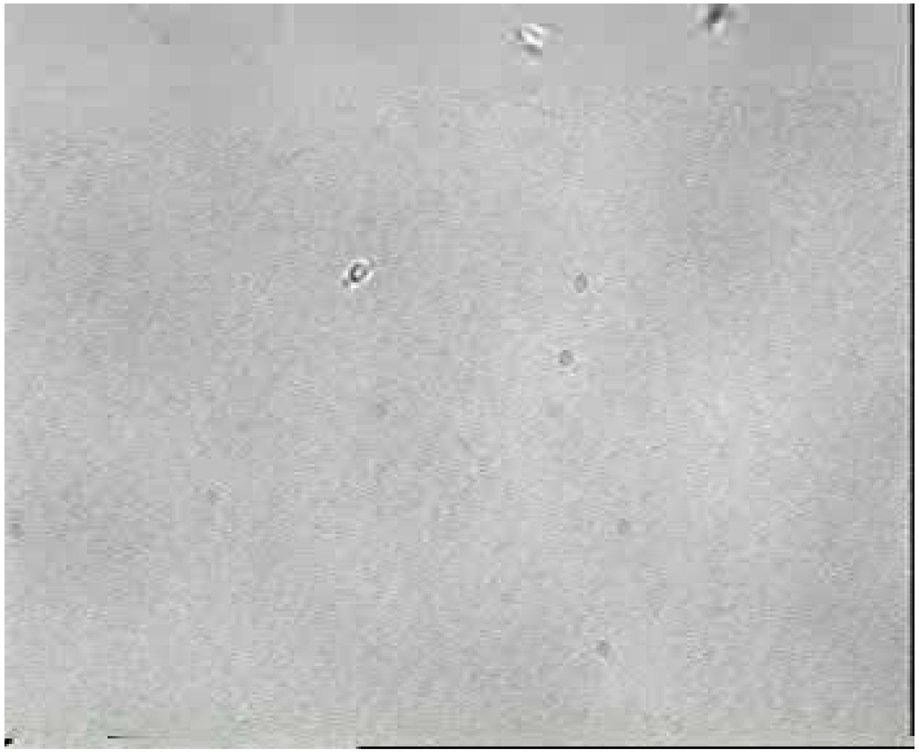


Experimental layout

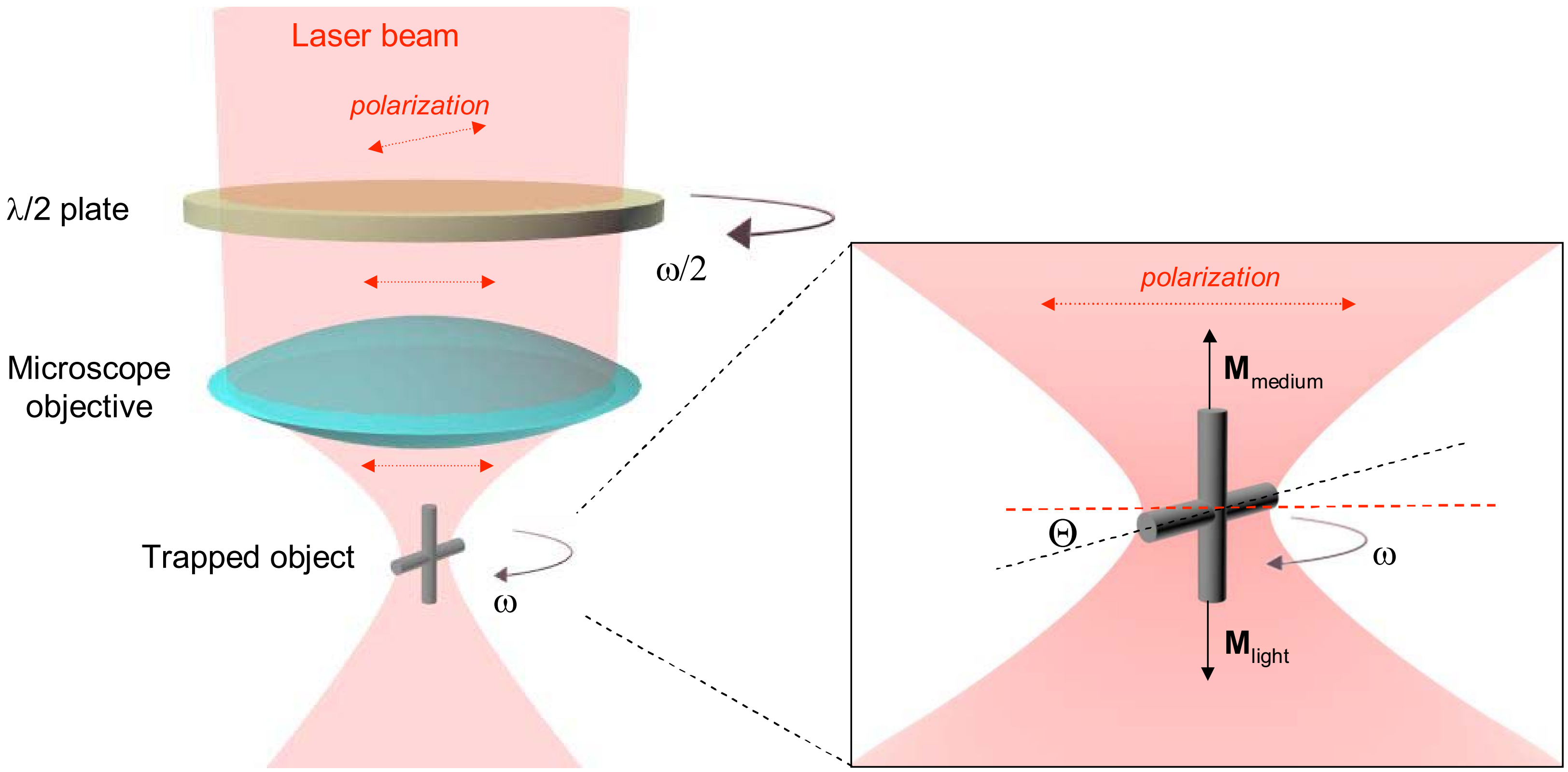


Main components:
- Zeiss Axiovert 135 (Zeiss Plan Apochromat oil immersion 100x/1.4 objective)
- Cell Robotics 980-1000, 995 nm llaser
–λ/2 és λ/4 plates rotated with stepping motors
- camera, digitizer, computer

Rotation of trapped particle



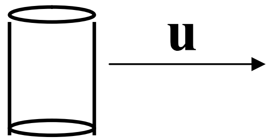
Measure the connection between torque and orientiation



Viscous drag

In balance: $M_{drag} = M_{light}$

For a cylinder:

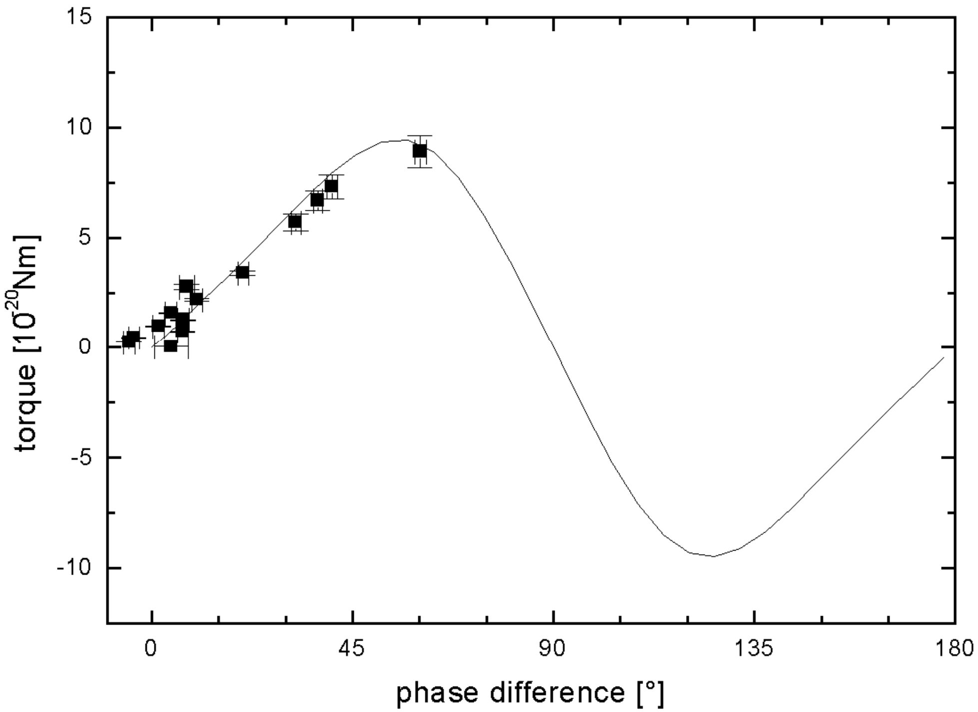


$$F_{drag} = \frac{4\pi\eta u l}{\frac{1}{2} - C - \ln\frac{Ru\rho}{4\eta}}$$

η: *viscosity*, **u:** *speed*, **R:** *radius*, **l:** *length*, ρ: *density*, **C:** *Euler constant*

Torque as a function of phase dirrerence

experiment vs. ray tracing simulation



Galajda and Ormos, Opt. Exp. (2003)

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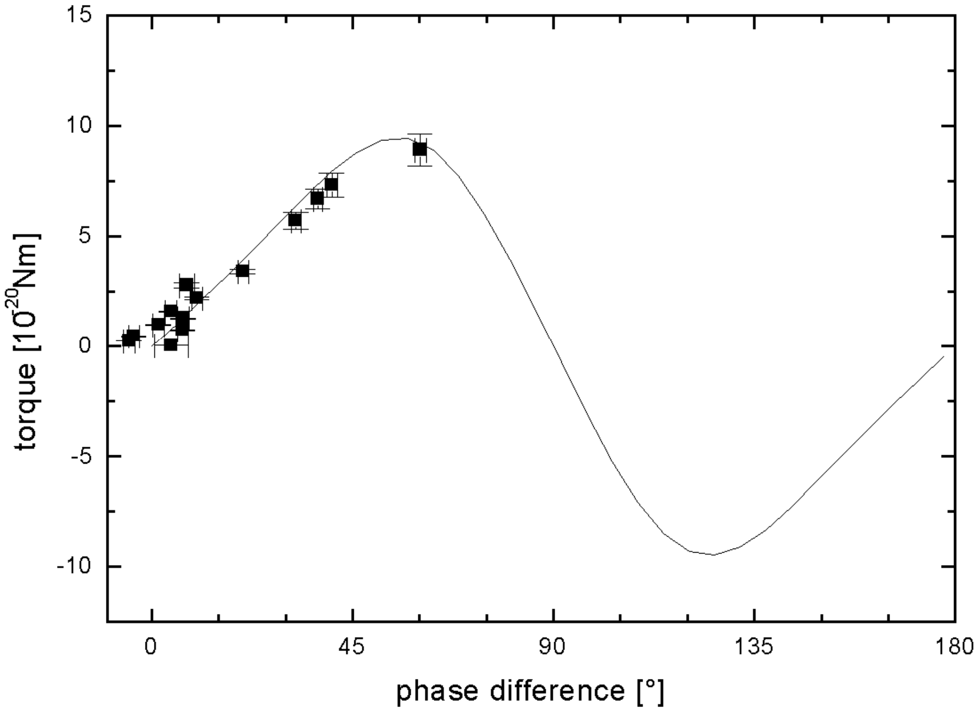


Galajda and Ormos, Opt. Exp. (2003)

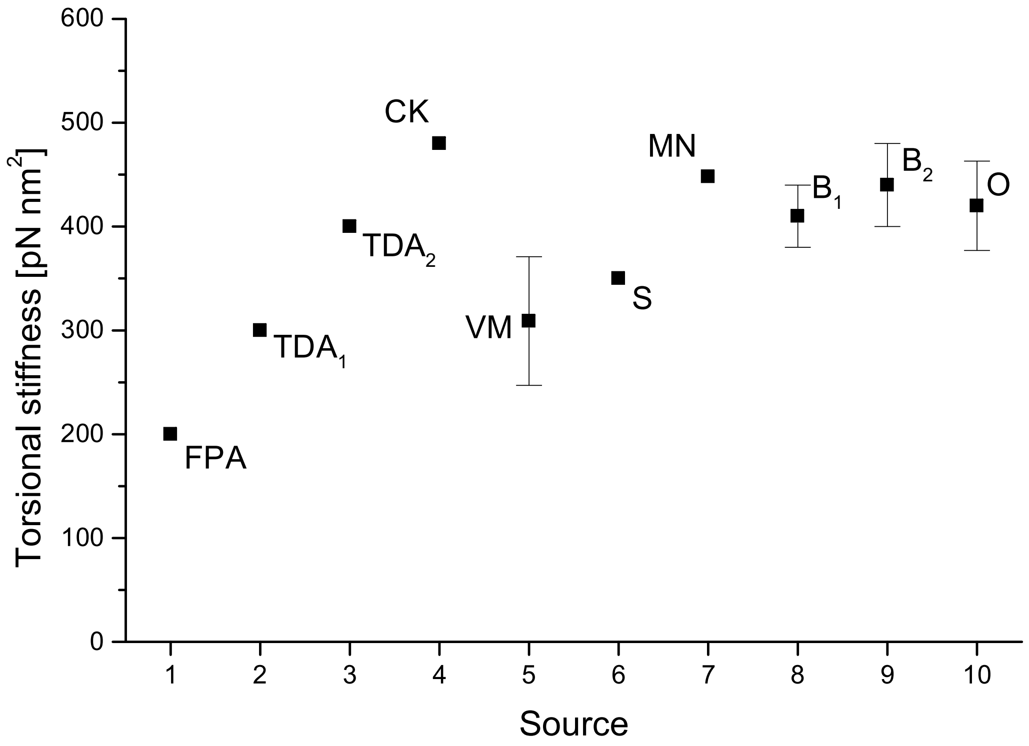
Good properties of the method

- Torque can be applied and measured continuously

  (statically or dynamically)

- Torque can be adjusted independently from grabbing force
  - to a large extent

Torsional stiffness of DNA according to different sources



Marks:

FPA: typical values obtained from fluorescence anisotropy

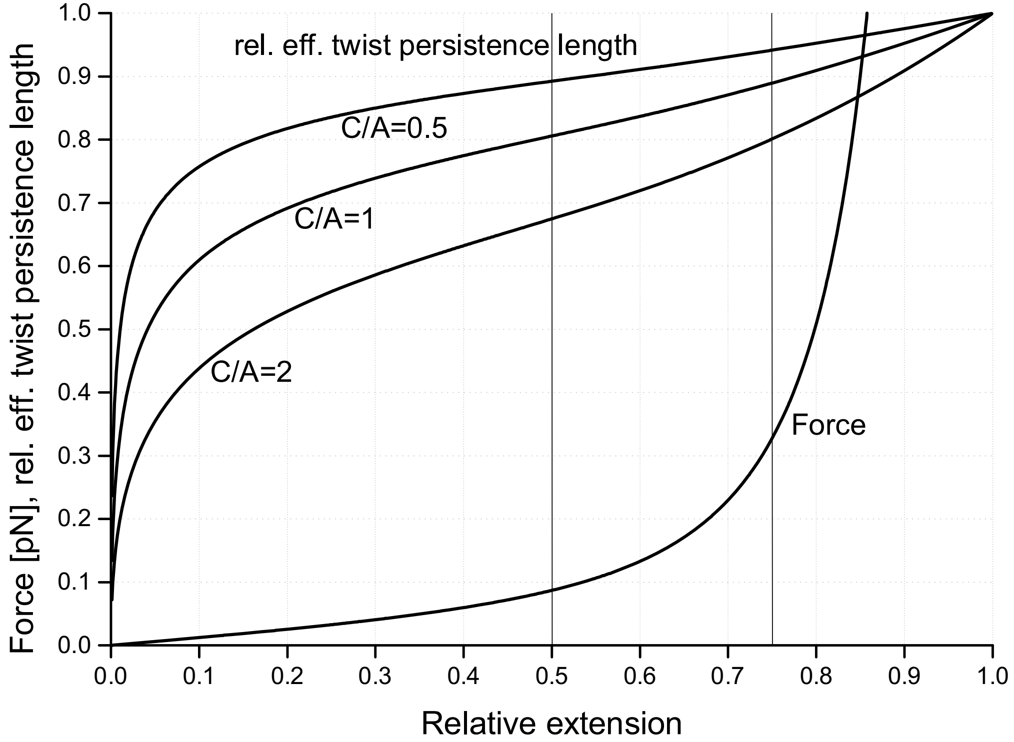
TDA$_1$, TDA$_2$: values calculated based on the distribution of topoisomers

CK: ciklizációs kinetikai vizsgálatokból nyert érték values obtained from cyclisation kinetic experiments

VM, S, MN: values based on single molecule elongation experiments used different models

B$_{1,}$ B$_2$: values obtained by two independent types of experiments (Bustamante group)

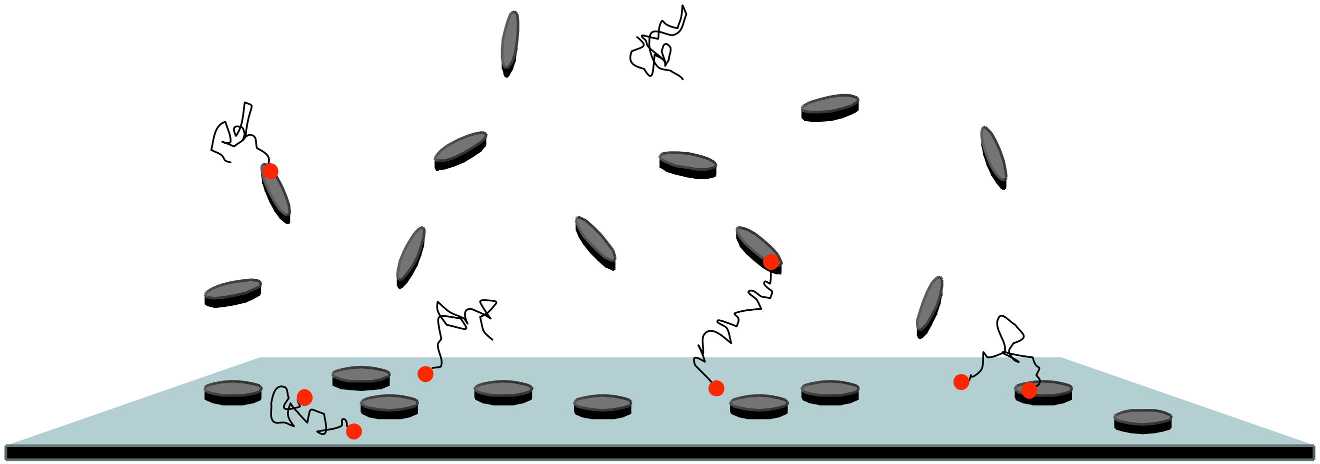
Elastic properties of polymers



Relative torsional persistence length as a function of relative elongation:

Moroz;Nelson model: the effective torsional stiffness (and the effective torsional persistence length C_{eff}) depend on the elongation. At maximal elongation C_{eff} equals C.

Twist single DNA molecules: the sample



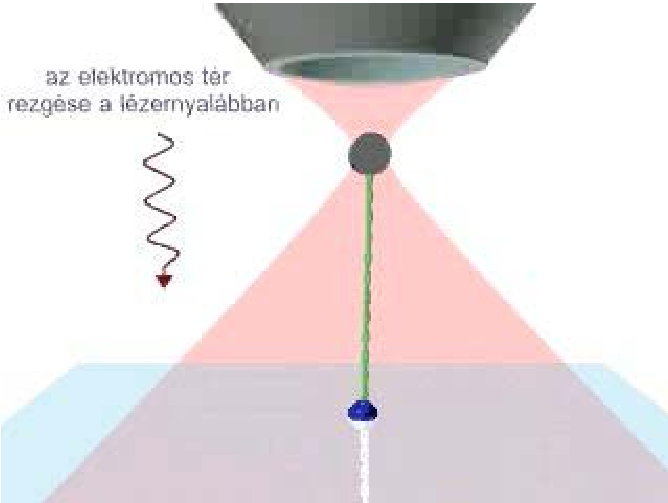
DNS:
λ-DNS in linear form (15.6 μm contour length, Fermentas)

Discs:
1 μm diameter polysryrol beads (Polysciences Polybead Polysterene Microspheres) compressed mechanically:

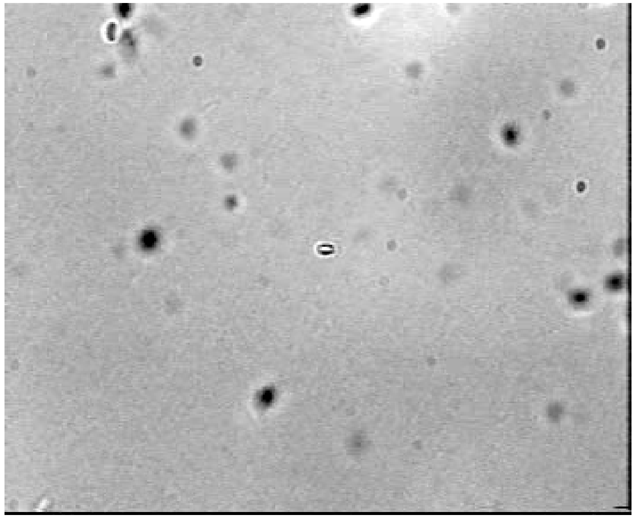
Suspension
MES 50 mM, *p*H 5.0: 2 μL λ-DNS suspension, 5 μL “disc suspension" and 100 μL MES.

Surface:
Thin polystyrol layer on glass (spin coat: polisztirol-toluol drop (50 mg/ml) on gass, 3000 rpm, 30 sec)

Twisting DNA with optical tweezers

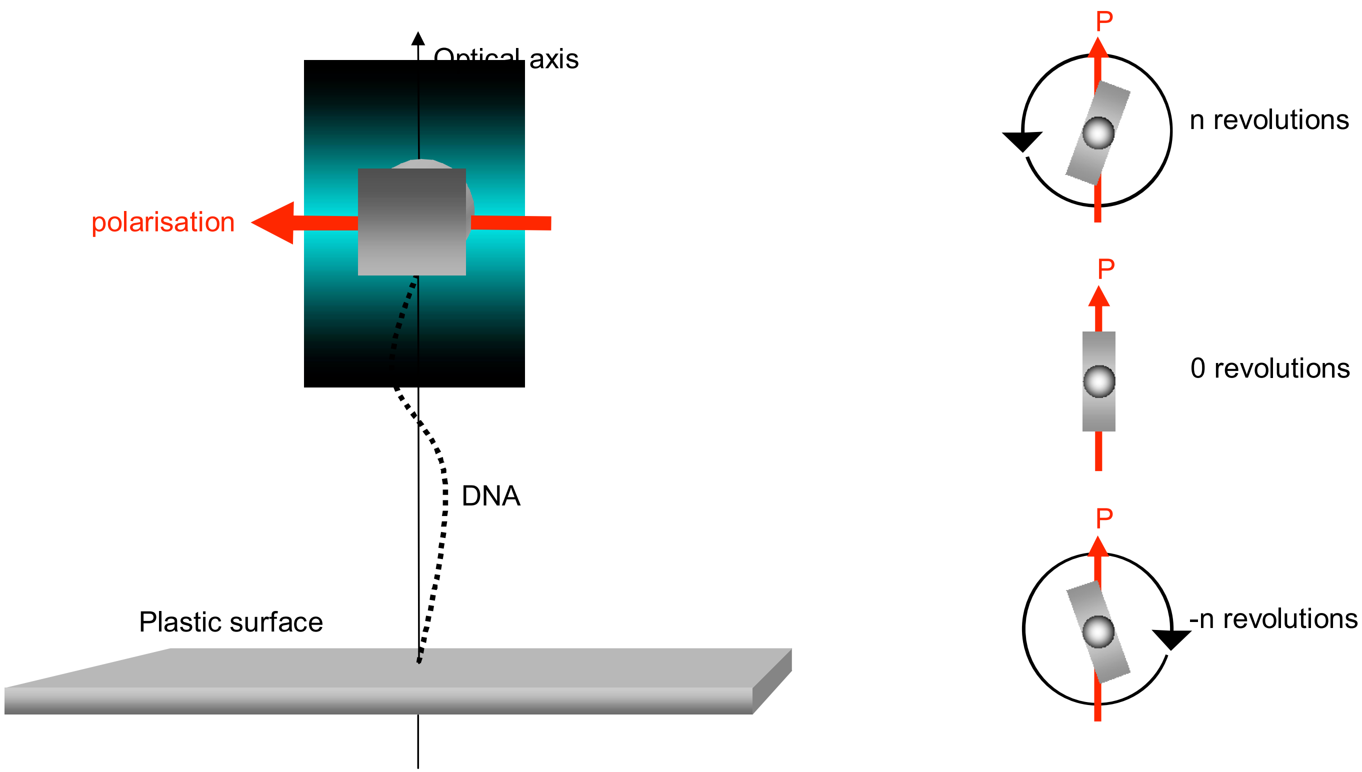


animation



experiment

Measuring the torque



Measuring torque

$$\tau = -k\alpha$$

$$E = \frac{1}{2}k\alpha^2$$

$$\rho(\alpha) \propto e^{-\frac{E}{k_B T}} = e^{-\frac{k\alpha^2}{2k_B T}}$$

} calibration

$$k_M\alpha_M = k_L\alpha_L$$

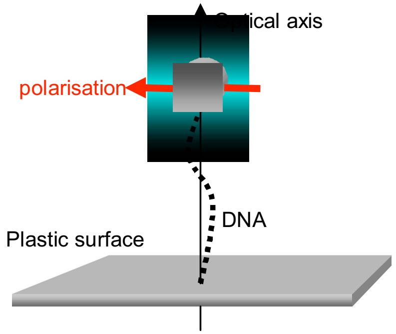
$$k_{eff} = k_M + k_L$$

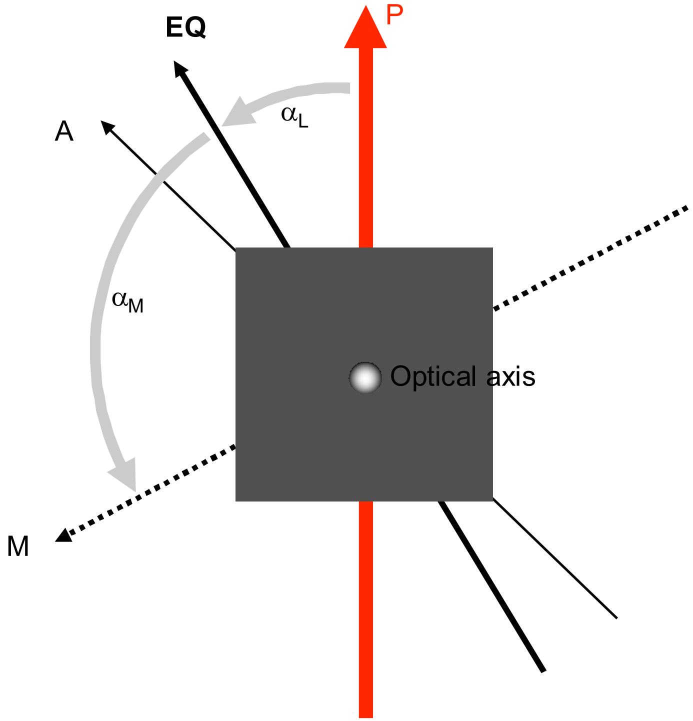
$$k_M = k_{eff}\left(1 - \frac{\Delta_{EQ}}{\Delta_P}\right)$$

} torque

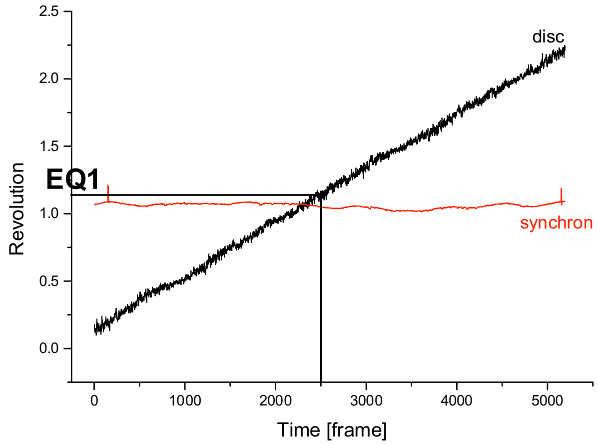
$$G = k_M l$$

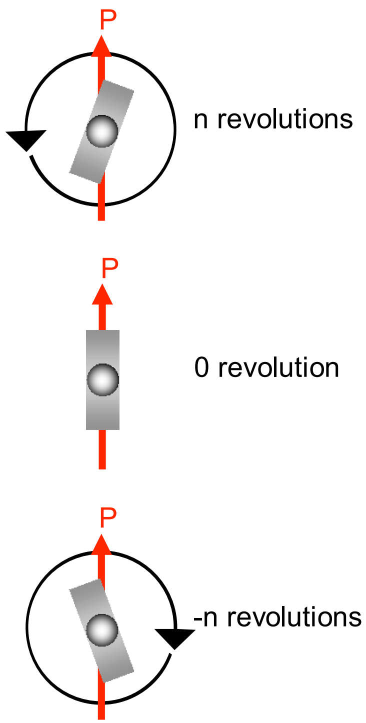
} torsional modulud

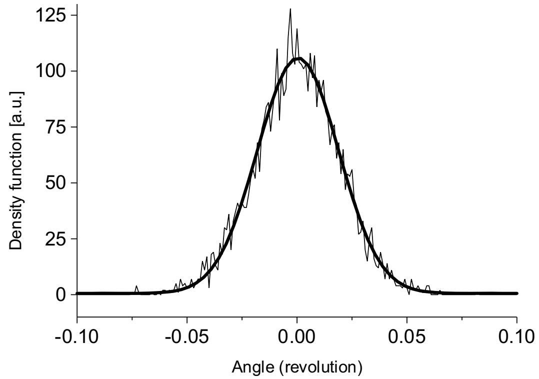


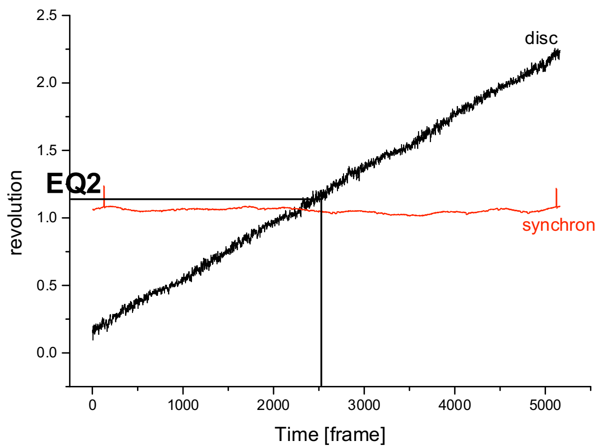


The measurement – typical experimental data

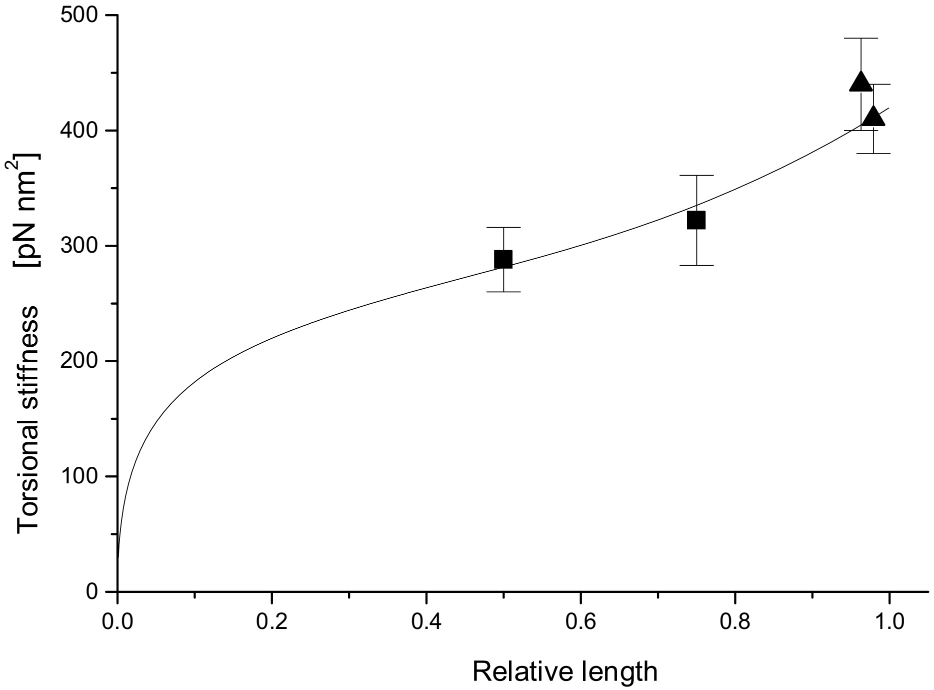








Results



Effective tgorsional stiffness of dsDNA measured at 0.5 and 0.75 relative elongations and the local torsional stiffness of 420 ± 43 pN nm^2 calculated with the Moroz-Nelson model.

Oroszi, et al. Phys.Rev.Lett(2006).

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