OPTICAL TWEEZERS

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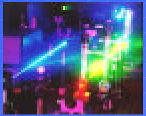
Main expertise

We study different aspects of the LASER-matter (nonlinear) interactions



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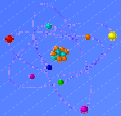
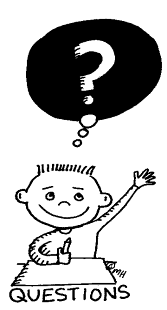


To identify:

- New optical materials
- New structures for guided optics
- New applications to optical communications… …and more recently to **bio-photonics**

Outline

- Optical tweezers: a powerful tool for micromanipulation
- Why an optical fiber tweezer? Motivation, state of the art and open problems
- A new approach to the fiber tweezers development



Outline

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- Why an optical fiber tweezer? Motivation, state of the art and open problems
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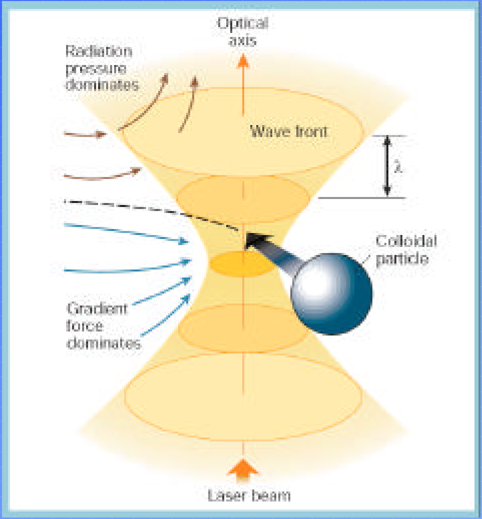
Optical tweezers: working principle

Optical trap: stable equilibrium point of optical forces acting on a particle.

The trap is created by a single laser beam tightly focused: large intensity gradients in both the axial and transverse directions

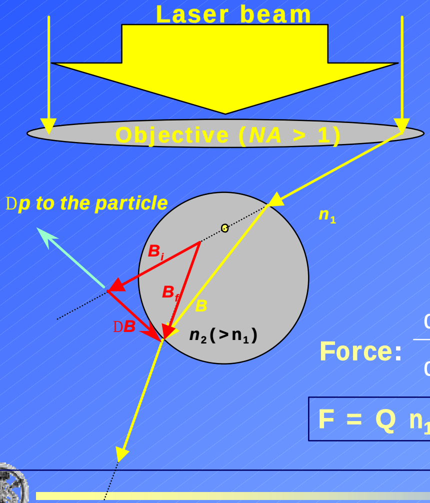


Particle size ranging from 0.1 to 100 mm

Optical tweezers: working principle

Origin of the force: two regimes

- Mie regime $2\pi n_1 a/\lambda \gg 1$ <u>ray optics</u>
- Rayleigh regime $2\pi n_1 a/\lambda \ll 1$



Refraction of the light by a sphere: change in the carried momentum.

An equal and opposite momentum is imparted to the sphere

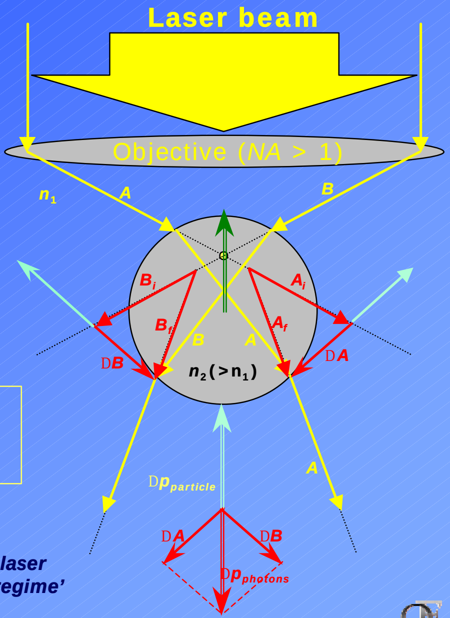
Force: $\frac{d\vec{p}}{dt}$ rate of the momentum change

$F = Q\, n_1 P/c$ Q : efficiency parameter

Optical tweezers: working principle

n2 > n1 the optical force arising from refraction is in the direction of the intensity gradient

n2 < n1 the optical force arising from refraction is opposite to the direction of the intensity gradient

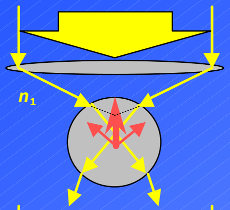


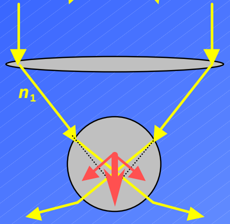
Axial gradient force : extremal rays

Scattering force: central rays

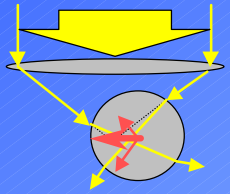
A. Ashkin, 'Forces of a single beam gradient laser trap on a dielectric sphere in the ray optics regime' Biophys. J., 61, 569, 1992

Optical tweezers: working principle





The equilibrium in axis is below the focus point



The equilibrium in the tranverse direction is ensured by the gradient components

F= k x k → pN / nm Trap stiffness

(tipical 100 pN/mm)

Typical displacements: 1 - 500 nm

Tipical force: 0.1-100 pN

1 pN = weight of a red bloodcell

Optical tweezers: Rayleigh regime

Radius a << λ The particle is treated as a point dipole.

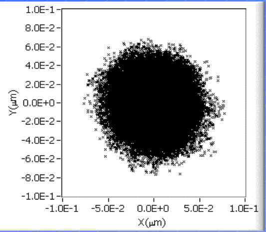
Scattering force: absorbtion and reradiation of light by the dipole

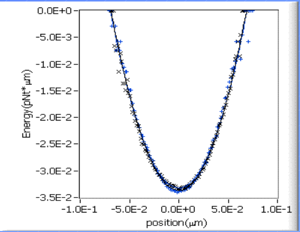
$$F_{scatt} = \frac{I_o s n}{c}$$

Gradient force: interaction of the induced dipole with the inhomogeneous field

$$F_{grad} = \frac{2pa}{cn^2} \vec{\nabla} I_o$$

A necessary and sufficient condition for stability is that the potential well of the gradient force is much larger than the kinetic energy of the Brownian motion of particle exp(U / k T) << 1





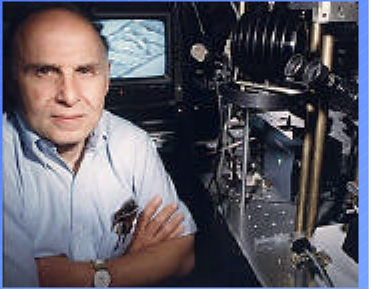
Seminal works

Most of the early work in this field was done by Arthur Ashkin of Bell Labs.

– 1970: two opposing laser beams were used to trap and cool atoms [1].

– 1986: a single laser focused through a microscope was used to trap polystyrene balls with diameters 10 µm to 25 nm [2].

– 1987: bacteria and protozoa were trapped, first with a 514.5 nm Ar laser, followed by a 1064 nm Nd:YAG laser [3], [4].



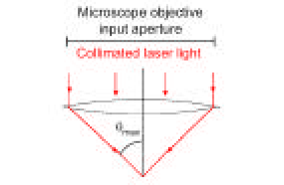
[1] A.Ashkin, 'Acceleration and trapping of particles by radiation pressure', Phys. Rev. Lett., 24, 156, 1970

[2] A.Ashkin, J.M.Dziezic, , J.E. Bjorkholm, S. Chu, 'Observation of a single beam gradient force optical trap for dielectric partticles, Opt. Lett., 11, 288, 1986

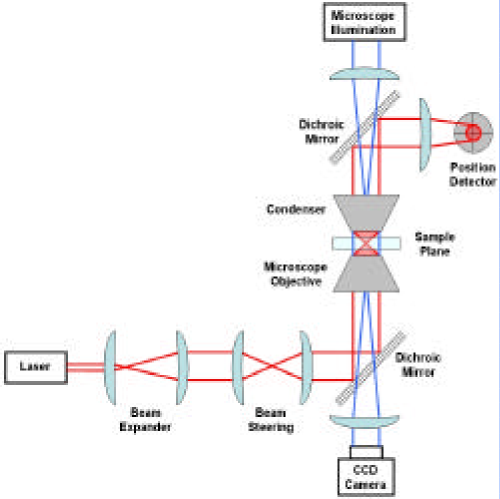
[3] A.Ashkin, J.M.Dziezic, T. M. Yamane, ' Optical trapping and manipulation of single cells using infrared laser beams', Science, 235, 1517, 1987

[4] A.Ashkin, J.M.Dziezic ' Optical trapping and manipulation of viruses and bacteria', Science, 235, 1517, 1987

Optical tweezers: working principle

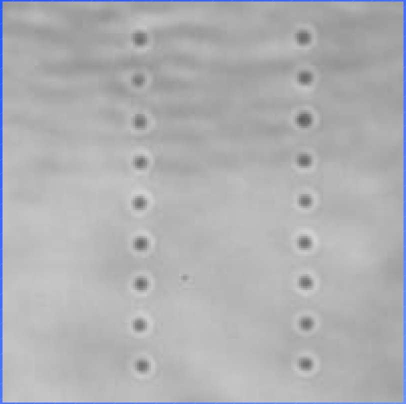


$$NA = n \sin(\theta_{max})$$



Typical wavelength : 800 - 1064 nm

Optical manipulation



A longway figure dance in which a new top couple begin on every repetition of the dance.

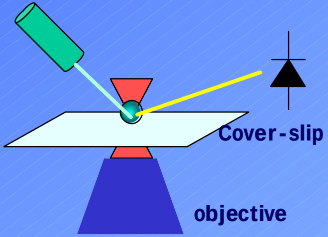
Courtesy of M. Padgett group – Glasgow University

Application in biology

Diagnostics at the single cell and sub-cellular level: possibility to interrogate a single cell eliminating signals from the environment

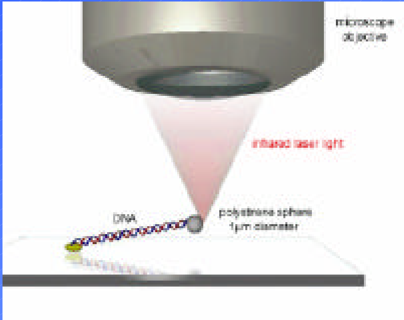
Trapping of living cells, combination with spectroscopic analysis and microsurgery

- ✓ Bacterial adhesion forces
- ✓ Membrane interactions
- ✓ Cell sorting

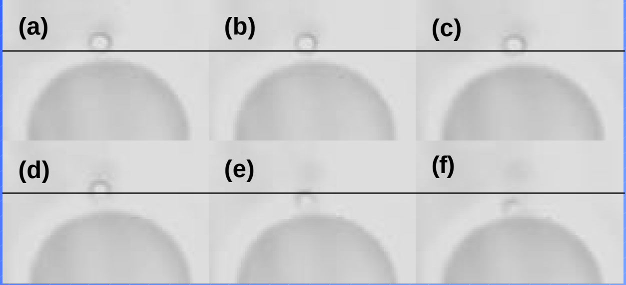


D. Grier, 'A revolution in optical manipulation', Nature 424, 810, 2003
K. C. Neumann, S.M. Block, 'Optical trapping', Rev. Scient. Intrum. 75, 2787, 2004

Application in biology

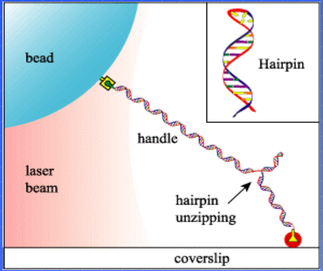


Study of the variation of the stiffness of the trap by recording the image at different lateral position



DNA stretching

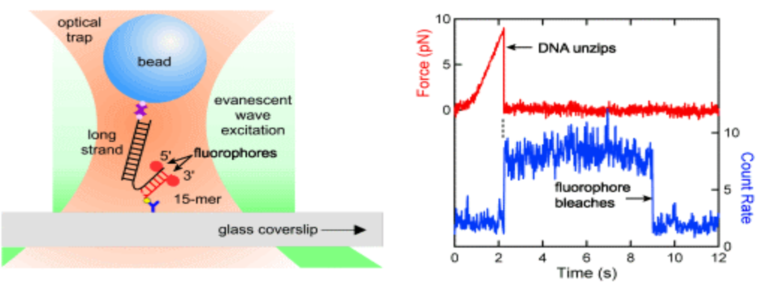
Application in biology



DNA unzipping experiment

The optical trap applies a force to the hairpin causing it to unzip

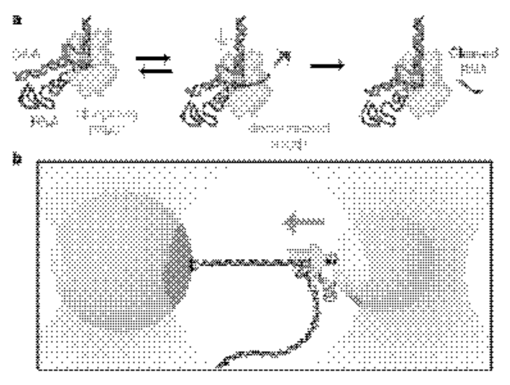
Fluorescence signal allows for a better location in time and space of a structural event



Lang et al, J. Biology (2003)

Application in biology

Experimental geometry exploited
for opposing force experiments



During transcription elongation
the beads are put togheter

Observation of transcriptional
elongation by the measure of the
smaller bead position as the
polymerase moves

S.M. Block et al, 'Backtracking by single RNA polymerase molecules observed at near-base-pair resolution', Nature 426, 687 (2003)

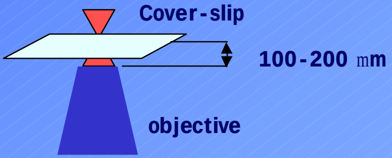
Outline

- Optical tweezers: a powerful tool for micromanipulation
- Why an optical fiber tweezer? Motivation, state of the art and open problems
- A new approach to the fiber tweezers development

Optical fiber tweezer: why?

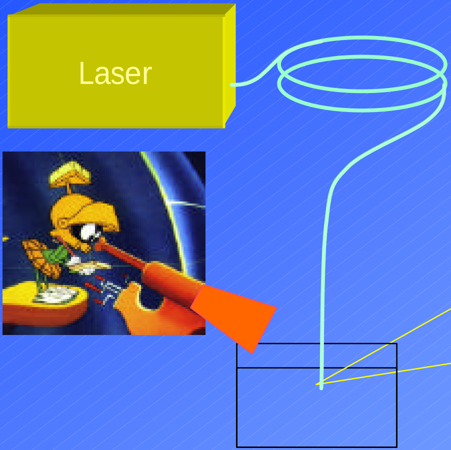
- ✓ Bulky and quite expensive (> € 20.000)
- ✓ Difficult to achieve trapping in thick or turbid solutions
- ✓ Limited field of view
- ✓ Not versatile: no in vacuum operation, difficult "in vivo" analysis

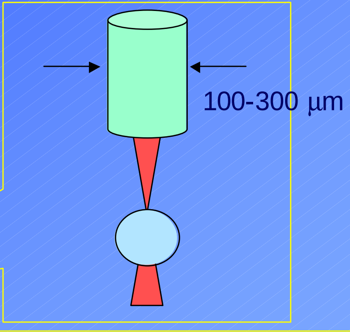
The trapping point is positioned only a few hundreds of micrometers from the objective



Optical fiber tweezer: why?

The fiber can carry the light close to the object to be trapped. It can be easily handled in any environment

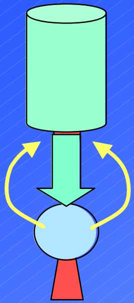




The sample under test can be observed with an independent microscope with any magnification and large field of view

!!! A proper optical system must be fabricated on the fiber-end to achieve the tight focussing!!!

Optical fiber tweezer: why?



The fiber can be also used to carry different laser beams to probe the trapped sample, or can collect the signal emitted by the sample

The fiber based technology is extremely mature due to the advancement of the optical communication systems

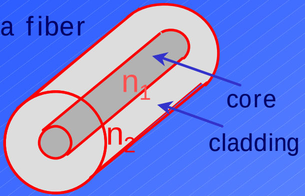
In situ probing and detection: enhancement of the signal/noise ratio

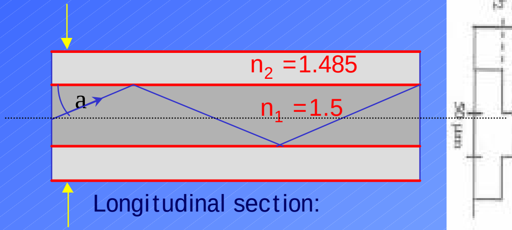
Optical fibers

The light is guided due to the total reflection at the core-cladding interface

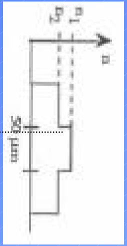
$n_1 > n_2$

Silica fiber

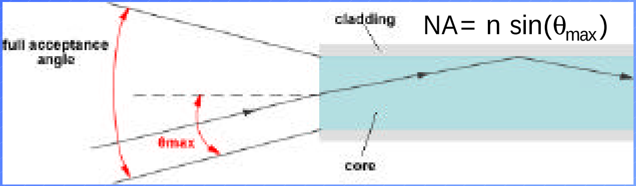




Longitudinal section:



NA: half angle of the cone of acceptance

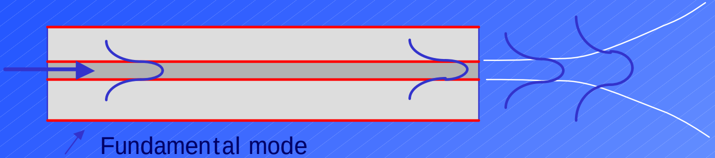


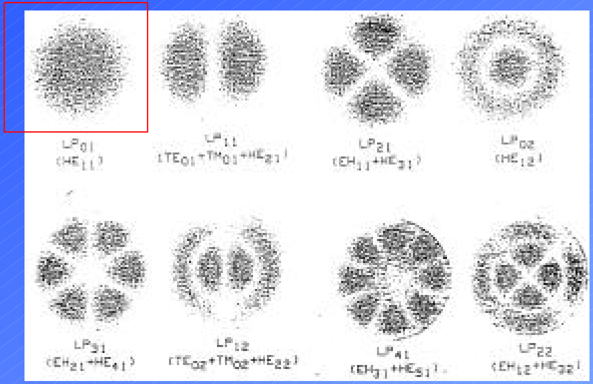
$NA = n \sin(\theta_{max})$

$NA = 0.1$

$\theta_{max} \sim 6°$

Optical fibers



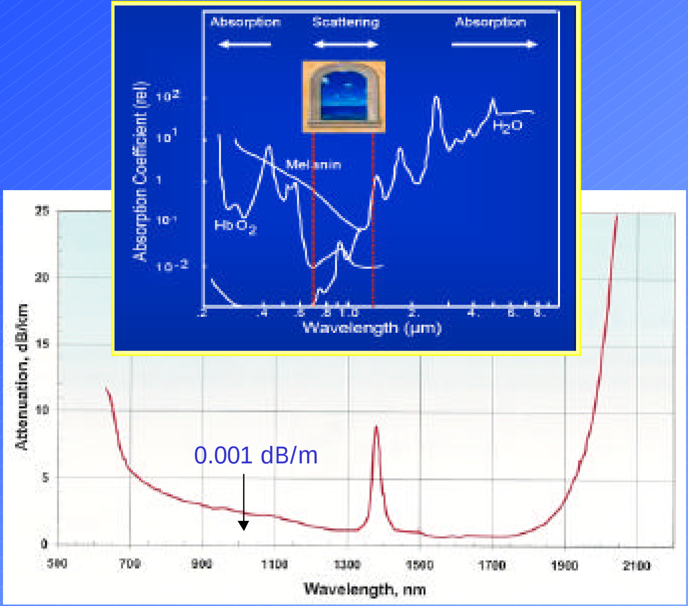


The solution is represented by a family of modes indexed by l = 0,1,2, ...

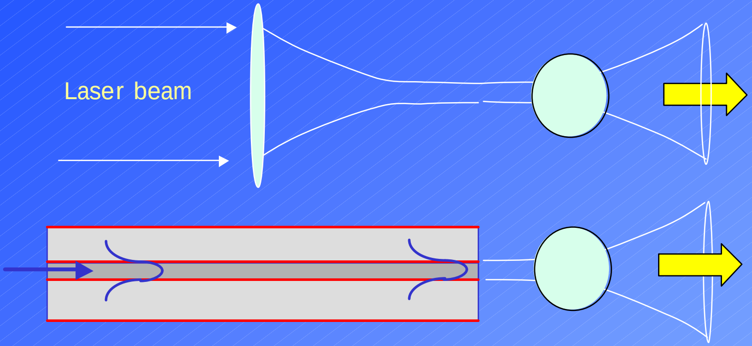
modes = eigenfunctions of propagation equations (they constitute a set of orthogonal functions)

The field propagating through the fiber is obtained by linear superposition of modes

Optical fibers: attenuation

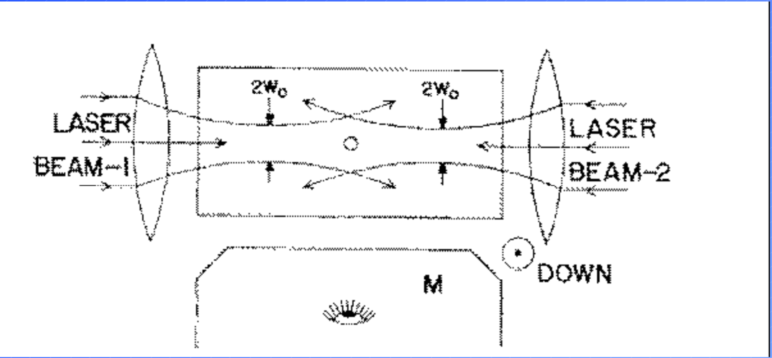


Optical fiber trapping



The NA of the equivalent lens is too low: the scattering force is not counter-balanced by the gradient force

Optical fiber



A. Ashkin, 'Acceleration and trapping of particles by radiation pressure', Physical Review Letters, Vol. 24, No. 4, 156, 1970

Dual fiber optical tweezer

Scattering force are counterbalanced

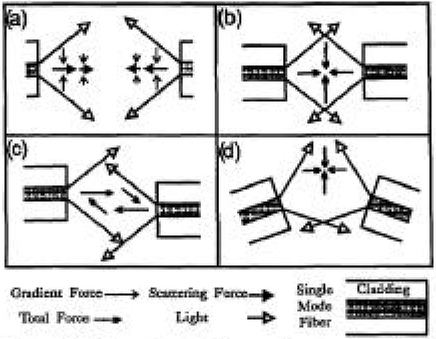


Fig. 1. (a) Schematic of the gradient and scattering forces for each of the two fibers that compose the trap. (b)–(d) Directions of the total forces when the fibers are (b) perfectly aligned, (c) translationally misaligned, and (d) rotationally misaligned.

- Large capture volume and possibility to hold large cells due to the divergent beams
- Fiber can be separated to allow simultaneous investigations.
- Greater field of view

The allignment of the two counterpropagating beams must be guaranteed within a fraction of the beam waist: VERY CRITICAL

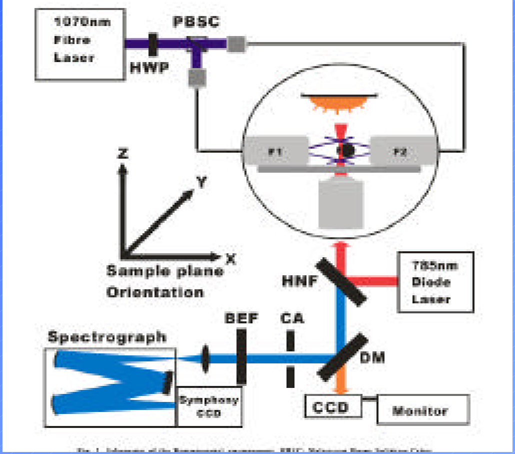
A. Constable et al, ' Demostration of a fiber trap' Opt. Lett. 18, 1867, 1993

Dual fiber optical tweezer

Optical fiber tweezer + Raman spectroscopy

Raman spectroscopy : specific molecular vibrations are identified giving a finger print of the chemical composition

Using the mechanical motion of the fibers the particle is scanned across the laser exciting the Raman transitions



P.R.T. Jess et al. 'Dual beam fibre trap for Raman micro-spectroscopy of single cells' Opt. Expr. 14, 5780, 2006

Dual fiber optical tweezer

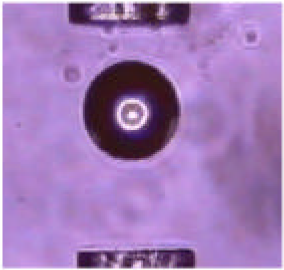
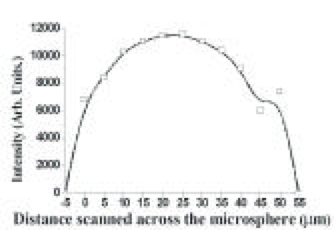


Fig. 2. A 100 micron polymer sphere trapped in a fibre optical light force trap, viewed from below. The fibre trap uses 62.5/125μm (core size/ cladding size) multimode fibre, a trapping power of 800mW in each fibre arm and a fibre separation of 240μm.

Localized Raman response

50 μm polymer sphere with 40 mW of light travelling in each single mode fiber



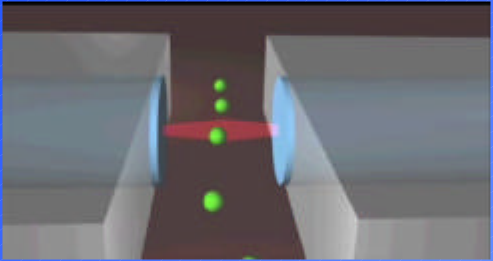
Using the mechanical motion of the stage the particle was scan across the laser exciting the Raman transition

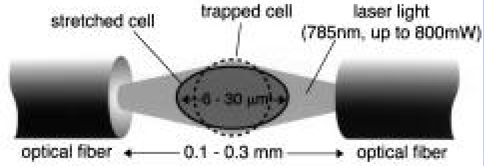
A benzene ring mode was monitored

P.R.T. Jess et al. 'Dual beam fibre trap for Raman micro-spectroscopy of single cells' Opt. Expr. 14, 5780, 2006

Dual fiber optical tweezer

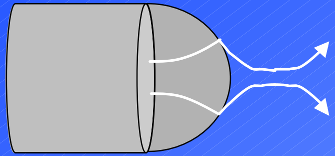
Optical fiber tweezer + Optical stretcher





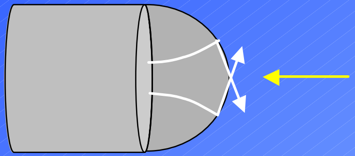
J. Guck et al. "The optical stretcher: A novel laser tool to micromanipulate cells", Biophys. J. 81, 767 (2001)

Lensed optical fiber



Low refractive index contrast : lens with a very low curvature ray.

The mode changes very rapidly out of the fiber



The mode size is very low: the trapping point is attached to the fiber

NA of the order of 0.5
Not sufficient to counter-balance the scattering force

Single fiber trapping experiment

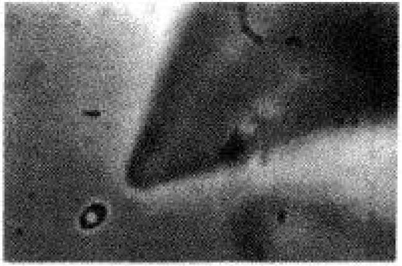


Fig. 2 *Photograph of yeast cell trapped near focal point*

Tapered spherical- end 2- 4 - 6 mm
The lenses are obtained through polishing
Power: few mW
Wavelength: 1480 nm and 1064 nm

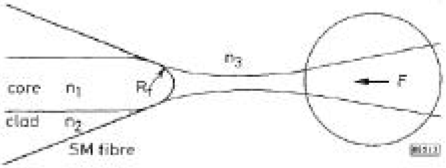
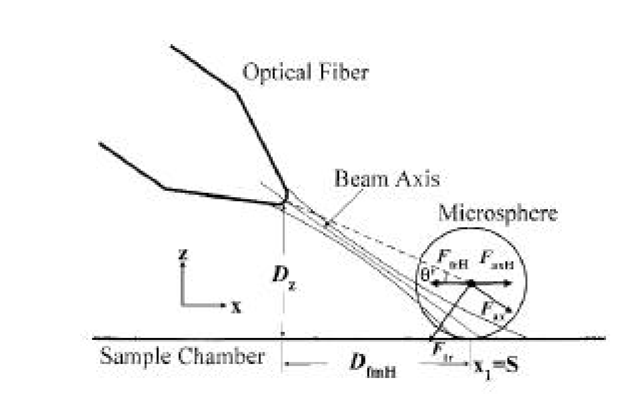


Fig. 3 *Schematic diagram of micro-sphere trapped by focused beam emitted from tapered spherical end*

K. Taguchi et al. 'Optical trapping of dielectric particle and biological cell using optical fibre' Electron. Lett. 33, 413, 1997

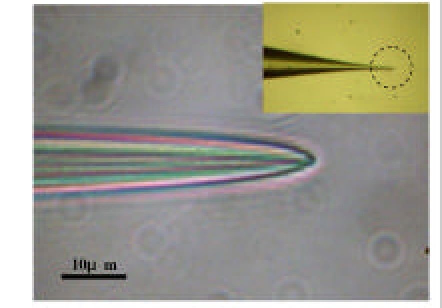
Single fiber trapping experiment

Actually the scattering force was balanced by the reaction opposed by the bottom of the recipient holding the cell



K. Taguchi et al. ' Single laser beam fiber optic trap, Opt. Quantum Electron. 33, 99, 2001

Single fiber trapping experiment

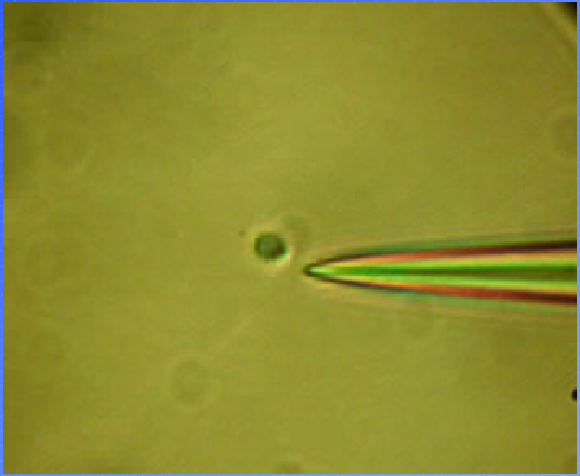


Heating and drawing technique
The diameter is gradually reduced from 125 mm to 10 mm until the fiber breaks in the waist zone.

Parabola like profile is formed at the fiber-end

Liu et al. *'Tapered fiber optical tweezer for microscopic particle trapping: fabrication and application' Opt. Express 14, 12513, 2006*

Single fiber trapping experiment



Liu et al. *'Tapered fiber optical tweezer for microscopic particle trapping: fabrication and application' Opt. Express 14, 12513, 2006*

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New proposal by our group

Patents by the University of Pavia:

CRISTIANI I., LIBERALE C, MINZIONI P. (2007). Manipolazione ed analisi di particelle micrometriche tramite tweezer in fibra ottica. MI2007A000150.

CRISTIANI I., LIBERALE C, MINZIONI P. (2007). Method and optical device for trapping a particle. PCT/EP/2007/056798. 27. Date: 5th July 2007.

Publication on Nature Photonics

C. Liberale, P. Minzioni, F. Bragheri, F. DeAngelis, E. Di Fabrizio and I. Cristiani, "Miniaturized all-fiber probe for three dimensional optical trapping, manipulation and analysis“ Nature Photonics, 1, 12, p. 723, 2007.

OPTICAL TWEEZERS

All-fibre design

Optical tweezers enable precise, controlled and non-contact manipulation of small biological specimens. Rather than using a bulky microscope, it is now possible to create optical tweezers at the end of a fibre probe.

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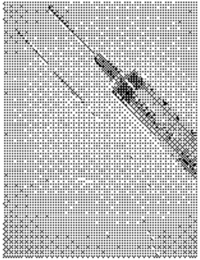
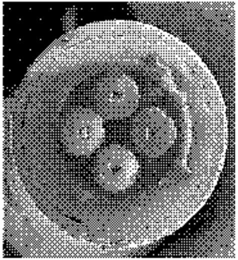
In the 20 years since they were pioneered by Arthur Ashkin and his co-workers, optical tweezers have become a mainstream research tool in both the biological and physical sciences. Most optical tweezers rely on the force acting on a dielectric particle that arises whenever there is a large gradient in the intensity of the optical field. Usually this gradient is achieved by the strong focusing of a conventional laser beam using a high-magnification microscope objective. Indeed, most optical tweezers are themselves based around high-quality microscopes where the same objective lens is used for both focusing the trapping beam and viewing the trapped sample. Now, Carlo Liberale and colleagues have come up with a different approach, one that enables tweezing using a single optical-fibre probe (page [illegible]).





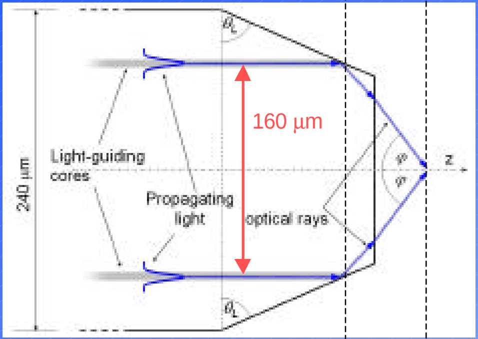
[illegible]

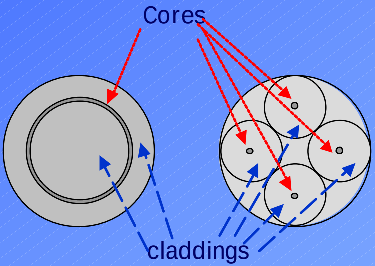
New approach

P. Minzioni, F. Bragheri (Dipartimento di Elettronica-Università di Pavia)
Carlo Liberale, Enzo DiFabrizio (BIONEM lab. Università Magna Graecia)

Two concepts: fiber bundles (or annular core fibers)
total internal reflection instead of refraction

$\theta_L = 66.5°$



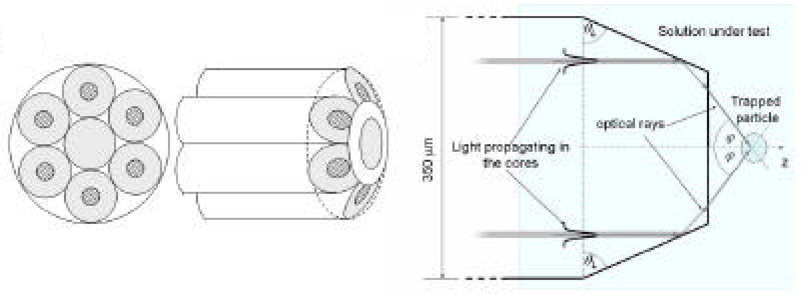


$$j = \sin^{-1}\left[\frac{n_F}{n_M}\sin(p - 2J)\right]$$

φ = 53 ° → NA equivalent = 1.06

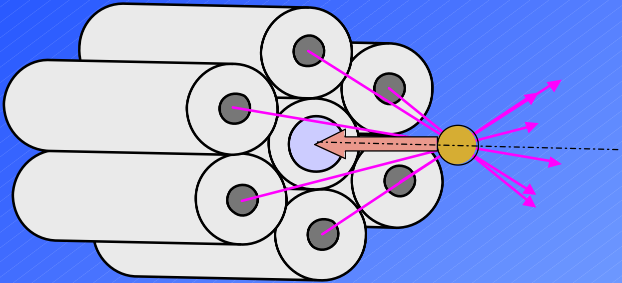
60 µm

New approach



The central part of the equivalent gaussian beam is suppressed: the effect of the scattering force is highly reduced

Optical analysis and manipulation



- ✓ Controlled translation: by trimming the power in each fber
- ✓ Multiple traps
- ✓ Particle squeezing

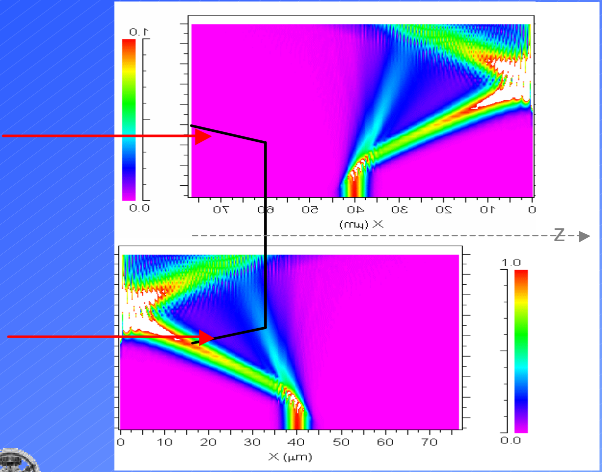
New approach

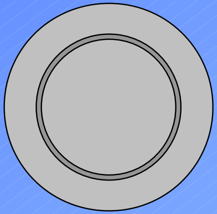
Design?

Numerical calculation of the forces

The optical field is calculated through different methods:

- a commercial software, beam-propagation method for the annular core case
- a software realized in matlab for the 4-fiber bundle





Numerical calculation of the forces

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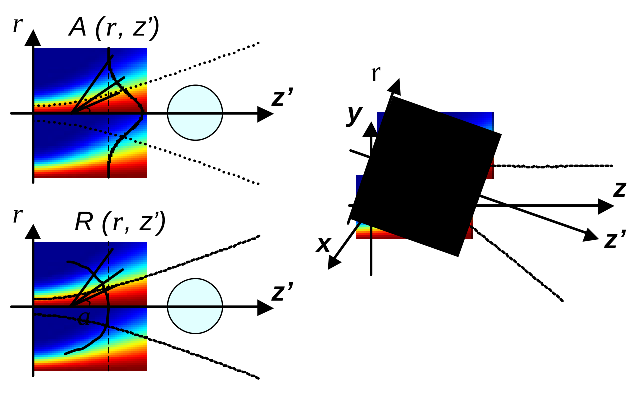
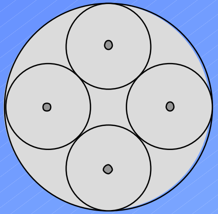
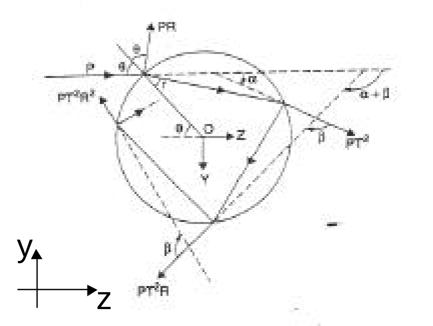




Numerical calculation of the forces



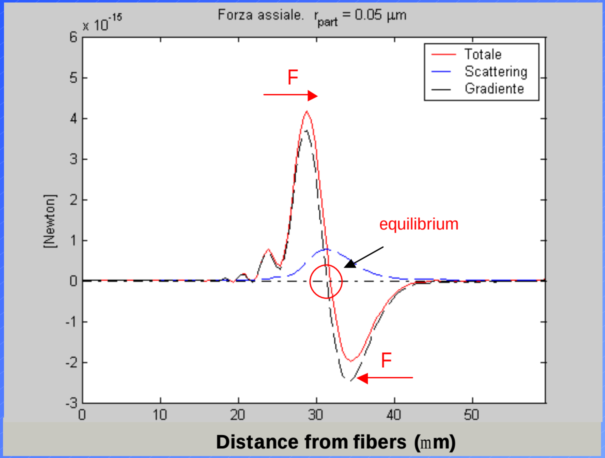
Optical forces are calculated

in the Mie regime

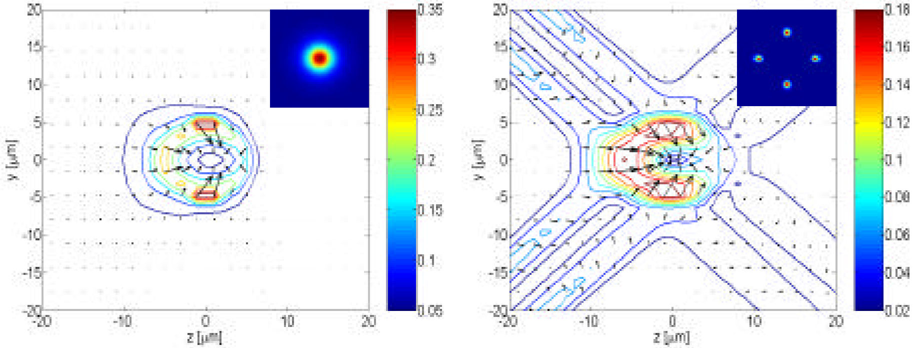
$$F_y = F_G = \frac{n_M P}{c}\left\{\left[R\sin(2J)\right] - \frac{T^2\left[\sin(2J-2r) + R\sin(2J)\right]}{1 + R^2 + 2R\cos(2r)}\right\}$$

$$F_z = F_S = \frac{n_M P}{c}\left\{\left[1 + R\cos(2J)\right] - \frac{T^2\left[\cos(2J-2r) + R\cos(2J)\right]}{1 + R^2 + 2R\cos(2J)}\right\}$$

Numerical calculation of the forces (on-axis)



Numerical calculation of the forces



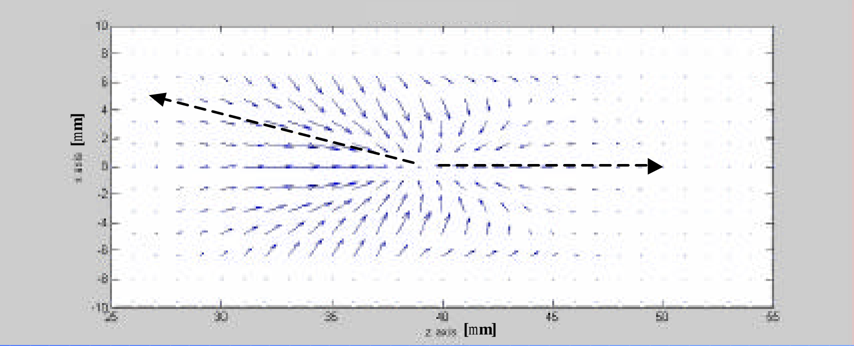
Standard optical tweezer:
gaussian beam

Fiber optic tweezer:
4-fiber bundle

The new escape energy parameter

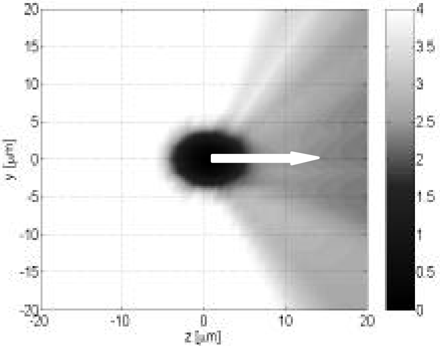
In Mie regime the forces can be calculated as the sum of the momentum-transfer between the particle and each optical ray impinging on it.

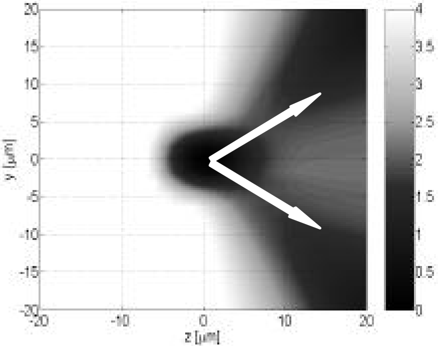
Which is the “best” parameter to evaluate the “trap strength”?



We evaluated the total work required to an external source to move a particle from the trapping position to any other point in the space, along a straight trajectory

Escape energy

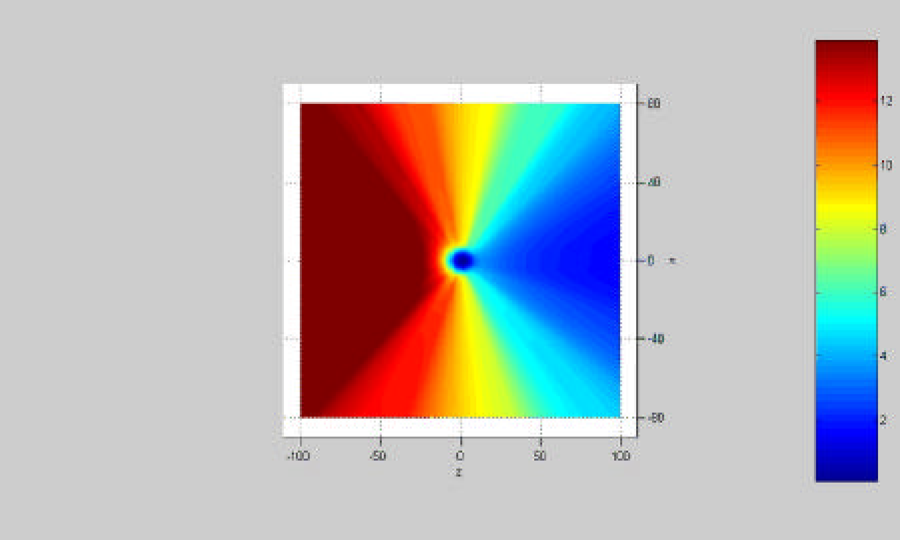




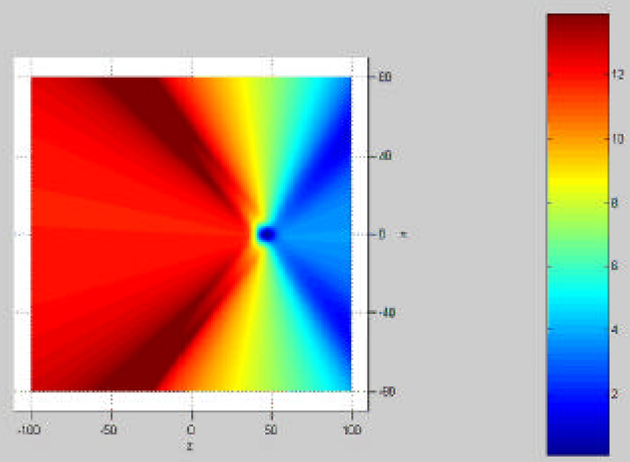
Standard optical tweezer:
gaussian beam

Fiber optic tweezer:
4-fiber bundle

Escape energy: gaussian beam



Escape energy: 4-fiber bundle

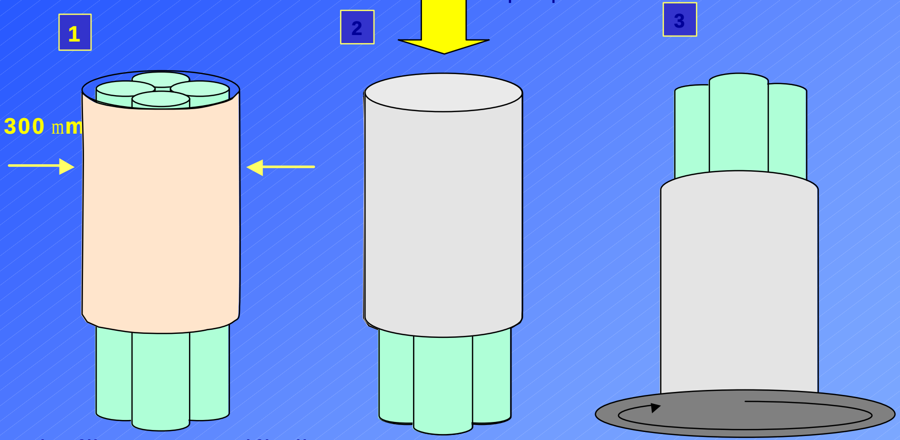


New approach

Fabrication?

Bundle fabrication

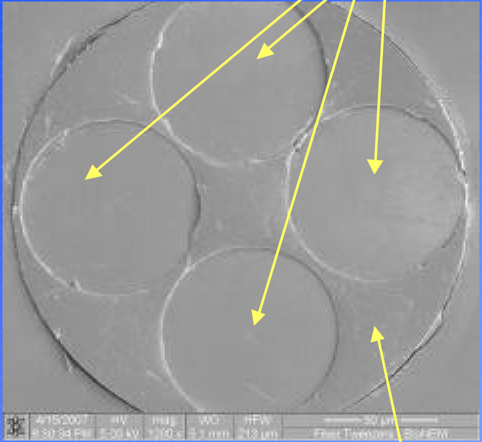
The fibers are blocked through a resin that penetrates in the fiber bundles thanks to a vacuum pump



The fibers are specifically designed to be monomode at 1064 nm with a large mode area

The end face of the bundle is then polished on a rotating plate with diamond powders to reach sub-µm roughness

Four-fibers bundle



Focused Ion Beam - FIB

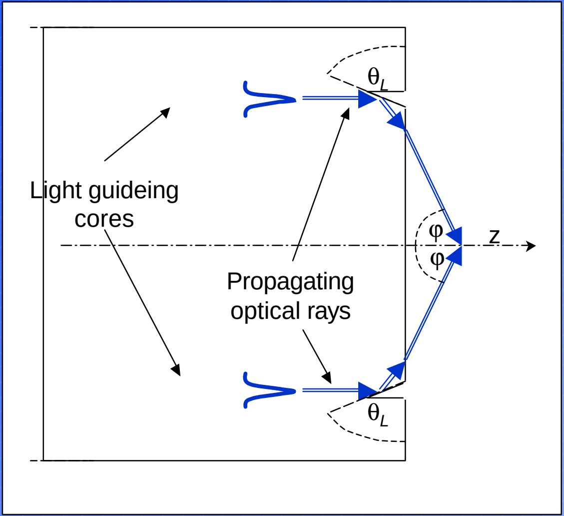
FIB uses a focused beam of gallium ions accelerated to an energy of 5-50 keV, and then focused onto the sample by electrostatic lenses. FIB can deliver tens of nanoamps of current to a sample, or can image the sample with a spot size on the order of a few nanometers.

FIB is inherently destructive to the specimen. When the high-energy gallium ions strike the sample, they will sputter atoms from the surface.

Because of the sputtering capability, the FIB is used as a micro-machining tool, to modify or machine materials at the micro- and nanoscale.

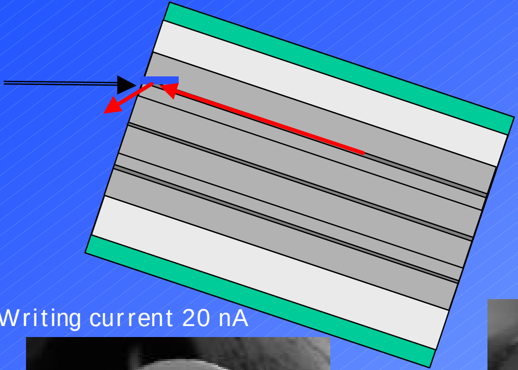
FIB is assisted by a SEM for the imaging

Fibers microstructuration

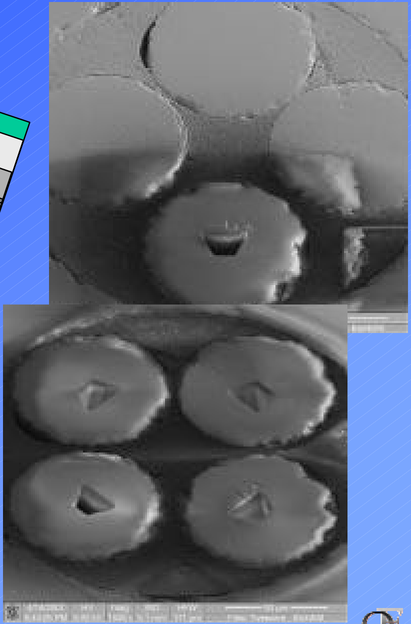


With the micro machining we dig just the core regions where the total internal reflection takes place.

Fibers microstructuration



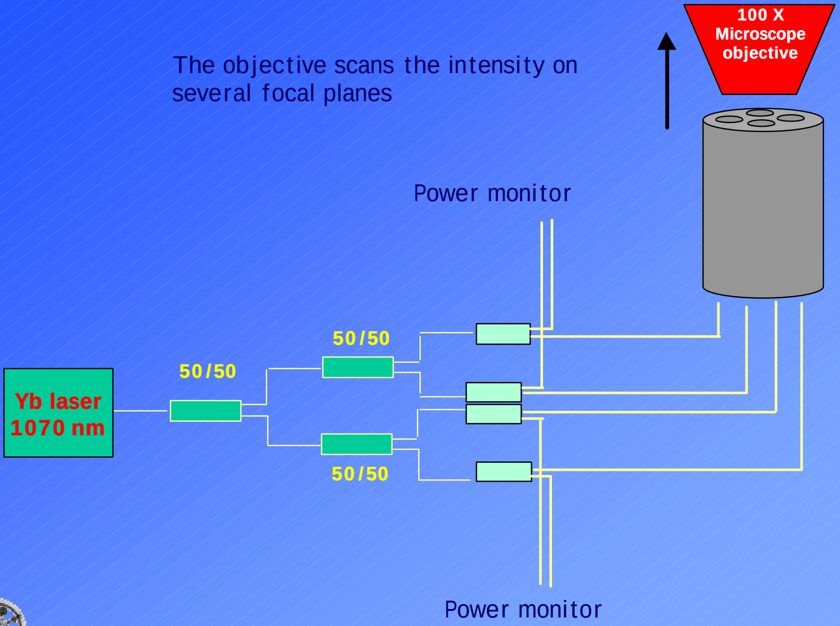
Writing current 20 nA



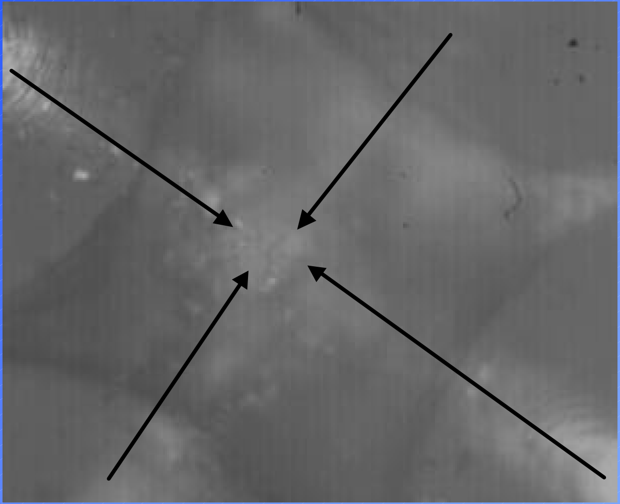
New approach

Test?

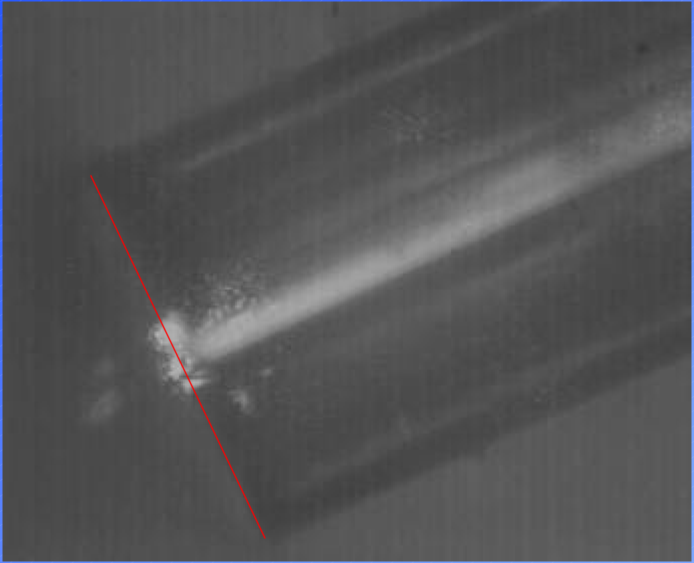
Probe analysis



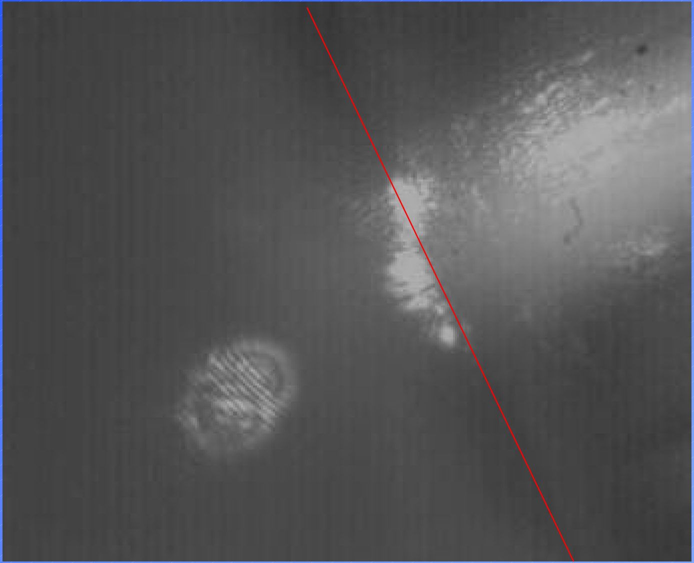
Output beams



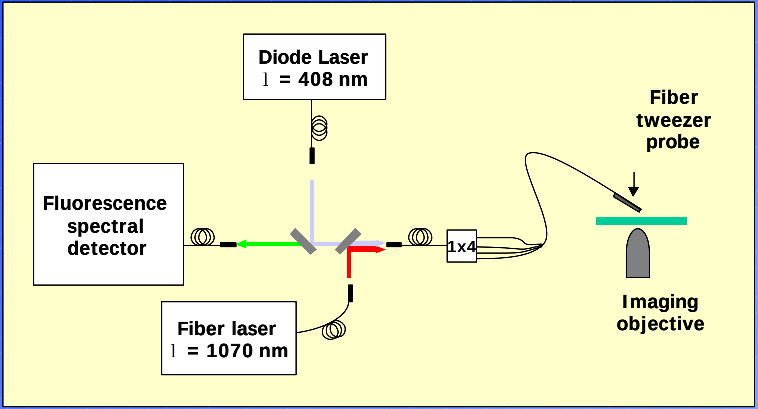
Trapping!



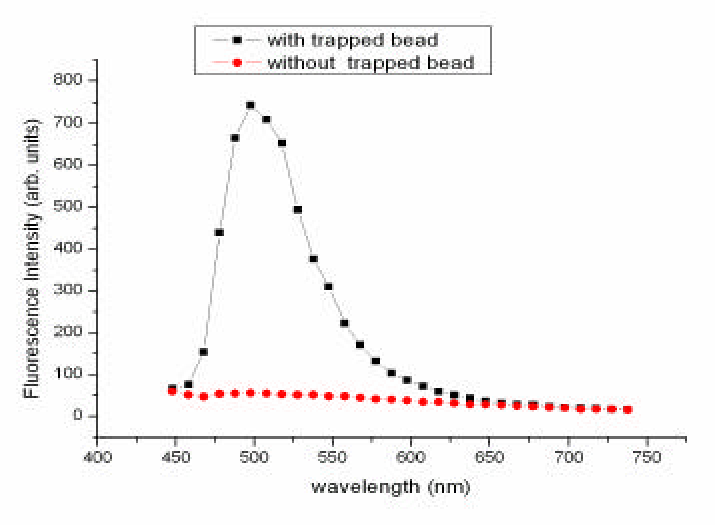
Trapping!



Fluorescence collection



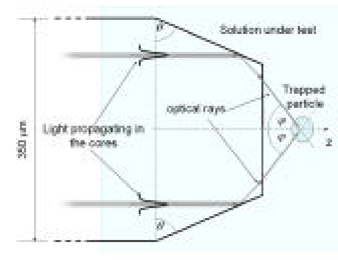
Fluorescence collection



Conclusions

<u>Trapping stiffness and working distance</u>

- Numerical aperture that depends essentially on the cutting angle θ - fiber-end metallization
- Mode field diameter
- Annulus size



<u>Mechanical stability of the structure</u>

- Optimization of the bundle fabrication procedure: resin adhesion

<u>Realization of a dual fiber optical tweezer and optical stretcher</u>

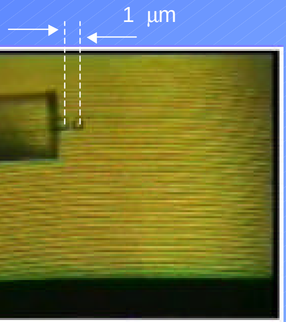
Thank you!

www.unipv.it/eqn

Single fiber trapping experiment

The doughnut mode can trap high-index particles in the doughnut ring and low-index particles in its dark core.

In addition, the doughnut beam has orbital angular momentum along the spiral axis.



The scattering force balance was unexpected!!

? Electrostatic return force due to negative charge of the glass partcles in water

R.S. Taylor and C. Hnatovsky, 'Particle trapping in 3D using a single fiber probe with an annular light distribution ' Opt. Express. 11, 2775, 2003

Microstructured probes