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Optical Forces Acting on a Particle near Photonic Crystal Surface

Natalia A. Kostina[*]
Mihail I. Petrov[†]
ITMO University
Saint-Petersburg, Russian Federation

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Abstract. We consider optical forces acting on resonant particles located near the surface of a photonic crystal (PC). The band structure of the PC makes it possible to change the direction of propagation of the BSW (Bloch surface wave) to the opposite when varying the wavelength of the incident radiation, which leads to a change in the direction of the reactive optical force component. Therefore, there is an effect of switching between the modes of optical attraction and repulsion of particles in narrow spectral ranges, which is prospective for precise sorting of resonant particles. Here we consider sorting of core-shell dielectric-gold nanoparticles with varying shell thickness.

Keywords: optical forces, resonant particles, sorting, Bloch surface wave.

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Since the first works [1, 2] on optical tweezing the optical forces is declared to be the most promising tool for precise nanoscale manipulation. High demand in biology for transport and sorting of living cells, fabrication of nanoscale particles for various research in photonics, realizations lab-on-a-chip platforms arise new tasks, such as optical control over small objects, precise sorting of the resonant nanoparticles, tuneable transport, and positioning of subwavelength particles. At the same time optical manipulation schemes must be simple and compact in order to be implemented as a part of the nanoscale devices.

Additional degrees of freedom introduced into optomechanical schemes provides more versatile control over the nanoparticles' motion. For example, the presence of a flat interface does not enlarge the system drastically, while enables such an effects as optical tractor beams [3, 4] or high-resolution self-organization of the objects [5, 6]. These schemes could be also interesting for optical sorting based on particles near-fields interaction with a resonant substrate. At the same time with conventional methods, it is hard to sort particles with close spectral positions of the resonances, precision could be lost with decrease in difference of the particle's size [7, 8].

Here, inspired by the recent results by the group of A. Fedyanin [9, 10], we propose an analytical model for precise sorting of resonant dipolar nanoparticles via photonic crystal (PC) surface mode (Bloch surface wave, BSW). We report, that due to multiple narrow peaks in the reflection from the PC it is possible to distinguish particles with close resonances at any spectral range, that is prospective for many applications.

Let us consider silica-gold core-shell particles with core radius 36 nm and shell thickness varying from 3 to 8 nm. The electric dipole resonances of the particles are in the wavelength range 600–800 nm, with redshift for thinner shells. If we place the particles near one-dimensional PC surface and illuminate with p-polarized light (see Fig. 1), the optical force induced by the

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[*] natalia.kostina@metalab.ifmo.ru https://orcid.org/0000-0002-1141-1169
[†] mihail.petrov@metalab.ifmo.ru https://orcid.org/0000-0001-8155-9778

directional Bloch surface wave excitation would be proportional to the phase difference between dipole moment projections of the particle (1) [11].

$$F_x^{BSW} \sim -\mathrm{Im}[p_x^* p_z]\,\mathrm{Im}\,\partial_x G_{xz}, \tag{1}$$

where p_x, p_z are dipole moment of the particle components, $\partial_x G_{xz}$ is a component of the Green's function derivative.

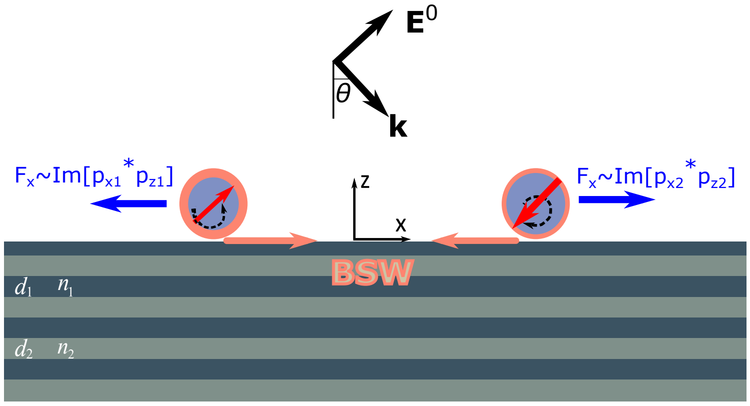

Fig. 1. The scheme of the optical sorting of core-shell nanoparticles near PC

It means, that the direction and magnitude of the force is sensitive to the angle and wavelength of the incident light (defining the reflection from the substrate) and position of the particles' resonance. Thus, even for non-resonant particles, there are multiple positive-to-negative optical force variations due to Fabry–Perot peaks in the reflection from the PC. For resonant particles, before the resonance optical force changes sign to the opposite, and with the change of the shell, the resonance shifts. It is easy to see, that by tuning parameters of the PC for reflection to fit the particle's resonances, we could efficiently sort the resonant particles in any desired range.

Here we use 1D PC with five pairs of alternating layers of $n_1 = 3.5$, $d_1 = 260$ nm, $n_2 = 1.4$, $d_2 = 320$ nm, and the topmost layer thickness is 100 nm. At the air-PC interface we place resonant core-shell particles. The 8 nm shell particle resonance is under 700 nm thus this parameter could be considered as reference or an analogy of non-resonant case, one could see the optical force sign variations due to reflection from the PC only (Fig. 2). For the case of 6 nm shell the force sign is changed at around 720 nm, thus, particles with 6 nm and 8 nm shell will move opposite directions for 720 nm and the same direction for bigger wavelengths. Particles with 5 nm shell experience opposite force at 735 and 755 nm, while for 3 nm shell thickness the resonance is shifted above 800 nm, and optical force is positive.

To summarize, we illustrate that optomechanical effects near PCs open a way to step-by-step sorting of resonant nanoparticles. Here, even the single electric dipole resonance shift for tens of nanometers is enough to see the difference in the optical force direction, that makes possible to sort even deeply subwavelength particles with high precision. The method is applicable for particles with arbitrary positions and widths of the resonances and needs only the optimization of the PC modes structure to be done for specific parameters.

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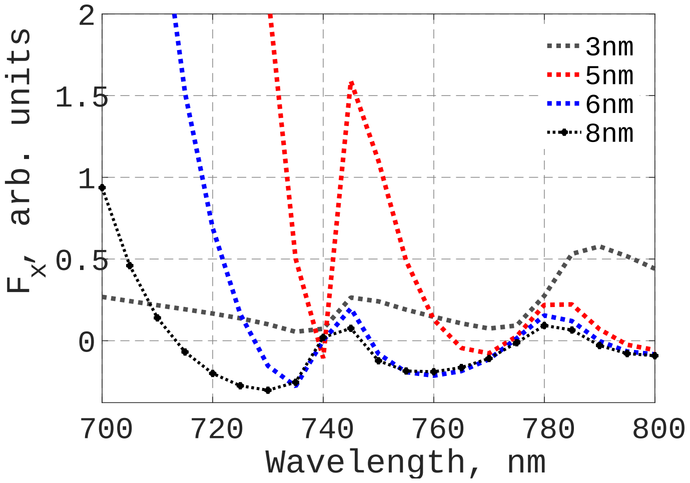

Fig. 2. Optical force, acting near one-dimensional PC on the core-shell silica-gold nanoparticles with shell thickness 3 nm (grey dotted line), 5 nm (red dotted line), 6 nm (blue dotted line), 8 nm (black solid line)

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Оптические силы, действующие на частицы вблизи фотонного кристалла

Наталия А. Костина
Михаил И. Петров
Университет ИТМО
Санкт-Петербург, Российская Федерация

Аннотация. Мы рассматриваем оптические силы, действующие на резонансные частицы, расположенные вблизи поверхности фотонного кристалла. Зонная структура ФК позволяет изменять направления распространения ПВБ на противоположное при варьировании длины волны падающего излучения, что приводит к изменению направления реактивной оптической силы. Таким образом, имеет место эффект переключения между режимами оптического притяжения и отталкивания частиц в узких спектральных диапазонах, что может быть использовано для прецизионной сортировки резонансных частиц.

Ключевые слова: оптические силы, резонансные частицы, сортировка, поверхностные волны Блоха.