Numerical calculation and Cartesian multipole decomposition of optical pulling force acting on Si nanocube in visible region

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Abstract. The multipole decomposition of optical force and scattering cross-section is considered for the two plane waves incident on Si nanocube. The obtained results show the high impact of a toroidal moment and high order multipoles in optical force, while they aren't represented main resonances in scattering cross-section.

1. Introduction

Since the first laser tweezers were introduced by A. Ashkin, the most popular and utilized principle for optical manipulations is pulling of an object to a maximum of the electric field that formed with tightly focused laser beams. Only laser tweezers allow to non-invasively control mechanical motion of organic and inorganic objects in nano- and microscales, that plays a crucial role for biology and medicine applications [3].

Optical tweezers are widely used in particle sorting [4], microfabrication [5] and with the developments of digital processing and 3D printing technologies (particularly two-photon photopolymerisation [6]) light trapped and controlled functional micro and nanoscale devices approaching new applications and developments [7,8]. Beside original classical approach for optical control in nano- and microscales there are very fast developing alternative approaches based on an interplay of an object with a substrate [9,10], manipulation using re-scattered light [11,12], optical binding [13,14], unusual optical beams (not a Gaussian or plane waves) [15,16]. One of the biggest breakthroughs in the optical tweezing become spatial light modulation allowing simultaneous control over tens trapping beam points and generate an arbitrary spatial distribution of electric field amplitude and its phase manipulation about $2\pi$ [17,18].

The opportunity to assemble arbitrary beam and fast development of all-dielectric based metamaterials [19,20] lead to necessity of analysis of complex systems and conditions. One of the tools allowing to perform an analysis is the optical force multipole decomposition [15]. In this work we performed numerical computation of Si nanocube in optical frequency range and multipole analysis of scattering cross-section and optical force acting on nanocube using Cartesian multipoles [15,19]. We are reporting two typical regions of the forces pulling an object in direction of the source. The first one is clearly explained by negative influence of electric and magnetic dipole interplay (cross-term) and the second one is frequently accompanied by contribution of electric toroidal moment and high-order multipoles cross-terms.
2. Results and discussion

Two plane waves forming Bessel Beam were directed on the Si nanocube as it is shown in Fig. 1. As it was reported [15] strongly inclined electric fields produce force overcoming radiation pressure allowing to obtain optical force pulling a particle back to the source.

Figure 1. The field composed from two incident plane waves incident at angle of 70 deg to x-axis scattering on the Si nanocube with a=200[nm] (a). The XY and XZ cross-sections of normalized E-field amplitude for incident radiation with wavelength 600[nm] is illustrated in (b) and (c).

Using Cartesian multipole decomposition [15] of the electric field scattering cross-section and time-averaged optical force were obtained and shown in Fig.2. Due to the incident fields have the large angle of incidence the dominant optical response in scattering cross-section Fig2(a) and optical force Fig.2(b) is defined by magnetic dipole, less electric dipole; electric quadrupole and magnetic quadrupole.

Figure 2. The multipole decomposition of scattering cross-section (a). The multipole decomposition of time-averaged optical force shown on panel (b) and panels (c,d) demonstrated regions, where optical pulling force is obtained.
moments are observed in short wavelength spectral region. The time-averaged optical force for the most part of spectral region coincided with the profile of scattering cross-section except the regions, where the interplay between the high order multipoles or toroidal one with electric and magnetic dipoles is observed. For the long wavelengths coupling between electric and magnetic dipoles leads to negative directed optical force Fig.4(d). That is the typical region for simple geometries (sphere, cylinder, cube, etc) of all-dielectric nanoparticle dependent on inclusions of incident radiation and less on the particle shapes. The second region presented in Figure 2(c) shows the negative force, caused by the interplay of high order multipoles with basic ones. The geometry and small changes of shapes more significantly cause the contribution to optical force. For the case of Si nanocube, we succeeded to forces consisting of electric and magnetic cross-term, magnetic toroidal cross-term and electric quadrupole toroidal cross-term overlapping at 680 [nm] and giving the substantial contribution to the negative force. The interplay of magnetic quadrupole and magnetic dipole, electric quadrupole and magnetic quadrupole for the chosen geometrical parameter and shape were shifted to the blue region and suppressed by pure magnetic dipole contribution.

In conclusion, it should be emphasized, that for the chosen medium and size of the nanoobject the optical force will have 2 typical regions defined by a simple interconnection of electric and magnetic dipoles and defined by several interconnections produced by high order multipoles. The analysis achieved using 3rd order Cartesian multipole decomposition for consideration of regions caused by multipoles larger order will produce difficulties, due to the very big number of interplays. The optical pulling force was achieved for all dielectric particle with low losses, that could be very helpful for further experimental studies

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