Trapping with local evanescent light fields

A. Zelenina [1], R. Quidant[1], D. Petrov[1,2], G. Badenes[1], M. Nieto-Vesperinas [3]

[1] ICFO–Institut de Ciències Fotòniques, Jordi Girona 29, Nexus II, 08034 Barcelona, Spain
[2] ICREA–Institució Catalana de recerca i estudis avançats
[3] ICMM, Cantoblanco, 28049 Madrid, Spain

ABSTRACT

Following the recent advances in nano-optics, optical manipulation by evanescent fields instead of conventional propagating fields has recently awaken an increasing interest. The main advantages of using low dimensionality fields are (i) the possibility of integrating on a chip applications involving optical forces but also (ii) the absence of limitation by the diffraction limit for the trapping volume. Previous works have investigated theoretically and experimentally the guiding of dielectric and metallic beads at an interface sustaining an extended surface wave. In this work, we study theoretically the radiation forces exerted on Rayleigh dielectric beads under local evanescent illumination. Especially, we consider the configuration where a three-dimensional Gaussian beam is totally reflected at the interface of a glass prism. The results point out the illumination parameters where the gradient forces exceed the scattering force and allow for a stable trapping. The effect of the Goos-Hänchen shift on the location of the trapping site is also discussed.

Keywords: Near-Field Optics, Optical manipulation

1. INTRODUCTION

Optical manipulation has become a non-invasive and accurate technique that has found applications in various fields from biology[1] to quantum optics.[2] Since the first experiments by Ashkin,[3] attention has been mainly focused on elaborating the conventional technique based on a strongly focused 3-D propagating laser beam so that to increase the manipulation degrees of freedom. It is now possible to rotate and manipulate dynamically in the three dimensions several micrometer objects.[4]

Lately, an increasing interest has been developed around evanescent optical traps.[5–8] The interest of a configuration based on evanescent waves relies on the sharp transversal localization of the electromagnetic fields which offer (i) the automatic confinement of the trapped system in the surface-plane, of great interest for lab-on-a-chip integration and (ii) prevent from using high incident laser powers.

Previous works from Kawata et al demonstrated the efficient guiding of micrometer and sub-micrometer dielectric beads both at a glass/air interface illuminated under total internal reflection[9] and on top of a waveguide.[10] This configuration has been modeled using different formalisms.[11, 12] Also the optical potential exerted on dielectric and metallic beads by a totally reflected beam has been quantitatively measured.[13–15]

Radiation forces from an asymmetric illumination by an extended and homogeneous collimated beam result in guiding along the incident in-plane wave vector. Trapping requires an additional confinement in the surface plane. The in-plane confinement can be achieved both by patterning[16] or focusing the incident beam.[17]

In this work we are interested in studying theoretically the optical forces on Rayleigh dielectric particles when illuminated by a 3-D gaussian beam totally reflected at an interface. In particular, we investigate the different trapping regimes that can be observed depending of the particle specifications and the illumination parameters. For this purpose, we compared two models, the dipolar approximation and the Green dyadic formalism and comment on the requirement of accounting for the multipolar effects and multi-reflection with the surface.

In the first section, the optical forces on a Rayleigh dielectric bead induced by an extended evanescent illumination are computed with both the dipole model and the Green dyadic formalism. The second section discusses the ability to trap of a totally reflected 3D gaussian beam with a micrometer beam waist.

Send correspondence to Romain Quidant
E-mail: romain.quidant@icfo.es

2. GREEN DYADIC FORMALISM VERSUS DIPOLAR APPROXIMATION

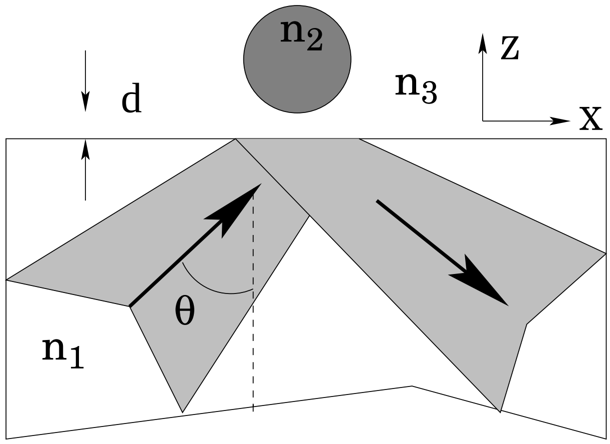

Figure 1. Geometry of the system.

2.1. Dipolar approximation

When considering small particles with sizes much smaller than the incident wavelength, their behavior in an optical potential is well described by the dipolar approximation. The u component of the electromagnetic force experienced by a dipole $p(\mathbf{r_0}, \omega)$ located at $\mathbf{r_0}$ can be written:

$$F_u(\mathbf{r_0}) = (1/2)\Re \sum_{v=1}^{3} p_v(\mathbf{r_0}, \omega) \frac{\partial E_v^*(\mathbf{r_0}, \omega)}{\partial u}$$

where u and v stand for the cartesian components x, y and z. In these expressions the electrical field is given by the incidence at $\mathbf{r_0}$ and consequently does not account for the influence of the particles and especially the multiple reflections between the particle and the interface. This approximation has shown to be valid provided the particle size does not exceed a third of the incident wavelength and is located at a larger distance from the surface than the particle radius.[11]

The total radiation force exerted on a dipole can be expressed as the sum of two contributions: the scattering force along the illumination direction induced by the change in the Poynting vector and the gradient force resulting from the optical field gradient.

2.2. Green dyadic formalism

For particles that cannot be described under the dipolar approximation, a more complex model that accounts for the multipolar character of the sphere and its interaction with the surface is required. The model we use is based on the Green dyadic formalism or coupled dipole method.[18, 19] In this procedure, the particle is meshed in N small polarizable cubic subunits. The electric field $\mathbf{E}(\mathbf{r}, \omega)$ at each subunit is calculated from:

$$\mathbf{E}(\mathbf{r}, \omega) = \mathbf{E_0}(\mathbf{r}, \omega) + \sum_{j=1}^{N} [\mathbf{G_0}(\mathbf{r}, \mathbf{r}_j, \omega) + \mathbf{G_S}(\mathbf{r}, \mathbf{r}_j, \omega)] \alpha_j(\omega) \mathbf{E}(\mathbf{r}_j, \omega)$$

where $\mathbf{G_0}(\mathbf{r}, \mathbf{r}_j, \omega)$ and $\mathbf{G_S}(\mathbf{r}, \mathbf{r}_j, \omega)$ account respectively for the linear response to a dipole in free space and its correction introduced by the presence of the surface under the quasi-static approximation. $\alpha_j(\omega)$, the polarizability of the subunit j, is expressed as:

$$\alpha_j(\omega) = \alpha_j^0(\omega) / [1 - (2/3) i k_0^3 \alpha_j^0(\omega)]$$

where $k_0 = \omega/c$ stands for the modulus of the incident wave vector of the electromagnetic field in vacuum and $\alpha_j^0(\omega)$ is given by the Clausius-Mossotti relation:

$$\alpha_j^0(\omega) = \frac{3d^3 \varepsilon(\omega) - 1}{4\pi\varepsilon(\omega) + 2}$$

Once the electric field is obtained, the component of the total averaged force exerted on the j can be deduced from the both the field and it derivative at position $\mathbf{r}_j$:

$$F_u(\mathbf{r_j}) = (1/2)\Re \sum_{v=1}^{3} p_v(\mathbf{r_j}, \omega) \frac{\partial E_v^*(\mathbf{r_j}, \omega)}{\partial u}$$

Then the total force on the particle $\mathbf{F}$ is obtained by summing on the N subunits.

$$\mathbf{F} = \sum_{j=1}^{N} \mathbf{F}(\mathbf{r_j})$$

3. ELECTROMAGNETIC FORCES INDUCED BY AN EXTENDED EVANESCENT FIELD

In this first part of results, a direct comparison of the dipolar approach and the Green dyadic method is presented in the simple case of an extended and homogeneous evanescent illumination from the total reflection of a linearly polarized plane wave. The validity of the dipolar approximation is discussed as a function of the particle parameters. In all the following, we consider a heavy flint glass substrate ($n_3 = 1,78$). The dielectric sphere

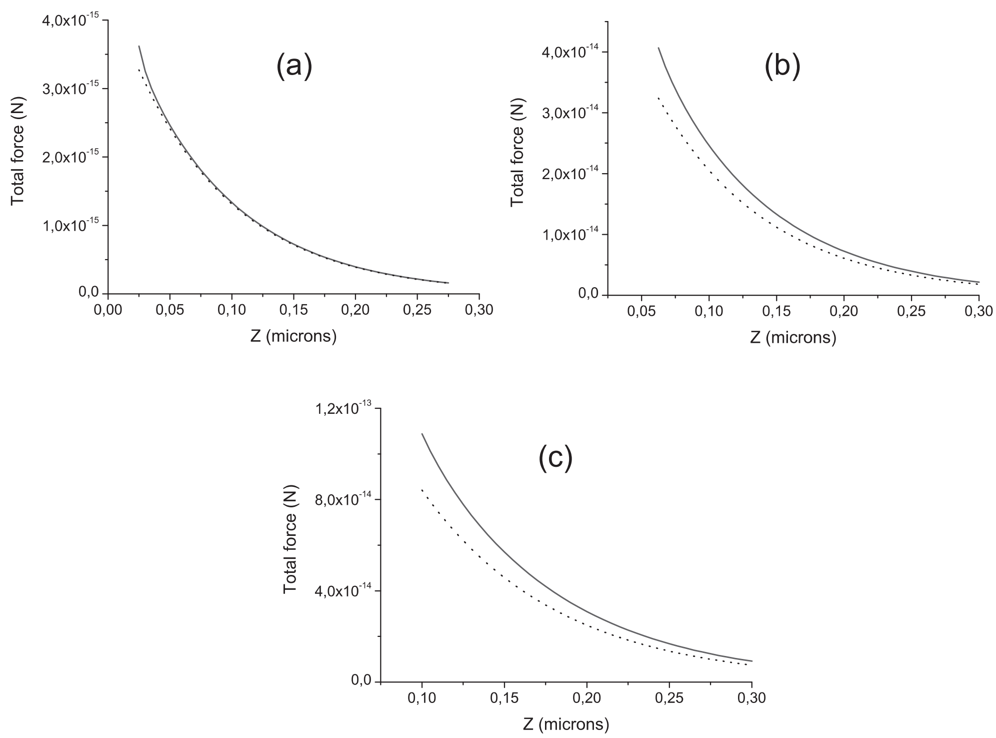

Figure 2. Z-dependence of the total force for different particle radius: (a) 25 nm, (b) 62.5 nm and (c) 100 nm. The full line corresponds to the Green dyadic method and the dashed line to the dipole approximation.

with radius a and refraction index n_2 is immersed in water ($n_3 = 1.33$) as shown in figure 1.

In figure 2 the z-dependence of the total force exerted on a dielectric sphere ($n_2 = 1.5$) is plotted for different radius values. The illumination is performed for p-polarized plane wave at 840 nm and under an incidence $\theta = 80^o$. For radius much smaller than the incident wavelength, $a = 25$ nm, the force is very well restituted by the dipolar approximation. Only a weak mismatch is observed when the particle gets very close from the interface. The disagreement with the Green dyadic method increases with increasing radius a but stays smaller than 15% even for $a = 100$ nm.

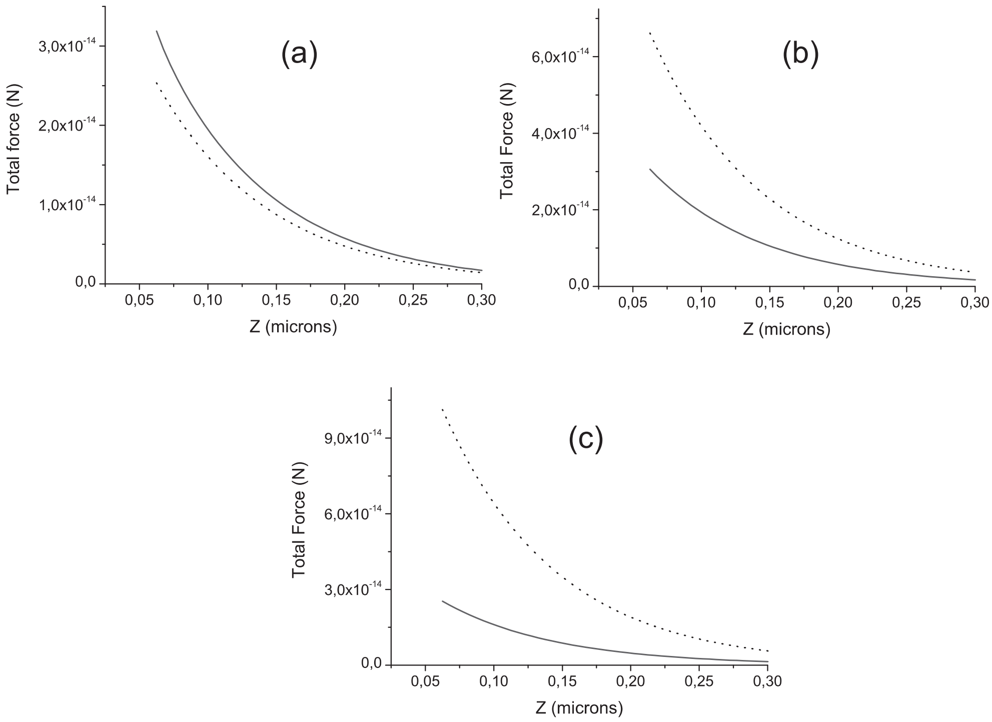

Figure 3. Z-dependence of the total force for different refraction indexes of a 62.5 nm radius sphere: (a) $n_2 = 1.5$, (b) $n_2 = 1.8$ and (c) $n_2 = 2.1$. The full line corresponds to the Green dyadic method and the dashed line to the dipole approximation.

The calculations are repeated at a fixed radius, $a = 65$ nm for increasing values of the refraction index of the sphere n_2. When increasing the dielectric contrast between the sphere and water, the validity of the dipole approximation quickly degrades as can be seen in figure 3. This effect is mainly attributed to the increase of multiple scattering with the plane interface that is not considered in the dipole model (see figure 4). The multiple reflection of the field scattered by the particle in the small particle-surface gap induces a local field that tends to reduce the force amplitude.[20]

4. TRAPPING REGIMES IN A TOTALLY REFLECTED GAUSSIAN BEAM

Results from the previous section have permitted to validate our model for an accurate calculation of the optical forces exerted on a small dielectric particle close from an interface. In this section, we investigate with the Green Dyadic model the trapping ability of a local evanescent illumination from the total reflection of a 3-D gaussian beam. As mentioned in the introduction, an asymmetrical extended evanescent illumination would guide the particle along the interface but does not allow for its trapping. Immobilizing it requires an additional confinement in the surface plane. In the case of a confined beam the ability for trapping depends on the respective contribution of the scattering and gradient forces.

Instead of the homogeneous plane wave considered in the previous section, the illumination is now performed by a 3-D gaussian beam with a micrometer beam waist. By changing the illumination parameters (waist and the

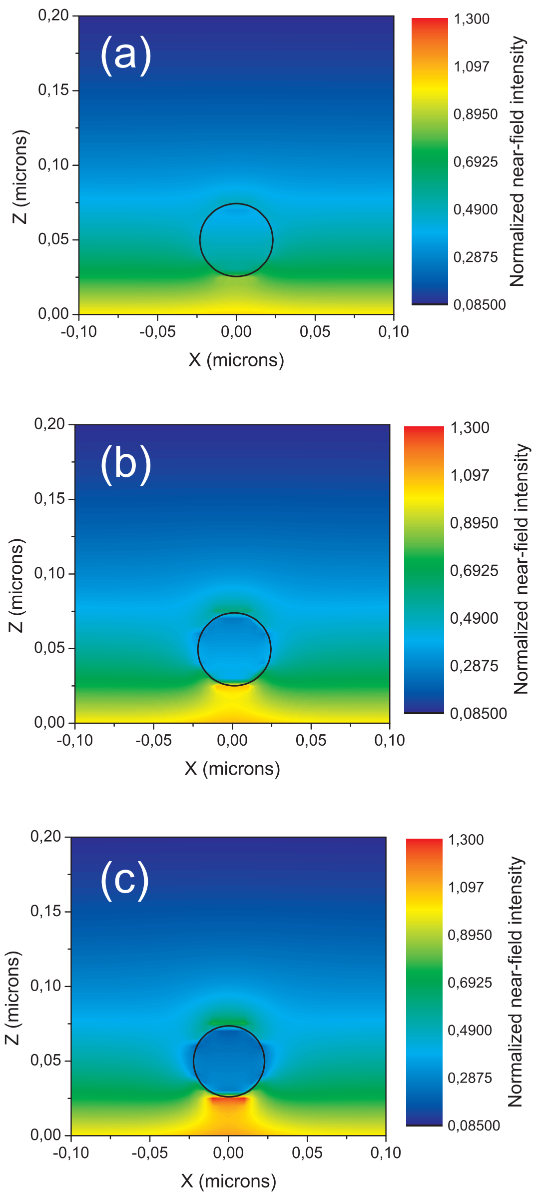

Figure 4. Distribution of the near-field intensity in the $x - z$ plane for a particle of 25 nm radius and for three different refraction indexes (a) $n_2 = 1.5$, (b) $n_2 = 1.8$ and (c) $n_2 = 2.1$

incidence angle) and the particle parameters (radius, refraction index), the ratio between the different components of the forces is modified and distinct trapping regimes are found.

Figure 5.a shows the near-field map associated to the total reflection at the glass/water interface ($\theta = 50^o$) of a gaussian beam with $2\mu m$ waist, centered at the origin of coordinates. The asymmetry of the evanescent field with regards to the center results from the Goos-Hänchen shift.

In figure 5, the vector force is plotted for three different configurations. In the first one 5.b, the gradient forces dominates the scattering force and the sphere is maintained trapped by the beam. The trap position is shifted from the center and corresponds approximatively to the maximum of field intensity in figure 5.a. For a bigger sphere with $a = 40nm$, the magnitude of the scattering force gets closer from the one of the gradient force resulting in an unstable trapping regime (figure 5.c). Finally, for this last particle, a change of incidence from

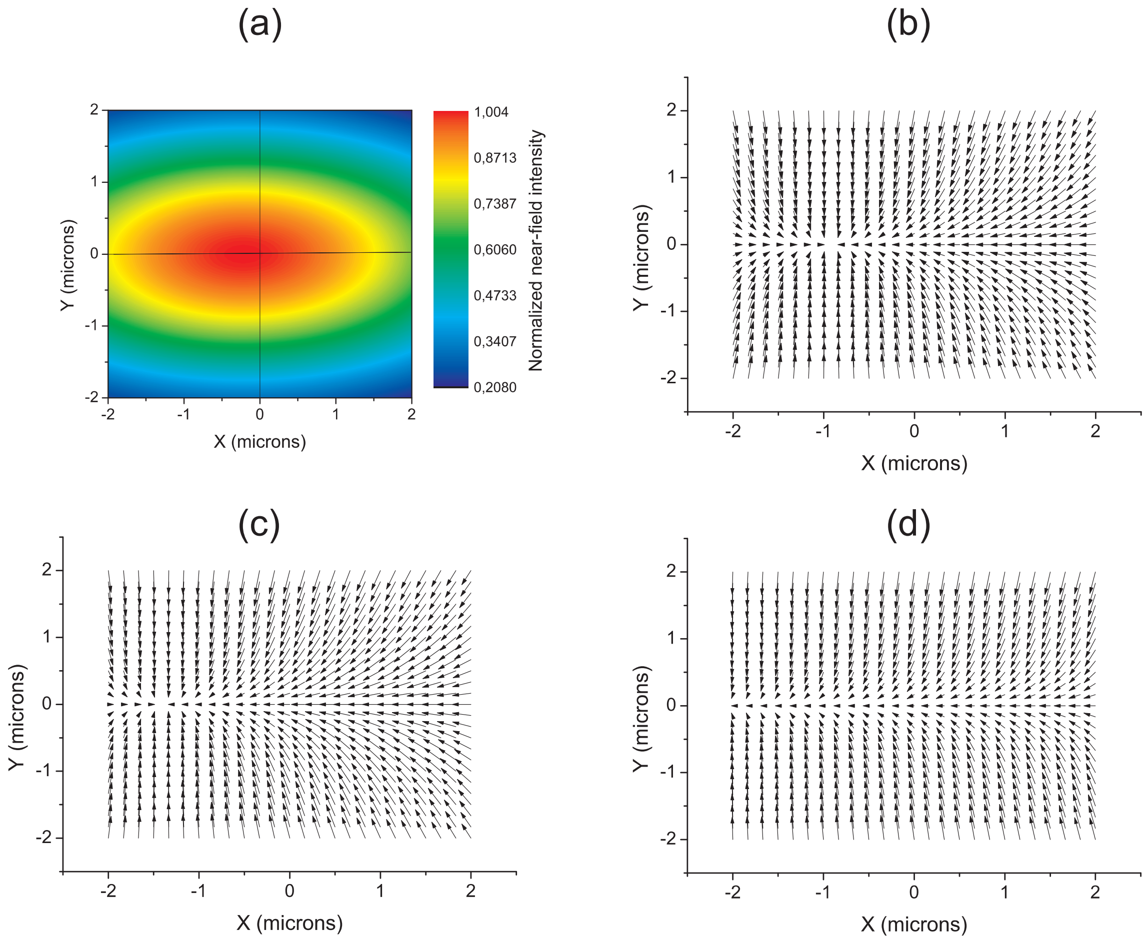

Figure 5. (a) Distribution of the near-field intensity above a totally reflected ($\theta = 50^o$) gaussian beam with waist 2μ. (b-d) Map of the vector force for: (b) $a = 25\ nm$, $\lambda = 840\ nm$ and $\theta = 50^o$, (c) $a = 40\ nm$, $\lambda = 840\ nm$ and $\theta = 50^o$ and (c) $a = 40\ nm$, $\lambda = 840\ nm$ and $\theta = 70^o$

$\theta = 50^o$ to $\theta = 70^o$ is enough to loose the trap (figure 5.d). In this case, the small sphere is guided parallel to the interface and push away from the illumination beam.

Acknowledgments

This research has been carried out in the framework of ESF/PESC (Eurocores on Sons), through grant 02-PE-SONS-063-NOMSAN, with the financial support of the Spanish Ministry of Science and by the European Commission through grant ATOM3D FP6-508952.

REFERENCES

1. S. M. Block, "Optical tweezers as a tool to study cells and biomolecules", Science **13**, 258 (1992)
2. S. Bergamini, B. Darqui, M. Jones, L. Jacubowiez, A. Browaeys and P. Grangier, "Holographic generation of microtrap arrays for single atoms by use of a programmable phase modulator", JOSA B **21**, 1889 (2004)
3. A. Ashkin, "Acceleration and trapping of particles by radiation pressure", Phys. Rev. Lett. 24, 156 (1970)
4. D. G. Grier, "A revolution in optical manipulation", Nature 424, 810 (2003)
5. L. Novotny, R. X. Bian and X. S. Xie, "Theory of nanometric optical tweezers", Phys. Rev. Lett. **79**, 645 (1997)
6. P. Chaumet, A. Rahmani and M. Nieto-Vesperinas, Phys. Rev. Lett. **88**, 123601 (2002)

7. K. Okamoto and S. Kawata, "Radiation Force Exerted on Subwavelength Particles near a Nanoaperture", Phys. Rev. Lett. **83**, 4534 (1999)
8. R. Quidant, G. Badenes, S. Cheylan, R. Alcubilla, J-C. Weeber and Ch. Girard, "Subwavelength patterning of the optical near-field", Optics Express **12**, 282 (2004)
9. S. Kawata and T. Suguira, "Movement of micrometer-sized particles in the evanescent field of a laser beam", Opt. Lett. **17**, 772 (1992)
10. S. Kawata and T. Tani, "Optically driven Mie particles in an evanescent field along a channeled waveguide", Optics Lett. **21**, 1768 (1996)
11. M. Nieto-Vesperinas, P. Chaumet and A. Rahmani, "Near-field photonic forces", Phil. Trans. R. Soc. Lond. (A) **362**, 719 (2004)
12. E. Almaas and I. Brevik, "Radiation forces on a micrometer-sized sphere in a evanescent field", JOSA B **12** 2429 (1995)
13. K. Sasaky, M. Tsukima and H. Masuhara, Appl. Phys. Lett. **71**, 37 (1997)
14. K. Wada, K. Sasaki and H. Masuhara, "Three-dimensional potential of radiation pressure exerted on a single microparticle", Appl. Phys. Lett. **76**, 2815 (2000)
15. K. Sasaki, J. Hotta, K. Wada and H. Masuhara, "Analysis of radiation pressure exerted on a metallic particle within an evanescent field", Optics Lett. **25**, 1385 (2000)
16. V. Garcés-Chávez, K. Dholakia and G. C. Spalding, "Extended-area optically induced organization of microparticles on a surface", Appl. Phys. Lett. **86** 031106 (2005)
17. M. Gu, J. B. Haumonte, Y. Micheau, J. W. M. Chon and X. Gan, "Laser trapping and manipulation under focused evanescent wave illumination", Appl. Phys. Lett. **84**, 4236 (2004)
18. P. C. Chaumet and M. Nieto-Vesperinas, "Coupled dipole method determination of the electromagnetic force on a particle over a flat dielectric surface", Phys. Rev. B. **61** 14119 (2000)
19. C. Girard, A. Dereux, O. J. F. Martin and M. Devel, "Generation of optical standing waves around mesoscopic surface structures: scattering and light confinement", Phys. Rev. B. **52**, 2889 (1995)
20. J. R. Arias-González, M. Nieto-Vesperinas, "Optical forces on small particles: attractive and repulsive nature and plasmon resonance conditions", JOSA A **20**, 1201 (2003)