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Position locking of a resonant gain-assisted metallic/dielectric nano-shell in Optical Tweezers

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Summary. — We calculate optical forces on dye-enriched resonant nano-shells in dual-beam Optical Tweezers. We investigate the non-linear gain-assisted enhancement of their optomechanics and study their behaviour through Brownian dynamics simulations. When the wavelength is red detuned with respect to the plasmon resonance, we observe that the particles are efficiently trapped at the laser beam intensity maxima of the dual beam standing wave. Conversely, for blue-detuned wavelengths the nano-shells are channelled through the standing wave antinodes due to the sign reversal of the optical force. This open perspectives for gain-assisted optomechanics where non-linear optical forces are finely tuned to manipulate controlled nano-photonic systems.

1. – Introduction

Optical forces [1, 2] exerted by light beams play a key role in the manipulation of single or multiple nanostructures [3-5]. Light can be used to trap, push or bind a variety of nano- and micro-particles, directly in liquid, air or vacuum environment. In single-beam optical trapping, *i.e.*, standard optical tweezers [2, 3], a laser beam is generally focused by a high numerical aperture (NA) objective to a diffraction-limited spot. Thus, a nanoparticle can be trapped near the focal point by optical forces associated with the high intensity gradients surrounding the focal region. These gradient forces generally overcome the unavoidable light scattering forces which tend to push the particle in the

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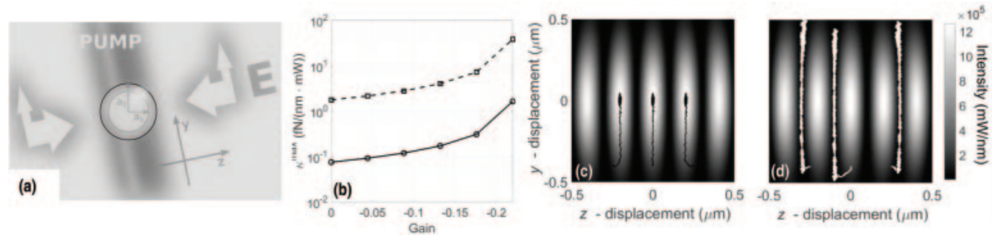

Fig. 1. – (a) Sketch of the double beam trap acting on the core-shell particle composed of a silver shell and a silica core doped with rhodamine dye molecules acting as gain material. (b) The maximum value of the trapping constants, normalized to power P, $\kappa_\rho^{\max}$ (solid line) and $\kappa_z^{\max}$ (dashed line) in counterpropagating configuration is plotted as a function of the gain in semi-logarithmic scale. (c) Nanoparticle position locking on yz-plane. Intensity maxima correspond to the minima of the potential when $\lambda \simeq 531.90$ nm. (d) Nanoparticle channelling on yz-plane. Intensity maxima correspond to the maxima of the potential when $\lambda \simeq 531.47$ nm.

(axial) propagation direction, downstream of the beam focus [5]. However, for small nanoparticles this destabilizing effect of scattering forces combined with thermal fluctuations can overwhelm trapping forces for typical incident laser powers [4]. The detrimental effects of scattering forces can be suppressed through the use of two counter-propagating beams [1]. These dual-beam traps are based on the use of low NA lenses and allow trapping of nanoparticles with reduced incident power in a focal region that is wider than for standard optical tweezers [6]. When the beams are linearly polarized in the same direction, a standing wave trap is formed and many equilibrium positions are generated by the interference fringes that form along the beam axis [7].

2. – Gain-assisted nonlinear optical trapping

In this context, the study of optical forces on optically trapped gain-enriched plasmonic nanostructures is of particular interest. In fact, many remarkable phenomena occurs in these systems due to the resonant interaction between plasmonic structures and gain media, *e.g.*, dye molecules or quantum dots [8]. The coupling with a gain medium located in the core of a metallic nanoshell, when excited by means of an external pump, produces intense changes of the electromagnetic fields around the structure [9]. Therefore, this phenomenon determines the behaviour of the optical forces acting on the nanostructure itself, thus producing novel features which can be useful over a variety of applications [8, 9].

Our work consists of the optical forces study in the quasi-static limit acting on a silver nanoshell doped by gain medium. A sketch of the system is shown in fig. 1(a). Specifically, we have analyzed the optomechanical non-linear response of this nanostructure in a dual-beam optical trap [10]. We observe a rich spectrum of localization in the visible range studying the trend of trap stiffnesses κ as a function of wavelength and for different gain levels (which can be achieved by fixing the molecular density of the gain medium and by varying the power of the external pump). In particular, the characterization of the highest spring constant $\kappa^{\max}$ shows that optical trapping strongly depends not only on the wavelength but also on the gain level (see fig. 1(b)). This suggests that a measure of the trap stiffnesses could be used as a signature of the coupling between plasmonic particles and gain media, unraveling the near field interaction in these nanophotonic systems.

We also investigate theoretically the stability configurations and particle dynamics in the trap by means of Brownian dynamics simulations [11]. Thus, we directly observe how the particle dynamics is more confined for increasing gain and power. Moreover, by changing the light wavelength within a fraction of a nanometer around the plasmon resonance, it is possible to switch the sign of the optical forces and use the dual-beam configuration for position locking (red detuning with respect to the plasmon-enhanced resonance) or channelling (blue detuning with respect to the plasmon-enhanced resonance) of particles in a micro-fluidic flow, see figs. 1(c) and (d), respectively.

3. – Conclusions

In conclusion, we performed a systematic investigation of the optomechanical interaction of dye-enriched core-shell nanoparticles with gain in a double-beam optical trap. Nonlinear optical trapping has been studied through Brownian dynamics simulations. We observed that by tuning the light wavelength we can switch sign to the optical force to yield particle position locking or gain-assisted channelling. More details of this complete work can be found in [12].

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