Optical binding near hyperbolic metamaterial substrates

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Abstract. We study optical binding of two dielectric nanoparticles near a boundary between air and hyperbolic metamaterial. Three kinds of modes contribution are analyzed and it is shown, that evanescent waves allow formation of stable bound dimer due to hyperbolic metamaterial modes. We have found the most profitable parameters of hyperbolic metamaterial substrate, providing enhancement of the optical binding effect.

1. Introduction
Mesoscale particles under an illumination can form stable arrays by occupying equilibrium positions. Varying the stiffness of such an optical trap and the distances between the particles allows creating the nanostructures with subwavelength period and is of great interest to physical, biological and chemical research [1, 2].

The optical binding effect can be understood as particles self-organization caused by incident illumination scattering and forming an interference pattern. Each of the particles tends to occupy position with zero optical force acting on it in high-intensity region of this pattern. The distance between the particles is usually defined by the incident wavelength and limited by the diffraction limit. There are several ways to improve characteristics of the optical manipulation, trapping and binding, including plasmonic materials employment [3-7], using several beams trap [8], evanescent fields [9] and auxiliary nanostructures and metamaterials [10-13].

Here we investigate optical binding of two nanoparticles near hyperbolic metamaterial. Evanescent waves from the particle in a free space are converted to propagating modes inside the substrate, because of hyperbolic metamaterial dispersion relation [14]. Utilizing Green’s function approach, it is possible to estimate hyperbolic modes contribution into optical binding force and tune parameters of the substrate to enhance contribution of the evanescent waves [15, 16].

2. Optical force calculation
We study a pair of dielectric nanoparticles under a plane wave illumination. The wave is incident along z and polarized along x-axis. Dipoles are placed on top of the hyperbolic metamaterial substrate with dielectric permittivity in the form of a tensor
In materials of such kind dispersion relation can be written as \( \left( \frac{\omega}{c} \right)^2 = \frac{k_x^2}{\varepsilon_{xx}} + \frac{k_z^2}{\varepsilon_{zz}} \), where \( k_x \) and \( k_z \) denote wavevector components, and \( \omega \) is the frequency of the wave, \( c \) is speed of light in vacuum.

The time-averaged optical force exerted on a dipolar particle can be expressed as [17]

\[
\bar{F} = \frac{1}{2} \Re \sum_i \alpha(\omega) E_i^* (\vec{r}, \omega) \nabla E_i (\vec{r}, \omega),
\]

where \( E_i \) corresponds to the \( i^{th} \) component of the electric field, \( i = x, y, z \), \( \vec{r} \) denotes location of the particle, and \( \alpha(\omega) \) is a dipole polarizability in vacuum

\[
\alpha = \frac{\alpha_{es}}{1 - i \frac{k_0^3}{6\pi\varepsilon_0} \alpha_{es}}; \quad \alpha_{es} = 4\pi\varepsilon_0 R^3 \frac{\varepsilon - \varepsilon_1}{\varepsilon + 2\varepsilon_1},
\]

\( \varepsilon_0 \) is vacuum permittivity, \( \varepsilon, \varepsilon_1 \) is permittivity of the particle and the upper half-space, respectively.

Expression for the electric field should take into account interaction of the two dipoles and contribution of the substrate, thereby it is given by the equation

\[
\vec{E}(\vec{r}, \omega) = \frac{\omega^2}{c^2 \varepsilon_0} \vec{G}(\vec{r}, \vec{r}') \vec{p}
\]

Here \( \vec{G}(\vec{r}, \vec{r}') \) is a Green’s function, that field in \( \vec{r} \) from the source placed in \( \vec{r}' \), \( \vec{p} \) is electric dipole moment. Green’s function can be decomposed into three parts, describing modes propagating in free space, evanescent modes, i.e. surface plasmon-polariton (SPP) and volumetric (hyperbolic) modes of the substrate.

Figure 1. The scheme of the problem. Two dipoles are placed in vicinity of hyperbolic metamaterial substrate and illuminated by a plane wave. Dielectric permittivity of the particles is \( \varepsilon = 3 \) and radius is \( R = 15 \text{ nm} \). \( \varepsilon_{xx} \) and \( \varepsilon_{zz} \) are transversal and longitudinal components of the dielectric permittivity of the substrate.

The time-averaged optical force exerted on a dipolar particle can be expressed as [17]
3. Results and discussion
Let us consider optical binding force exerted on one of the dipoles as a coordinate dependent function. We use parameters of the substrate $\varepsilon_{xx} = -2 + 0.03i$, $\varepsilon_{zz} = 5 + 0.1i$ for which surface wave does not have predominant contribution. The optical binding force dependence is shown on the Figure 2. It is seen that evanescent modes of the semi-infinite hyperbolic metamaterial substrate increase optical binding force by ten times and decrease distance between the bound particles. We should note, that surface plasmon-polariton and hyperbolic modes are excited due to incident field scattering on a dipolar nanoparticle and do not require auxiliary structures.

Figure 2. Transversal optical binding force component dependence on the distance between the particles. Blue and red lines correspond to the optical binding near semi-infinite substrate, without evanescent wave contribution and with all kinds of modes contributions, respectively. The distance between the particles is normalized over incident wavelength $\lambda_0$ and $F_x$ is normalized over radiation pressure force $F_0$.

In conclusion, we have studied optical binding near hyperbolic metamaterial substrate. It is shown, that evanescent waves of this system can significantly enhance characteristics of particles’ interaction and parameters of the substrate can be tuned in order to provide further improvement.

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