Optically-driven Rotation of Perfectly Absorbing Nanoparticles

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Abstract. Optical manipulation of small scatterers assisted with auxiliary nanostructures is a very promising and already proven concept. In this work, we investigate an interesting application of angular momentum transfer in light scattering by dielectric nanoparticles. We show that, when illuminated by a circularly polarized plane wave, the scattered Poynting vector from a homogeneous dielectric cube presents a divergence-free component. Such Poynting vector distribution induces rotational motion via angular momentum transfer to any strong absorbing particle in the vicinity of the scatterer. We illustrate this effect in the case perfectly absorbing dipolar nanoparticles. The proposed design is the first step towards an efficient all-dielectric mixing scheme for micro-fluidics applications.

1. Introduction
Mechanical momentum carried by electromagnetic radiation can be effectively transferred to a structure via scattering and absorption. A self-consistent electromagnetic field interacts with induced polarization charges and, as a result, an averaged macroscopic Newtonian force acts on the structure. Opto-mechanics studies mechanical action of light on material bodies, e.g. micro and nano-scale particles, and, apart from its fundamental significance, has a broad range of practical applications [1–4]. When illuminated by an electromagnetic field, microscopic particles can form stable structures due to optical binding, an effect rooted in the mutual interaction and the corresponding optical forces that exist as long as the external excitation remains active. Optical binding was first studied in [5] and, since then, several aspects of it have been considered [6–9].

Optical trapping experiments with focused laser beams (optical tweezers [10]), started the era of optical manipulation [11]. Ever since then, this concept has been successfully applied to various fields of science and engineering, such as laser cooling [12], particle sorting [13], optomechanical light modulators [4], among many other research areas. One of the primary goals of optical manipulation research is to reduce the overall power of a trapping beam and to achieve stiff and highly localized potential light profiles.

Apart from the undesirable environmental temperature effects, high light intensities could be harmful for trapped objects, especially for biological specimens (e.g., Ref.[14]). Complex shaping of beams could improve the quality of trapping (e.g., Ref. [15]), however they present additional technical complications in comparison with traditional light sources. A promising alternative for microfluidic manipulation consists in taking advantage of the fields scattered by dielectric
nanoparticles and the optical forces they induce on other subwavelength scatterers [16–19]. Dielectric particles have very low absorption, and therefore heat losses to the medium can be considerably reduced. Relying on the above, the investigation of optical forces induced by carefully engineered high-index dielectrics is of considerable interest and could lead to new remarkable phenomena. In particular, we study the conversion of Spin Angular Momentum (SAM) of an incident circularly polarized plane wave into Orbital Angular Momentum (OAM) by an isolated cubic dielectric nanoparticle. This effect implies the rotation of the scattered Poynting vector of the cube in the plane perpendicular to the direction of incidence. Small absorbing particles placed in the vicinity interact with the scattered field and experience a non-conservative optical torque, consequently revolving around the incident beam axis. We utilize a semi-analytical approach in order to prove the latter in the hypothetical case of perfectly absorbing dipolar nanoparticles.

2. Results and discussion

We consider the same geometry utilized in Ref. [20], a cubic Si nanoparticle in free space, with a side of 250nm, excited by an incoming left circularly polarized plane wave propagating along the z-axis. For such an incident field one can calculate the angular momentum flux density using the expressions for paraxial waves [21]. The z component can then be written in the general form:

$$j_z(\mathbf{r}) = \frac{cE_0}{2i\omega} E_0^* (\hat{r} \times \nabla)E_0 \bigg|_z + \frac{cE_0}{2i\omega} E_0^* \times E_0 \bigg|_z$$

(1)

Where $E_0$ is the electric field. The first term in the right-hand side of (1) corresponds to the orbital angular momentum flux density (OAM) carried by $E_0$, while the second term can be interpreted as the spin angular momentum flux density (SAM). Substituting into (1) the expression of an elliptically polarized plane wave yields:

$$j_z = \sigma \frac{I_0}{\omega}$$

(2)

$$\sigma = \sin \delta$$

(3)

The OAM term is zero in this case, and the total angular momentum flux density is entirely given by the SAM flux density. $\sigma$ is the wave helicity, bounded between +1 and -1 for left and right-circular polarization respectively, $\delta$ is the phase difference between the x and y components of the incident electric field and $I_0$ is the incident light intensity. Because the total angular momentum is conserved in the scattering of a lossless particle, when the incident field is scattered by the cube, the total angular momentum conservation law implies that part of the SAM is transferred to the orbital and spin terms of the scattered field.

Moreover, the angular momentum surface density of the scattered wave is defined in full analogy with classical mechanics [22] as:

$$\mathbf{J} = \frac{r \times \mathbf{S}}{c}$$

(4)

Since $\mathbf{J}$ is non-zero due to the above, equation (4) implies that the Poynting vector of the scattered field has non-zero tangential components. This fact can be understood in analogy with the field scattered by a rotating electric dipole [23]. In this case, the Poynting vector distribution on a plane perpendicular to the direction of excitation presents a remarkable spiral-like behavior, illustrated in figure 1(b). We can now proceed to study the effect of the scattered field on small dipolar particles. In this case, the time-averaged optical forces can be written as [24]:

$$\langle \mathbf{F} \rangle = \frac{\alpha}{2} \sum_{i=x,y,z} Re \{E_i^* \nabla E_i \} + \frac{\alpha^*}{2} \sum_{i=x,y,z} Im \{E_i^* \nabla E_i \}$$

(5)
Figure 1. (a) Near electric field distribution, (color plot), and resulting scattering force field acting on absorbing dipolar nanoparticles, calculated with equation (5) (red arrows) in the plane perpendicular to the propagation direction of the incident light. (b) Poynting vector of the scattered field, taking into account only the transverse components.

Where $\alpha'$ and $\alpha''$ denote respectively the real and imaginary parts of the dipole polarizability. The first term in the right-hand side of (5) corresponds to conservative (curl-free) forces acting on the particle. The second term correspond to the non-conservative forces or scattering forces. This last term can be shown to be directly related to the Poynting vector and the SAM flux density $\mathbf{J}_s$ [24]:

$$\langle \mathbf{F}_{\text{scat}} \rangle = \frac{\sigma}{c} \langle \mathbf{S} \rangle - \frac{\sigma}{2} \left[ \nabla \times \langle \mathbf{J}_s \rangle \right]$$  \hspace{1cm} (6)

Where $\sigma$ is the conductivity of the particle. Taking the curl of (6) and assuming a negligible contribution of the second term clearly shows that rotation torque will be induced on the particles only when $\nabla \times \mathbf{S} \neq 0$. In order to illustrate this effect, we assume perfectly absorbing dipolar particles with negligible real part of the polarizability. In this situation, only scattering forces are present. As expected, the spiral behavior of the Poynting vector is also mirrored by the scattering force field distribution in the transverse plane (figure 1(a)).

3. Conclusion
In conclusion, we have shown that angular momentum transfer between an incident circularly polarized wave and the scattered field of an isolated cubic dielectric nanoparticle results in a spiral trajectory of the scattered Poynting vector in the transverse plane. Perfectly absorbing particles in the vicinity of the cube are thus driven by scattering forces, which induce rotational motion perpendicular to the incident wave propagation axis. Our results are the first step towards the design of efficient all-dielectric microfluidics mixers.

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References

[1] Ivinskaya A, Petrov M I, Bogdanov A A, Shishkin I, Ginzburg P and Shalin A S 2017 Plasmon-assisted optical trapping and anti-trapping Light Sci. Appl. 6 e16258-6
[2] Petrov M I, Sukhov S V., Bogdanov A A, Shalin A S and Dogariu A 2016 Surface plasmon polariton assisted optical pulling force Laser Photonics Rev. 10 116–22
[3] Shalin A S and Sukhov S V. 2013 Plasmonic Nanostructures as Accelerators for Nanoparticles: Optical Nano cannon Plasmonics 8 625–9
[4] Shalin A S, Ginzburg P, Belov P A, Kivshar Y S and Zayats A V. 2014 Nano-opto-mechanical effects in plasmonic waveguides Laser Photonics Rev. 8 131–6
[5] Burns M M, Fournier J M and Golovchenko J A 1989 Optical binding Phys. Rev. Lett. 63 1233–6
[6] Čižmr T, Romero L C D, Dholakia K and Andrews D L 2010 Multiple optical trapping and binding: New routes to self-assembly J. Phys. B At. Mol. Opt. Phys. 43
[7] Dholakia K and Zemánek P 2010 Colloquium: Gripped by light: Optical binding Rev. Mod. Phys. 82 1767–91
[8] Kostina N, Ivinskaya A, Sukhov S, Bogdanov A, Toftul I, Nieto-Vesperinas M, Ginzburg P, Petrov M and Shalin A 2017 Optical binding via surface plasmon polariton interference Phys. Rev. B 99 125416
[9] Sukhov S, Shalin A, Haefner D and Dogariu A 2015 Actio et reactio in optical binding Opt. Express 23 247
[10] Ashkin A 1970 Acceleration and Trapping of Particles by Radiation Pressure Phys. Rev. Lett. 24 156–9
[11] Gu Y and Sundquist W I 2003 Good to CU Nature 424 21–2
[12] Wineland D J, Drullinger R E and Walls F L 1978 Radiation-pressure cooling of bound resonant absorbers Phys. Rev. Lett. 40 1639–42
[13] Xiao K and Grier D G 2010 Multidimensional optical fractionation of colloidal particles with holographic verification Phys. Rev. Lett. 104 1–4
[14] Bergman K, Neuman K C, Chadd E H, Block S M and Liou G F 2009 Characterization of Photodamage to Escherichia coli in Optical Traps Biophys. J. 77 2856–63
[15] Woerdemann M, Alpmann C, Esseling M and Denz C 2013 Advanced optical trapping by complex beam shaping Laser Photonics Rev. 7 839–54
[16] Shalin A S, Sukhov S V., Bogdanov A A, Belov P A and Ginzburg P 2015 Optical pulling forces in hyperbolic metamaterials Phys. Rev. A - At. Mol. Opt. Phys. 91 1–6
[17] Shalin A S, Ginzburg P, Orlov A A, Iorsh I, Belov P A, Kivshar Y S and Zayats A V. 2015 Scattering suppression from arbitrary objects in spatially dispersive layered metamaterials Phys. Rev. B - Condens. Matter Mater. Phys. 91 1–7
[18] Bogdanov A A, Shalin A S and Ginzburg P 2015 Optical forces in nanorod metamaterial Sci. Rep. 5 1–9
[19] Ivinskaya A, Kostina N, Proskurin A, Petrov M I, Bogdanov A A, Sukhov S, Krasavin A V., Karabchevsky A, Shalin A S and Ginzburg P 2018 Optomechanical Manipulation with Hyperbolic Metasurfaces ACS Photonics 5 4371–7
[20] Shamkh H K, Baryshnikova K V, Sayanskiy A, Kapitanova P, Terekhov P D, Karabchevsky A, Evlyukhin A B, Belov P, Kivshar Y and Shalin A S 2018 Transverse scattering with the generalised Kerker effect in high- index nanoparticles Arxiv:1808.10708 1–22
[21] Dogariu A and Schwartz C 2006 Conservation of angular momentum of light in single scattering Opt. Express 14 8425
[22] Jackson J D 1999 Classical electrodynamics (New York, {NY}: Wiley)
[23] Gough W 1986 The angular momentum of radiation Eur. J. Phys. 81
[24] Novotny L and Hecht B 2012 Principles of Nano-Optics (Cambridge University Press)