Tractor beams at metamaterial substrates

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Abstract. Optical forces acting on nanoobjects can be enhanced, inverted or cancelled out by
the presence of carefully chosen environment. Here we consider metamaterial substrate which
can modify optical forces through the excitation of surface waves and volumetric hyperbolic
modes. Both types of interaction channels will be discussed in the present work where we
show new effect of pulling forces on subwavelength dielectric particles above multilayer
hyperbolic substrates.

1. Introduction

A special class of metamaterials - hyperbolic metamaterials - can support both volumetric modes
and surface waves and are especially interesting for optomechanical applications. Hyperbolic
metamaterials based on vertically aligned metal nanorods were assessed as a platform for flexible
optomechanical manipulation [1], [2]. While a set of peculiar effects including tractor beams were
predicted by employing homogenization approach [1], consideration of near-field interactions within
actual unit cells of the nanorod arrays require more detailed numerical analysis [2].

In this work we focus on metamaterial multilayer substrates for optomechanical applications. For a
particular substrate, surface waves, being the key for effects such as tractor beam [3], anti-trapping in
Gaussian beam [4], anisotropic binding [5], have many in common if certain peculiarities in the
excitation process and interaction mechanism are omitted. Leaving out these differences and
concentrating on the main features, we study a basic setup exceptionally sensitive to surface waves
and modes in the structure, that is a particle over the metamaterial substrate illuminated by a plane
wave.

2. Formalism

The force on a dipole particle with polarizability \( \alpha \) near semi-infinite substrate, Fig. 1, can be written as [6]

\[
F_x = \frac{1}{2} \text{Re}(\alpha E_0^\text{tot} \hat{\nabla}_x G_x^0) + \left| \alpha \right|^2 \nu_0 \text{Im}(E_z^\text{tot} G_x^0) \text{Im}(\hat{\nabla}_x G_x^0),
\]

(1)
where $E^m$ is a local field at the particle location, $E^0$ is incident field, $G$ is Green’s function. Green’s function defines structure response to incident field and enters both expression for total field $E^{tot}$ and the force $\mathbf{F}$.

\begin{equation}
\partial_x G_{xz} = \frac{1}{8\pi k_1^2} \int_0^\infty r e^{-2ik_0z} \, dk_0
\end{equation}

Hyperbolic materials can support both surface and bulk waves. Volumetric waves with hyperbolic dispersion have non-resonant features, whereas existence of surface modes can be identified via observation of poles in the reflection coefficient. Those coefficients for the case of the uniaxial crystal with an optical axis, pointing perpendicular to the interface, ($\varepsilon_x, \varepsilon_z$ are permittivities along main axes) are given by

\begin{align}
  r_s &= \frac{\varepsilon_x k_{1z} - \varepsilon_z k_{2z}}{\varepsilon_x k_{1z} + \varepsilon_z k_{2z}}, \\
  k_{2z}^s &= \left(\varepsilon_x k_0^2 - \varepsilon_z^2 k_{z}^2 \right)^{0.5}, \\
  k_{1z} &= \left(\varepsilon_x k_0^2 - k_{\rho}^2 \right)^{0.5},
\end{align}

where $k_0$ is a wave vector of incident radiation in vacuum, $\varepsilon_i$ and $k_i = \sqrt{\varepsilon_i k_0}$ are the permittivity and the wave vector in the upper half-space (air is considered hereafter) with components $k_x$, $k_y$, $k_z$ and $k_{\rho} = (k_x^2 + k_y^2)^{0.5}$ is a transversal wave vector. The branch of the square root solution in Eq. (2) should be chosen with an imaginary part of $k_{2z}^s$ (wave vector in the substrate) positively defined for a wave to decay away from the interface. At the same time for idealized lossless hyperbolic materials, having different signs of permittivities along the two main axes and of the crystal $\varepsilon_x', \varepsilon_z'$, wave vector $k_{2z}^s$ acquires real part for $k_{\rho} = k_{\rho} \geq k_i$. It implies that at this condition evanescent waves scattered by the particle transforms into propagating volume modes inside the hyperbolic substrate.

3. **Multilayer substrates for negative transversal force**

For a setup with a particle over substrate excited by a plane wave, we start by overview of arbitrary uniaxial anisotropic substrates to identify dielectric parameters when strong response of optical forces takes place compared to free space. While certain types of dielectric permittivity tensors are hardly
accessible, hyperbolic materials are very promising and are given by feasible multilayer geometries. Metal-dielectric multilayers are studied to find suitable geometric configurations. For hyperbolic isotropic and multilayered materials an emphasis is made on the difference in optical forces caused by surface waves and volumetric modes in such structures. Figure 2 shows that surface and volume modes in substrates with hyperbolic dispersion can lead to pulling forces over a broad wavelength range.

The material composition of the first layer (either metal or dielectric) of multilayer substrate has a crucial impact on the pulling force. This effect is solely related to the realization of the metamaterial and, of course, cannot be observed in the studies of the homogenized substrate. Those three different scenarios are considered hereafter. Fig. 2(a) demonstrates the value of the pulling force as the function of wavelength of the incident radiation (the silver filling factor is fixed at \( f_1 = 0.2 \)). The values of the force for the homogenized case typically lie in between those of multilayers with either dielectric (light blue lines) or metal (dark blue lines) top layer. If metal is set as an outer layer, maximum force amplification is achieved. At the longer wavelengths (infrared) regimes of metal or dielectric top layer can give an order of magnitude difference in force values. As expected, multilayers with smaller period (closely resembling the homogenized description) have broadband spectra while larger periods give sharper features.

![Figure 2. (a) Transversal force \( F_x \) acting on the particle, as the function of the wavelength. (b) Imaginary part of the reflection coefficient for semi-infinite Ag-polymer (n=1.05) multilayer composite as the function of the transverse wave vector. Dark (light) blue lines correspond to the case, when the top layer, interfacing the air, is metal (dielectric). Black line is obtained within the effective medium approximation. A set of multilayer periods is specified in the legend. Other parameters are: \( R = 15 \) nm, \( e = 3 \), \( z = 15 \) nm, the structure is illuminated by a plane wave, incident at 35°.](image)

4. Conclusions

The optical force acting on a nanoparticle near a planar substrate is governed by incident light and excitation of surface and volume modes of the substrate. Plane wave results in pulling forces towards the source for certain types of anisotropic substrates and multilayers. For multilayer substrate, top metal layer interfacing the air introduces additional enhancement of value of the pulling force.

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