Tractor beams for semiconductor spheres

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Abstract

The basic principles of optical manipulation are relatively simple for objects much smaller than the wavelength of incident light. In analogy with electrostatics, small particles develop an electric dipole moment in response to the light's electric field. By appropriate manipulation of interfering laser beams, it is possible to generate local vortices, complex Poynting vectors and light spin patterns. However, there is no way to accelerate a small particle towards the light source against the photon stream [1, 2].
Larger particles, in contrast, may develop not only electric dipoles, but also magnetic dipoles and higher-order multipoles. The multipole radiation field may present strong interference effects because the excitation is due to the incident coherent electromagnetic field [3]. In particular, interference may cause the radiated field to become strongly focused in the forwards direction (the direction of the incoming beam). This is in contrast with the isotropic radiation pattern of a small electric dipole [4, 5]. Because the total momentum must be conserved, stronger forwards scattering leads to a smaller forwards force. For a highly collimated laser beam (a plane wave), the interference effect on a multipolar particle is not enough to reverse the sign of the radiation pressure force. However, if the projection of the total photon momentum along the propagation direction is small, it is possible to create an attractive optical force that acts against the optical power flow.
Recently, it has been proposed [1,6] and lately demonstrated [7] the use of a Bessel beam for the practical realization of this phenomenon. A Bessel beam can be seen as a combination of plane-wave components whose propagating vectors form a cone that makes an angle θ_0 with the propagation axis, i.e. a propagating field, in cylindrical coordinates (ρ,ϕ,z), can be expressed in terms of Bessel functions as

$$\vec{E} = E_0 e^{im\phi + ik_0\cos\theta_0 z}\left(\sin\theta_0 J_m(k_0\sin\theta_0\rho)c_2\vec{e}_z - c_1\left(\vec{e}_z\times\vec{b}\right) + \cos\theta_0 c_2\vec{b}\right) \quad (1)$$

where $\vec{b} = iJ'_m(k_0\sin\theta_0\rho)\vec{e}_\rho - \dfrac{m}{k_0 r\sin\theta_0}J_m(k_0\sin\theta_0\rho)\vec{e}_\phi$. Equation (1) describes the superposition of phase-shifted TE ($c_1 = |c_1|e^{i\varphi_1}$) and TM ($c_2 = |c_2|e^{i\varphi_2}$) Bessel beams.

As the angle between the beams increases, the traditional radiation force goes to zero with the cosine of the angle; two counter-propagating waves produce no net radiation pressure force, whereas the contribution to the force coming from the strongly focused forwards scattering remains finite. Above a given angle, the conservation of momentum leads to a total force that points towards the light source.
Because the optical pulling force is strongly related to the existence of interference effects between multipole radiation fields, it is appropriate to investigate the different types and sizes of particle that could be pulled by such a tractor beam.
Researchers recently demonstrated that submicrometre semiconductor spheres are capable of exhibiting dipolar magnetic and electric responses [8]. In these particles, interference between the electric and magnetic dipolar fields can lead to anisotropic angular distributions of scattered intensity, including zero backwards and almost-zero forwards scattering intensities at specific wavelengths [9-10].
As we will show, for a given laser wavelength the pulling force is only possible in specific spectral regimes, because the required interference condition is only obtained for particular ranges of sphere radii, for specific materials and for specific beam configuration. As it would not be possible to pull arbitrary particles, we will study the optimal probe that can be pulled by a proposed tractor beam as a function of the beam configuration (see Fig.1). On the other hand, the dependency of this technique on particle size and material nature provides intriguing possibilities for particle sorting. In addition, these particles could be attached to almost transparent objects such as biological macromolecules. The optical pulling force could then be used to attract even transparent objects by using multipolar particles as pulling probes.

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Figures

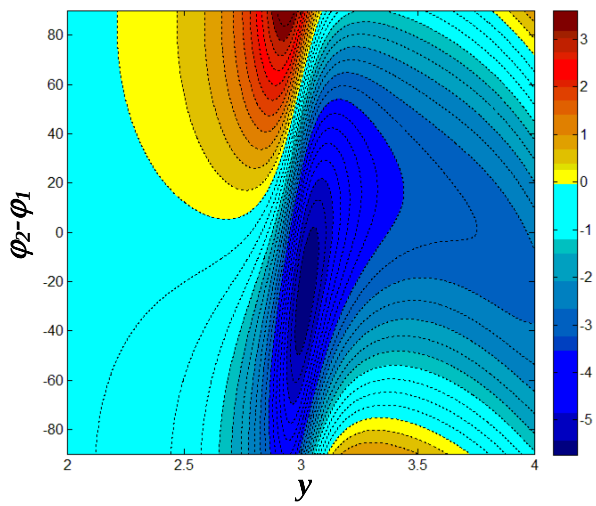

Figure 1. Optical pulling force map of a Silicon probe as a function of the phase shift, φ_2-φ_1 , and the y parameter, $y=nka$. The Bessel beam has characteristics $m=1$, $\theta_0=90º$ and $|c_2|=|c_1|$. Blue areas correspond to parameter ranges where the pulling force is negative, i.e. optical force acts against the optical power flow.