Radiation pressure forces and Mie scattering resonances over stratified spherical particles with negative refractive index layers

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Abstract

We extend our previous analysis of optical forces over homogenous and lossless negative refractive index (NRI) spherical particles in order to include radiation pressure forces over stratified spherical particles with arbitrary-material layers, using the generalized Lorenz-Mie theory (GLMT) to observe the new resonance effects on the Mie scattering coefficients.

1. Introduction

We have recently shown the fundamental ideas of what we have called double-negative (DNG) optical trapping, consisting on optically manipulating negative refractive index (NRI) spherical nano- or micro-particles for biomedical optics purposes [1]. Lossless and simple particles have been considered and radiation pressure forces analysed for both Gaussian and Bessel beams [2-5], revealing interesting and intriguing trapping properties. Although our previous method was theoretically useful, real NRI metamaterials must follow some lossy model to account for causality [6]. Besides, some authors have recently proposed the use of plasmonic or metamaterial coatings for achieving transparency, anomalous plasmonic resonances or to minimize optical forces over electrically small particles [7,8]. In this way, it is desirable to have some insights into the problem of determining how optical forces would be affected by the introduction of realistic lossy NRI layers into multilayered spherical structures, not only to minimize scattered fields and optical forces, but to redirect or enhance them.

Following [1-5], we now show the first numerical results of DNG optical trapping for multilayered spherical particles composed of PRI and/or NRI layers, showing how optical forces behave under the influence of plane waves, Gaussian and Bessel beams, and how they are affected by the new resonance points in the Mie scattering coefficients (MSCs). We adopt the integral localized approximation (ILA) in the framework of the generalized Lorenz-Mie theory (GLMT) to describe the incident beam and to determine the MSCs for optical force and scattered field calculations [9].

2. New radiation pressure force profiles for NRI stratified particles

Consider an arbitrary laser beam impinging on a L-th layer spherical scatterer with MSCs given by

$$a_n^m = g_{n,TM}^m \left[\frac{\psi_n(M_L x_L) H_n(x_L) - N_L \psi_n'(M_L x_L)}{\xi_n(M_L x_L) H_n(x_L) - N_L \xi_n'(M_L x_L)} \right], \qquad b_n^m = g_{n,TE}^m \left[\frac{N_L \psi_n(M_L x_L) K_n(x_L) - \psi_n'(M_L x_L)}{N_L \xi_n(M_L x_L) K_n(x_L) - \xi_n'(M_L x_L)} \right], \tag{1}$$

where $1 \le n < \infty$, $-n \le m \le n$, ψ and ξ are Ricatti-Bessel functions, $g_{n,TM}^m$ and $g_{n,TE}^m$ the TM and TE beam-shape coefficients (BSCs) for the incident beam [4,9], respectively, N_L (M_L) is the relative characteristic impedance (relative wavenumber) between the external medium and the most external L-th layer of the scatterer, and K_n and H_n are functions which depends on the electromagnetic and geometric properties of the (L-1) internal layers. Radiation pressure forces are then calculated using the MSCs in (1) [4], where it is clear that the introduction of a NRI instead of PRI layer can radically alter resonances simply because of the changes of sign introduced in the denominators of the MSCs, which were then advantageously used for optical cloaking purposes with plane waves [7].

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Fig. 1 shows the radiation pressure cross-section $C_{pr,x}$ along x for a particular $+z$-propagating x-linearly polarized Gaussian beam (time factor $e^{i\omega t}$) with wavelength $\lambda = 1064$ nm and spot $s = 2\lambda$, along a host medium with refractive index $n_{ext} = 1.33$, for a 2-layer particle (centred at the origin of the system) with four different ratios between the outer radio a_{out} and λ. All plots reveal how distinct optical forces would be if the outmost lossless PRI layer were replaced by a lossless layer of NRI nature. New resonances occur in (1), especially noticed for $a_{out}/\lambda = 0.01$ and 0.1, pronouncing or smoothing both attractive (positive $C_{pr,x}$) and repulsive (negative $C_{pr,x}$) optical forces at specific n_p's. Similar considerations can be made from Fig. 2 for a zero-order Bessel beam with the same λ and polarization.

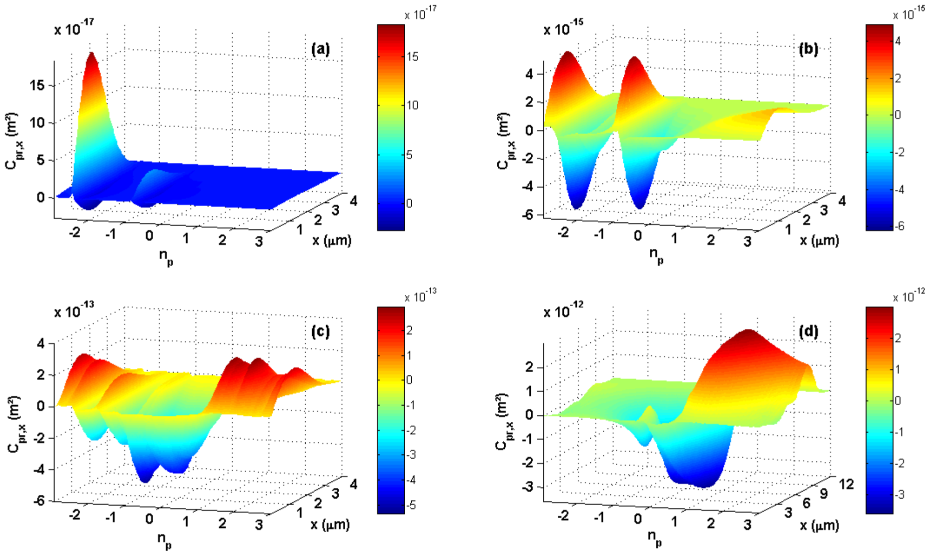

Fig. 1: $C_{pr,x}$ as function of the displacement x of the Gaussian beam and the refractive index n_p of the coating for a 2-layer sphere with a_{out}/λ = (a) 0.01, (b) 0.10, (c) 1.00 and (d) 10.0. The refractive index of the core is $n_c = 2$.

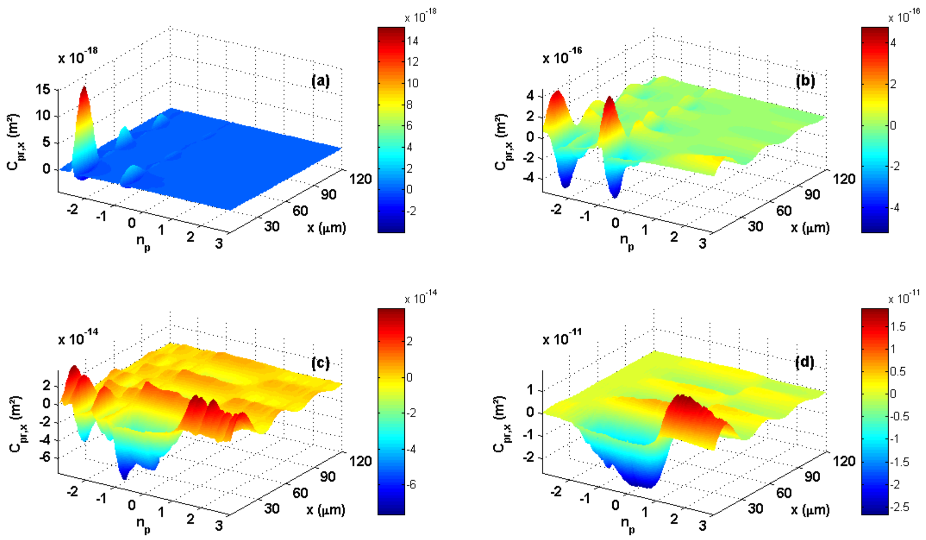

Fig. 2: The Gaussian beam is now replaced by a $+z$-propagating zero-order Bessel beam (BB) with an axicon angle $\theta_a = 0.0141$ rad (transverse spot $\Delta\rho = 28.89$ μm) and the same wavelength and polarization as before.

A lossy model can be implemented for the NRI layers to provide a more realistic picture of the two-layered particle, with crucial differences from the lossless case, as depicted in Fig. 3. L-layer particles ($L > 2$), optical torques, scattered and internal fields could also be investigated through the GLMT, and we intend to present some of these results during the conference, also emphasizing the resonant character of the Mie-scattering coefficients when weighted by the BSCs of particular laser beams.

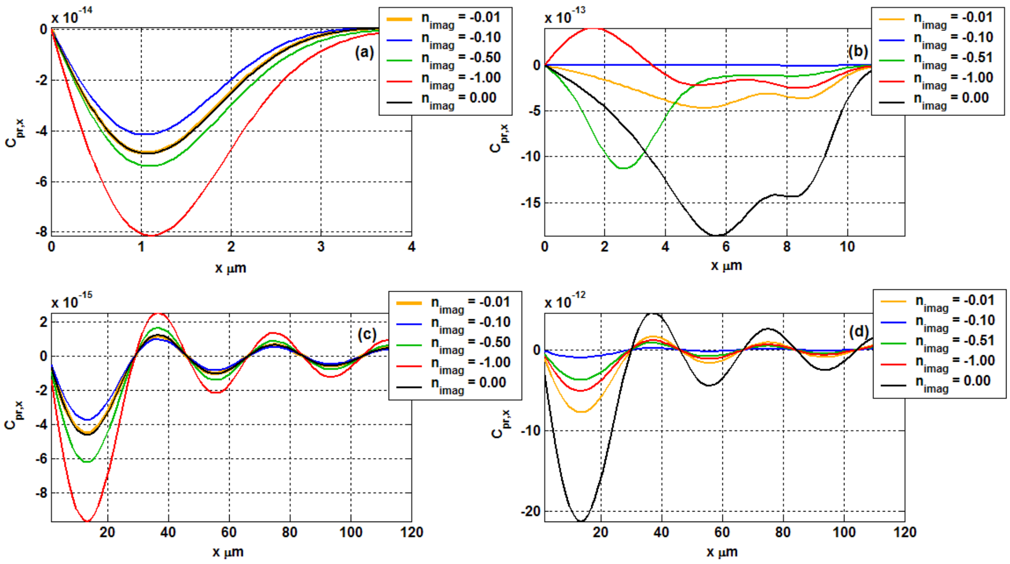

Fig. 3. (a) and (b) Gaussian beam of Fig. 1 showing the effects of losses introduced on the external layer for n_p = -1.98 (a_{out}/λ = 1) and n_p = -1.02 (a_{out}/λ = 10), respectively. (c) and (d) Same as before, but for the BB of Fig. 2.

3. Conclusions

New trapping properties can be expected for multilayered scatterers composed of NRI layers. These properties come mainly from the new values of the Mie scattering coefficients weighted by the beam-shape coefficients of some arbitrary beam when some or any of the PRI or plasmonic layers are replaced by these negative refractive index layers, thus opening new possibilities for applications in biomedical optics in the near future, especially in optical bistouries or optical trapping systems.

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