Optical binding near plasmonic substrates

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Abstract. In this work we consider optical binding of two dipolar nanoparticles near plasmonic substrates, that introduces additional degree of freedom into the system and allows precise and versatile control over the particles’ position. It is shown, that surface modes allow to overcome diffraction limit and increase stiffness of optical trapping by an order of magnitude.

1. Introduction
Through the last decades optical forces attracted a significant interest due to their applicability in biological, chemical and optoelectronical research. For ensembles of particles optical forces can lead to an optical binding effect [1], that is self-organization of the particles caused by light rescattering. One of the most important optical binding characteristics are locations of stable positions of the particles and stiffness of the optical trap. Usually, precision of the particles’ positioning is restricted by incident light wavelength and is hard to vary. Also, for stable trapping one needs to improve trap stiffness what requires high intensity of incident field. It was shown earlier, that the presence of a substrate with surface [2] or volumetric modes [3] affects drastically optical force on a single particle, and helps to improve trapping, or, for certain conditions, obtain anti-trapping effects [4].

2. Calculation of the optical binding force near the substrate
In this work we investigate the simplest case of two dipolar nanoparticles placed above the substrate and illuminated by a plane wave, figure 1.

![Figure 1. The scheme of the structure. Plane wave is polarized along x direction and incident along z. Origin of the coordinates coincides with the first particle’s position, and the second has coordinates (x, y, z). Dielectric permittivity of the particles ε =3, radius R=15 nm.](image)
The force acting on a small particle is described as follows:

$$ F = \frac{1}{2} \sum_i \text{Re}(p_i^* \nabla E_{i\text{loc}}^i), $$

where $p_i$ is the $i^{th}$ component of particle induced dipole moment, and $E_{i\text{loc}}^i$ corresponds to the local field at the location of the particle, $i=x,y,z$.

General expression for local field at the location of one of the nanoparticles is obtained by using Green’s function formalism:

$$ E_2 = E_0 + \frac{k^2}{\varepsilon_1 \varepsilon_0} G_1 p_1 + \frac{k^2}{\varepsilon_1 \varepsilon_0} G_2 p_2. $$

Here, $p_1$, $p_2$ are induced dipole moments for the first and second nanoparticles correspondingly, $E_0$ is incident field with wave vector $k$, and $\varepsilon_0$, $\varepsilon_1$ is vacuum permittivity and permittivity of the upper half-space. Green's functions $G_1$, $G_2$ for the first and second dipoles consist of the free space binding contribution, self-induced contribution through the substrate and multiple rescattering by the particles through the substrate.

3. Enhancement of optical binding

Figure 2 illustrates that surface plasmon polariton at the metal-dielectric interface enhances optical force by an order of magnitude in comparison with homogenous space. The distance between equilibrium positions of the particles can become smaller than diffraction limit due to dispersion relation of the plasmon. For example, the first equilibrium position at the substrate is around 140 nm, but it is approximately 400 nm for optical binding in a free space.

![Figure 2](image)

**Figure 2.** The optical binding force dependence on the distance between two dipoles. Blue line corresponds to the interaction in a free space, and red line in vicinity of the plasmonic substrate (silver with permittivity $\varepsilon_s=-1.75+0.3i$). For convenience the value for free space binding is multiplied by 10. The incident light wavelength is 350 nm.

Thus, in this work we analyze optical binding near to plasmonic substrates. It is shown that surface plasmon polariton interference plays crucial role in the interaction of nanoparticles. We demonstrate that two nanoparticles placed near metallic interface can be stably bounded at distances defined by surface plasmon polariton. While the classical diffraction limit prevents achieving deeply subwavelength arrangements, auxiliary nanostructures enable tailoring optical forces via additional interaction channels. In addition, the enhancement by one order of magnitude of the optical binding force is possible owing to the resonant surface plasmon polariton excitation. Moreover, stable configurations are formed along incident light polarization direction, while for binding in free space
they are mutually perpendicular. That makes possible control over a nanoparticle trajectory on subwavelength scales and opens opportunities for optical-induced organization of particles on a plasmonic substrate with different periods along the field polarization as well as perpendicular to it.

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References
[1] M. I. Petrov, S. V. Sukhov, A. A. Bogdanov, A. S. Shalin, A. Dogariu 2016, Laser Photonics Rev., 10, 116–122
[2] K. Dholakia, P. Zemánek 2010, Reviews of modern physics 82, 2, 1767.
[3] O. Kidwai, S. V. Zhukovsky, J. E. Sipe 2012, Physical Review A, 85, 053842
[4] A. Ivinskaya, M. I. Petrov, A. A. Bogdanov, I. Shishkin, P. Ginzburg, A. S. Shalin, 2017, Light: Science & Applications, 6(5), e16258.