Numerical Modelling of Optical Trapping in Hollow Photonic Crystal Cavities

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***Abstract*—Photonic Crystal (PhC) devices owing to their strong confinement of electromagnetic energy are considered to be ideal candidates for on chip optical trapping of dielectric or biological particles in the nanometer range. This would miniaturize optical manipulation devices to a large extent and make them possible on low power integrated silicon platforms. The main challenge in this direction would be the understanding of the type of cavities that are more suitable to optical trapping applications given their unique geometric shapes and mode field overlaps. In this work, we study and present hollow PhC cavities and characterize them for their trapping stiffness, trapping stability and variation of resonance wavelength due to the presence of a particle in the cavity.**

***Index Terms*—Optical Trapping, Photonic Crystal Cavities, Finite Element Methods**

I. Introduction

The force exerted by light has been used for optical tweezing since the 1970s. The strength of the trap depends on the gradient of the square of the electric field and the force is directly proportional to the intensity of the field in the cavity. Solving this problem requires finding gradient fields that satisfy the minimum trapping potential required to trap a particle. We are exploring hollow core PhC cavities as candidates for optical trapping as they have gradient forces present inside the cavity volume due to the presence of a cavity mode.

The attributes of an ideal PhC cavity for trapping should have a maximum field overlap with the cavity region, a strong gradient field and hence a high depth of potential for stable trapping times and a robust cavity mode that can operate in infiltrated conditions. This prompts us to study each cavity individually both numerically and experimentally in order to select a suitable cavity configuration for trapping.

A hollow cavity is formed when a defect state is introduced in the bandgap by adding hollow regions inside a PhC slab. These cavities are more interesting to study as they have a maximum field overlap with air and moreover they provides us with geometric confinement in the in-plane direction and a possibility of a strong gradient in the vertical direction. The shape of the mode and its overlap with the hollow region will determine the trapping stiffness and stability. The presence of a particle trapped inside the cavity region affects the quality factor and also shifts the resonance frequency of the cavity mode, a peculiar effect that is absent in a classical optical tweezers. These effects could lead to back action effects which could be exploited in PhC Cavities to create a spatial volume where the object in study remains trapped.

II. Modeling Results

The numerical study of the trapping forces and the gradients involved were computed using a commercial 3D Finite Element package (COMSOL). This study was performed to determine the evolution of the resonance frequency with the discrete variation of the position of the trapped particle along the vertical axis and also to compute the gradient forces involved by running a stationary analysis at the frequency of the stable trapping position. This position that we ascertain as a stable position strictly depends on the shape of the mode profile overlap over the hollow cavity region. Extension of these calculations would also lead us to the determination of the trapping potential and trapping stiffness. In this study, we have investigated two hollow cavities that are referred in the text as 'Big Hole Cavity' [1] and the 'Slot Cavity' [2] PhC structures as shown in Fig. 1.

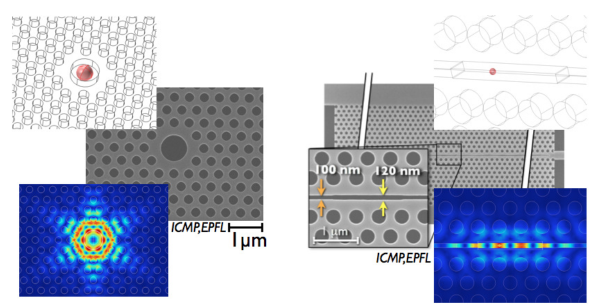

Fig. 1. **Big Hole cavity(left) and Slot Cavity(right) with their respective norm of electric fields, SEM images and the illustration of the particle inside the hollow cavity region**

A. Variation of Cavity Resonance

The presence of a particle in the cavity geometry is expected to enhance or decrease the resonance frequency(and Q factors) depending on where the particle is located inside the cavity volume. This effect could be explained with the variation of the mode in the dispersion diagram of the device owing to the change in the physical environment. This movement of the particle in the vertical direction in the cavity leads to the change in the resonance frequency of the system, which could be exploited as the back action effect, if properly detuned. This effect is shown in Fig. 2. Once moving away from the

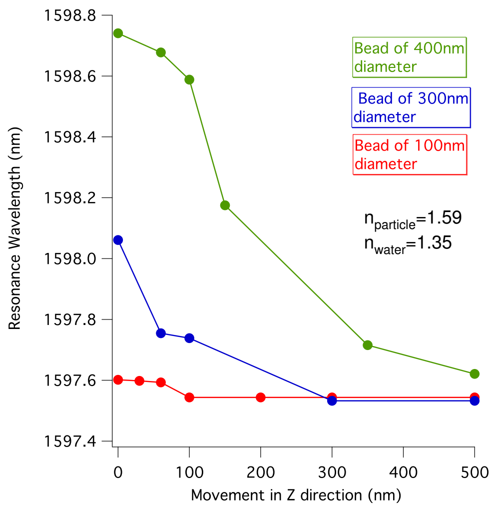

Fig. 2. **Variation of cavity resonance with position of particle along the vertical axis(bighole cavity)**

center, the resonance wavelength decreases, as expected from the dispersion diagram. This will correspond to the cavity mode moving towards the air band in the dispersion diagram of the structure. The variation seen in the figure is clearly proportional to the diameter of the particle in the cavity region. Polystyrene particles(n=1.59) in a Phosphate Buffer Solution environment(PBS, n=1.35) surrounding a 220nm PhC membrane with Silicon(n=3.46) were assumed in the calculations.

B. Trapping Potential

The calculation of trapping force is performed by computing the work required to move the particle from infinity to the trap center after injecting a plane wave and running a stationary analysis on the frequency of the cavity. This enables us to then calculate the force experienced by the particle by integrating the closed surface surrounding the spherical particle using the maxwell stress tensor formulation. The resulting force has to be normalized to a unit power value in Watt. For this purpose we use the normalization value as the total power dissipated from within the cavity volume. The computed trapping stiffness values and potentials for the bighole cavity are shown in Table 1. The values are a magnitude higher than many other devices that have been studied in various designs [3].

In the case of a conservative input power value of 10μW, the potential for a 300nm particle linearly scales down to around 2 kT. This is quite accessible under the experimental limitations of a standard tunable laser light source and a PhC cavity. This gives us a figure of merit for the possibility of trapping and the amount of power that we need to couple into the cavity geometry. The above-mentioned calculation is not a generic calculation and it has to be done in particular for each type of cavity mode and each size of particle. Scaling of potential for different sizes of beads might be appropriate for a certain

TABLE I
TRAPPING STIFFNESS AND POTENTIALS FOR BIG HOLE CAVITY

Diameter(nm)	Stiffness(k_z)	U(k_BT/mW)
100	0.12 pN/nm/W	1
300	28.1 pN/nm/W	197
400	88.5 pN/nm/W	208

extent, but largely depends on the shape of the mode profile of the cavity under consideration. We shall also present the computations performed on a Slot PhC cavity with a 120nm slot width and varying particle sizes.

C. Comparison with analytical model

An analytical model was constructed starting from a dipole field interaction theory which also took into account the Q factor, line shape of the cavity mode, the permitivity of the particle and surrounding environment, the effective mode volume, the resonance frequency and the input power excitation. The model is plotted along with the values from numerical computation(in black dots) for a comparison in Fig. 3. and the values are in good agreement with the predicted model.

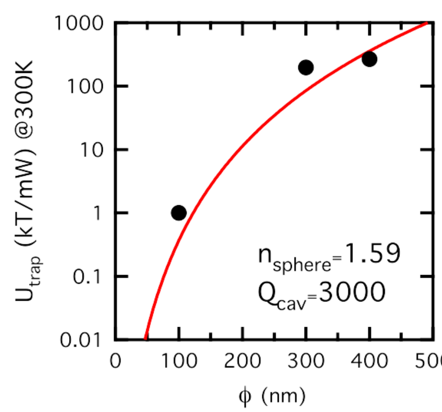

Fig. 3. **Trapping potential of the numerical model(black dots) *vs.* the analytical model(red) for a bighole cavity**

III. CONCLUSION

We have presented the numerical characterization of hollow-core PhC cavities for integrated optical trapping applications. We have shown that there is sufficient variation of resonance wavelengths for varying particle sizes placed inside the cavity region. These cavities have demonstrated trapping potentials that could enable them to be used with low input intensities. Along with the aid of integrated microfluidic channels, they could be tailored for various optical trapping studies such as single cell trapping, multiplexed cell sorting and cell imaging.

REFERENCES

[1] M. R. Lee and P. M. Fauchet. Nanoscale microcavity sensor for single particle detection. *Opt. Lett.*, 32:3284, 2007.
[2] J. Jágerská, H. Zhang, Z. Diao, N. Le Thomas, and R. Houdré. Refractive index sensing with an air-slot photonic crystal nanocavity. *Opt. Lett.*, 35:2523, 2010.
[3] X. Serey, S. Mandal, and D. Erickson. Comparison of silicon photonic crystal resonator designs for optical trapping of nanomaterials. *Nanotechnology*, 21:305202, 2010.