Optical manipulations via auxiliary substrates

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Abstract. We report flexible optomechanical manipulations by the help of surface and volumetric modes of the substrate. Optical binding effect can be sufficiently enhanced due to both surface plasmon-polariton and hyperbolic modes of the structure. Volumetric modes of the structure provide optical pulling force for inclined incident plane wave, while surface waves cause enhancement of the optical trapping force under Gaussian beam illumination. Moreover, antitrapping effect can occur for specific positions of the beam waist.

1. Introduction
Light-matter interaction is of particular interest of modern physics. It may be related with constant spreading of nanotechnologies and ever-increasing demand to control over small particles’ positions and dynamics [1-4]. Through the last decades a lot of configurations were proposed to increase the flexibility of optical manipulations. It became possible to achieve trapping of several nanoparticles [5-7], optical pulling forces [8] and increased characteristics of the optical traps via auxiliary structures [9-12], particles’ parameters or incident field modification [13]. The most straightforward way to change characteristics of the optical trapping is utilizing of the beams with predefined shape, for example, Gaussian, Bessel or Airy beam traps [14]. Moreover, the optical field can be transformed by the help of asymmetric structures [15, 16], photonic crystals [17], TIR geometries [18], metamaterials [19], metasurfaces [20] or even plasmonic materials as a substrate [12, 21, 22]. Using metallic particles is another common approach to get peculiar optical forces [23], however it is not the case, e.g., in biochemical research.

Here, we report optical manipulations of dielectric nanoparticles with auxiliary substrates supporting evanescent waves. By the help of surface modes of the substrates it is possible to obtain optical pulling forces, not only trapping but antitrapping effect in Gaussian beam, enhance characteristics of optical binding forces between several particles, while volumetric modes can also provide optical pulling force or enhance stiffness of the optical trap. These effects take place due to the additional degrees of freedom provided by the properties of substrate media.

2. Optical forces near interface
Let us consider dielectric nanoparticle placed in vicinity of the substrate under an illumination. Dielectric permittivity of the particle is considered to be $\varepsilon = 3$ and radius $R = 15$ nm. The scheme of
the problem is shown in figure 1. The second particle is shown to be translucent as long as it presents only for the case of optical binding of two particles.

![Figure 1](image)

**Figure 1.** The scheme of the problem. The particle above the substrate is illuminated by a plane wave or a Gaussian beam. Semitransparent particle illustrates another case of optical binding of the several particles illuminated by a plane wave. Evanescent waves from the particles are the cause of volumetric and surface modes of the substrate.

The optical force acting on a particle can be written as

$$F = \frac{1}{2} \operatorname{Re} \sum_{i=x,y,z} p_i \nabla E_i,$$

where $p$ is dipolar moment and $E$ is electric field in the location of a particle, $r$ defines position of a particle. One should take into account that electric field is also included into expression for $p$ and contains information about the whole structure such as reflection from the boundary, interactions of the several particles, etc. Green’s function approach allows us to derive total electric field expression of the complex structure.

3. Results and discussion

As was shown in [22], plasmon-polariton excitation on the surface could lead to the optical pulling force exerted on a single particle near the substrate, if inclined incidence of the plane wave takes place. However, we state, that for Gaussian beam oblique incidence is not required. By varying focus position with respect to the interface one can easily tune dipole moment orientation, and, therefore, sign of the optical force. In these cases, surface waves are in charge of the optical trapping enhancement for the focus position above the interface, and appearance of the antitrapping effect for the focus position below the interface. In addition, if two dipolar particles interact under a normal incident plane wave illumination, the interference of the surface plasmon-polariton modes provides formation of a stable bound dimer with interparticle distances smaller than the wavelength. As each of the particles occupy
positions at the maximums of the interference pattern, the distance between the dipoles is defined by the surface plasmon-polariton dispersion relation.

Furthermore, flexible optomechanical manipulation can be achieved by the help of volumetric modes of a hyperbolic metamaterial substrate. In this case inclined incidence of the plane wave creates the asymmetric hyperbolic modes excitation and optical pulling force is obtained. In similar way Gaussian beam excitation can provide antitrapping effect and enhancement of the optical binding force.

Thus, utilizing auxiliary substrates is a powerful tool for optomechanical manipulation of a single object and several nanoparticles. Surface and volumetric modes of a substrate lead to the enhancement and unusual properties of the optical forces.

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