Optomechanics of Nano-objects. Challenges and Perspectives in Physics and Biology

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SYMPOSIUM HONORING PROFESSOR JOSE S. MOYA
"GRAND CHALLENGES FACING MATERIALS COMMUNITY"

GRAN HOTEL LAS CALDAS, LAS CALDAS, 33174 OVIEDO, SPAIN
GOALS:

- Information retrieval with light at the nanometer scale conveys to beat the diffraction limit, (Abbe, Rayleigh):

  Resolved distance $\approx \lambda \times \left(\frac{\text{focal distance}}{\text{aperture of the objective}}\right)$

- Optomechanics at the nanoscale.

- MEMS (Microelectromechanical systems).

THz MEMS reconfigurable Metamaterials

BUT..., WHY LIGHT?
Kepler, 1619
Maxwell, 1873
Einstein, 1905
Compton, 1925
Letokhov, 1970’s
Askhin, 1970’s
Hänsch, Schalow, 1975
Pritchard, Cohen-Tanoudji, Phillips, Chu, 1980’s
Optical tweezers

- Laser power in the mW range. Irradiated areas of some $\mu$m$^2$

  Optical forces in the range: $10^{-12}$ - $10^{-19}$ N.

  $F = ma$, acceleration $a = 10^5$ g

  Gravitational force of the order of $\sim 10^{-4}$ pN for a glass particle with $a \sim 10^2$ nm.

Exploiting the effect of radiation pressure

Arthur Ashkin, 70's
HOW YOU SEE PARTICLES THROUGH THE INVERTED MICROSCOPE:

Dynamic Holographic Optical tweezers,
J.E. Curtis, B.A. Koss and D.G. Grier,
Arranging structures using light distributions

A computer simulation. T. Grzegorczyk. M.I.T
Light induced Optical Binding


FIG. 3. Mie calculations of the time-average intensity of the near fields of (curve a) 1.43- and (curve b) 1.53-μm spheres. The arrow indicates the distance separating two identical spheres when touching.
Optical Matter

United States Patent

Burns et al.

[54] OPTICAL MATTER


[21] Appl. No.: 773,980

[22] Filed: Oct. 8, 1991

Related U.S. Application Data


[51] Int. Cl. .......................... G02B 26/00
[52] U.S. Cl. ......................... 359/296; 372/27; 372/69

[58] Field of Search .......... 350/359, 362, 363, 162.2; 356/303, 334; 372/109, 27, 69; 359/296

[56] References Cited


(List continued on next page.)

Primary Examiner—Léon Scott, Jr.
Attorney, Agent, or Firm—Choate, Hall & Stewart
Reconfigurable metamaterials: nanoscale forces

1 to 5 THz  28 × 28 μm²

- Tunable anisotropy
- Terahertz var. waveplates
- Tunable filters
- Polarimetry

Y. H. Fu, A. Q. Liu, N. I. Zheludev, et.al.  
*Advanced Functional Materials* (2011)
Scientific Background on the Nobel Prize in Chemistry 2014

SUPER-RESOLVED FLUORESCENCE MICROSCOPY
Breaking the diffraction resolution limit
by stimulated emission:
stimulated-emission-depletion fluorescence microscopy

Stefan W. Hell and Jan Wichmann
Department of Medical Physics, University of Turku, Tykistökatu 6, 20521 Turku, Finland

February 1, 1995 / Vol. 20, No. 3 / OPTICS LETTERS

Proposed method for molecular optical imaging

E. Betzig
NSOM Enterprises, 17 Webster Drive, Berkeley Heights, New Jersey 07922

Illuminating Single Molecules in Condensed Matter

W. E. Moerner\textsuperscript{1} and Michel Orrit\textsuperscript{2}

\textsuperscript{1}Department of Chemistry, Stanford University, Stanford, CA 94305–5080, USA. \textsuperscript{2}Centre de Physique Moléculaire Optique et Hertzienne, UMR 5798, CNRS
Far-Field Optical Nanoscopy

Stefan W. Hell

SCIENCE  VOL 316  25 MAY 2007

A  Confocal

$\frac{\lambda}{2n \sin \alpha}$

$\sim 500 \text{nm}$

$\alpha$

B  4Pi

$\sim 90 \text{nm}$

$\alpha \approx 64-74^\circ$

E  PALM/STORM

Switch single molecules

Centroid

Stochastic read-out
Far-Field Optical Nanoscopy

Stefan W. Hell

SCIENCE  VOL 316  25 MAY 2007
IMAGE FORMATION IN NEAR-FIELD OPTICS

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Professor Emil Wolf
Arthur Ashkin opened the field of optical manipulation more than 40 years ago.

Optical "nanotweezers"
Optical tweezer for an object smaller than the wavelength of light

Arthur Ashkin
Manipulating the brain by light with nanotweezers

S. Ramanathan et al., Harvard U., 1-mm-long Caenorhabditis elegans nematode, neurons (302), synapses (7,000). Illuminate the spot within 25 ms to stimulate a single 5- to 10-µm neuron. Image and track behavior.
Jennifer Elisseeff et al., J. Hopkins U.

The cells where activated and migrated in the light direction by a 458 nm laser in a subcellular spot 10 μm in diameter for 30-s periods at 80-s intervals. The team studied the activity of Rac in the cells using fluorescence resonance energy transfer (FRET) imaging.

This helps to understand tissue regeneration and repair and the influence of surrounding cells.
Optofluidics “NanoTweezer”

“Optofluidics” Waveguide NanoTweezer:

Particles flows over optical waveguides.

When stimulated by infrared light, the particles are attracted to the evanescent field and reversibly immobilized until the light is turned off.
Optical trapping through a turbid medium

Dholakia et al., U. St. Andrews, U.K.

In situ wavefront correction and its application to micromanipulation

Tomáš Čížmár*, Michael Masiuk and Kishan Dholakia

In any optical system, distortions to a propagating wavefront reduce the spatial coherence of a light field, making it increasingly difficult to obtain the theoretical diffraction-limited spot size. Such aberrations are severely detrimental to optical performance in imaging, nanosurgery, nanofabrication and micromanipulation, as well as other techniques within modern microscopy. We present a generic method based on complex modulation for true in situ wavefront correction that allows compensation of all aberrations along the entire optical path. The power of the method is demonstrated for the field of micromanipulation, which is very sensitive to wavefront distortions. We present direct trapping with optimally focused laser light carrying power of a fraction of a milliwatt as well as the first trapping through lightly turbid and diffusive media. This opens up new perspectives for optical micromanipulation in colloidal and biological physics and may be useful for various forms of advanced imaging.

Shaping the future of manipulation

K. Dholakia* and T. Čížmár†

Optical forces can be used to manipulate biological and colloidal material in a non-contact manner. This forms the foundation of a wealth of exciting science, particularly in the fields of physics, biology and soft condensed matter. Although the standard Gaussian single-beam trap remains a very powerful tool, shaping the phase and amplitude of a light field provides unusual light patterns that add a major new dimension to research into particle manipulation. This Review summarizes the impact and emerging applications of shaped light in the field of optical manipulation.
Optical tractor beams
Optical tractor beams (so far...)

Incident light is a Bessel beam:
Optical pulling force

Jun Chen, Jack Ng, Zhifang Lin and C. T. Chan

Hong Kong

Single Gradientless Light Beam Drags Particles as Tractor Beams

Andrey Novitsky, Cheng-Wei Qiu and Haifeng Wang

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2 Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576, Singapore
3 Data Storage Institute (DSI), Agency for Science, Technology and Research, DSI Building, 5 Engineering Drive 1, Singapore 117608, Singapore

The vacuum (according to quantum mechanics)

\[ \langle \text{Energy} \rangle = \frac{\hbar \omega}{2} \]
The vacuum (a detail):
Casimir Effect

Macroscopic objects
(many interacting dipoles)

Hendrik Casimir (1948)

Perfect metal plates

\[
F / A = -\frac{\hbar c \pi^2}{240d^4}
\]

Attractive, monotonically decreasing

Pressure \( \sim 1 \) atm at \( d = 50 \text{nm} \)

A.W. Rodriguez
Fluctuation-Induced Interactions

quantum mechanics = charge fluctuations

Force even in the range of $10^{-24}$ Newton

$= 10^{-12} \times$ [optical tweezer force]

A.W. Rodriguez

fluctuating dipole: $\mathbf{p}_1$

induced dipole $\mathbf{p}_2$

Attractive forces between otherwise neutral atoms

van der Waals and Casimir-Polder forces
(short- and long-range interactions)

$U \sim -\frac{1}{d^6}$  $\rightarrow$  $F \sim -\frac{1}{d^7}$
Measurement of the Casimir force:

Plate width = 1 cm
Sphere radius = 200 µm

[U. Mohideen et al., PRL, 81 (1998)]
Testing Newton gravity law at large scales

Anomalies in astrophysics?

Serge Reynaud

Galaxy rotation curves show a deviation from Newton laws

An observation of Dark Matter and/or a modification of gravity laws?
PARALLEL WORLDS
A Journey Through Creation, Higher Dimensions, and the Future of the Cosmos

Michio Kaku
Nature shows Casimir's examples
The gecko fingers

Van der Waals adhesion forces between spatula pads (10 nm w. by 200 nm th.) and surfaces.

Industrial dry adhesives inspired by the gecko adhesive.


A.K. Geim et al. 2003, Nat. Mater. 2, 461

N.S. Pesika et al., J. Phys. Cond. Mat. 21, 464132 (2009)
Optical “gecko”

Metamaterial film attracted by a beam of light to a dielectric surface.

N. I. Zheludev et al. PHYS. REV. B 85, 205123 (2012)
Torsional MEMS oscillators driven capacitively by electrodes, where the frequency shifts due to the Casimir force can be measured electrically or optically. The setup involves a doped polysilicon 500m 500m plate anchored to a substrate and acting as a torsional oscillator. The angular displacement of the oscillator is obtained by measuring the capacitance change between the oscillator and the electrodes below, which involves biasing one of the electrodes and application of a small AC probing signal. The angular displacement at various sphere-plate separations is then normalized to obtain the force data.
Optical force analogous to Casimir's and created by a fluctuating source

Optical vacuum

\[
\frac{\hbar \omega}{2} \coth \left( \frac{\hbar \omega}{2k_B T} \right) = \hbar \omega \left[ \frac{1}{2} + \frac{1}{e^{\frac{\hbar \omega}{k_B T}} - 1} \right] \simeq \frac{\hbar \omega}{2}; \quad (T = 0)
\]

Planck energy at zero T.

\[
\frac{\hbar \omega}{kT} \gg 1 \text{ at } T = 300 \text{ K!}
\]
The “optical” Casimir, or Van der Waals, forces are only particular cases of optically created forces for a broad (e.g. Planck) spectrum and frequencies $\hbar \omega >> kT$.

**Choice:**

Magnetic and electric coherence in forward- and back-scattered electromagnetic waves by a single dielectric subwavelength sphere.
THE TIME-AVERAGED OPTICAL FORCE

\[ \langle F^e \rangle = \frac{1}{4} \text{Re} \alpha_e \nabla |E|^2 + \frac{k}{2n} \text{Im} \alpha_e \text{Re} \{E \times B^*\} - \frac{1}{2} \text{Im} \alpha_e \frac{1}{2} \nabla \times \text{Im} (E^* \times E) \]

Gradient force \hspace{1cm} Radiation pressure \hspace{1cm} spin force

Energía eléctrica \hspace{1cm} Vector de Poynting \hspace{1cm} Densidad de Spin

So, the future...?
Fifth Symphony, pointing ‘the way to a radiant future’

Sergei Prokofiev, summer of 1944