Modeling of Resonant Optical Trapping in a 2D Photonic Crystal Cavity

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Abstract

Photonic crystals (PhC) are optical nanostructures that are widely known for their strong spatial and temporal confinement of electromagnetic radiation. Light confinement at the nanoscale gives rise to large gradients of electromagnetic field that could allow us to trap small nanoparticles with very low optical powers. In this context, PhC cavities with a larger field overlap ratio with the surrounding medium are preferred due to the increase in interaction volume with the particle and these are referred to as hollow photonic crystal cavities [1,2]. Here, we study the resonant optical trapping of a single nanoparticle within a hollow circular photonic crystal cavity (Figure 1). The Electromagnetic Waves (emw) interface of COMSOL Multiphysics® was extensively used during the analysis of all our experimental results. The system under study comprises of a thin PhC cavity slab (220 nm) of dielectric material (n=3.46) surrounded by an aqueous layer (2 µm) above and below the slab. Dielectric particles sized from 100 nm to 500 nm (n=1.59) were placed inside the circular defect to study the interaction with the field. Adaptive meshing strategies were employed to handle the difference in the largest and smallest features involved in the system (Figure 2). In the first analysis, we perform the eigenfrequency study to compute the quality factors and eigenfrequencies of the PhC cavity when the particle is moved vertically away from the centre. A strong dependence on particle size was found and a 2.6 nm shift is numerically predicted for a 500 nm sized dielectric particle (Figure 3). To further understand the trapping characteristics, we performed a stationary analysis by sourcing a plane wave of 1 Watt and calculated the forces experienced by the particle with the aid of the Maxwell stress tensor formalism. The most important thing to note is the appearance of a renormalization in field strength due to the resonant nature of the field that gives rise to a variation in the trapping forces for each wavelength. The position of the maximum forces can also be seen to change according to the source wavelength (Figure 4). This analysis was performed for both the in-plane and out-of plane movement of the particle within the interaction volume, which qualitatively shows the presence of two distinct mechanisms of trapping in the cavity. In the first regime close to the unloaded resonance wavelength, the presence of the particle decouples the field and if the particle moves out of the interaction volume, the field builds up again and brings the particle back to the centre of the trap. In the second regime corresponding to farther detunings, the particle is strongly held in the trap until it is displaced out of the interaction volume that decouples the field letting the particle in free Brownian motion. Our numerical results have complimented both qualitatively and quantitatively with our experimental results [3,4]. These exciting results provide the basis for further analysis of the dynamics of a single particle within a resonant trap and the

study of anharmonic force profiles.

Reference

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[2] Jana Jágerská et al, Refractive index sensing with an air-slot photonic crystal nanocavity, Opt. Lett. 35, 2523 (2010).
[2] N. Descharmes et al,Observation of Backaction and Self-Induced Trapping in a Planar Hollow Photonic Crystal Cavity, Phys. Rev. Lett. 110, 123601 (2013)
[4] N. Descharmes et al, Single particle detection, manipulation and analysis with resonant optical trapping in photonic crystals, Lab Chip, 13, 3268 (2013)

Figures used in the abstract

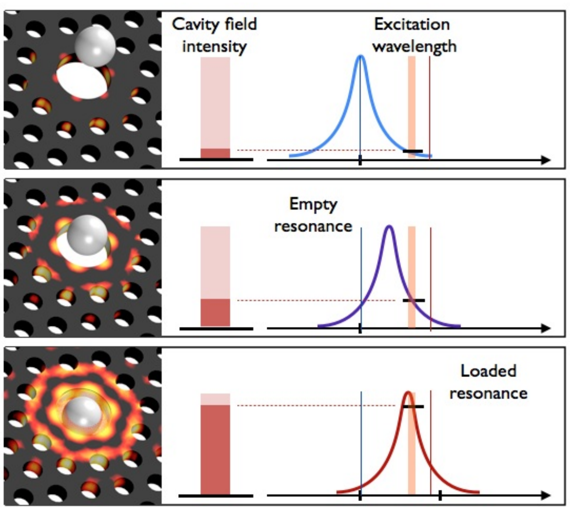

Figure 1: Resonant optical trapping of a single dielectric particle in a hollow PhC cavity

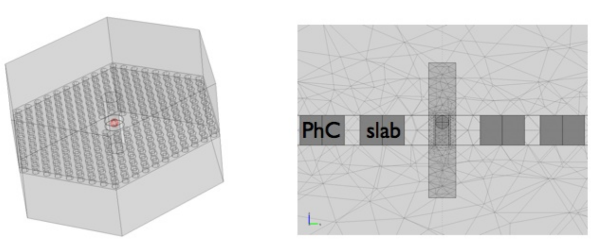

Figure 2: Adaptive meshing of the particle-cavity interaction volume

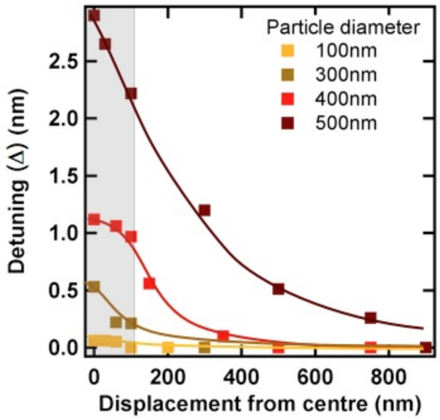

Figure 3: Position dependent eigenfrequency shift due to the presence of a particle

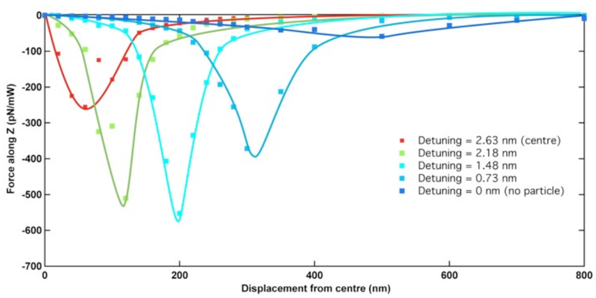

Figure 4: Force experienced by the particle as it is moved along the vertical axis from the centre of the silicon slab towards the outside for various values for detuning from the unloaded cavity wavelength