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Design of Nanoslotted Photonic Crystal Waveguide Cavities for Single Nanoparticle Trapping

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Abstract: We design and numerically simulate a photonic crystal waveguide cavity with a nanoslot structure for single nanoparticle trapping. A 135x enhancement of optical gradient trapping force compared to plain waveguide trapping devices has been achieved.

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1. Introduction

Optical trapping is ideally suited to manipulating living cells, virus particles, and even DNA molecules as a contactless and nondestructive tool. To date, most research on optical micromanipulation has focused on laser beam free space trapping [1]. However, it has been demonstrated that the optical force arising from an evanescent field can also be used to trap particles at the interface between two media. For example, using an integrated planar waveguide for on-chip particle manipulation dramatically decreases the system footprint, possibly allowing high-volume mass production using mature planar processing technology and hence very low cost [2-4]. However, waveguide optical trapping often requires large input power due to the low evanescent field intensity, a major roadblock towards its applications. Moreover scattering forces in the near-field also propel particles along the waveguide, making subsequent analysis of particles (e.g. confocal fluorescence/Raman microscopy) difficult, as their positions are not fixed. Finally, trapping particles smaller than 100 nm in diameter is difficult either using free space optics or evanescent trapping configurations with the limitation imposed by laser spot size and power.

In this paper, we propose and numerically verify a novel near-field trapping design utilizing nanoslotted waveguide photonic crystal (PhC) cavities. Resonant enhancement of optical fields effectively reduces the power required for stable trapping; trapping by standing wave inside the resonator also eliminates the traveling wave scattering forces [5,6]. Further, introduction of a nanoslot structure in the PhC cavity takes advantage of the large electric field discontinuity at dielectric boundaries and results in significant field concentration and enhancement. We show that such a cavity-based trapping device is capable for single nanoparticle trapping, and that the nanoslot cavity device setting is also ideal for single nanoparticle detection, given the strong cavity-enhancement effect and the ultra-small interrogation volume.

2. Device Design & Simulation

A waveguide PhC structure is formed by etching 1-d hole arrays in an SOI photonic wire waveguide (Si on SiO₂, refractive indices $n = 3.46$ and 1.45 , respectively), as shown in Fig.1. A PhC cavity with tapered boundary regions is introduced by locally varying the hole spacing using a Gaussian envelope function. Compared to a conventional PhC cavity design with abrupt disruption of hole periodicity, such a gradual change of hole spacing minimizes radiative loss of the cavity mode and effectively improves the cavity Q-factor from 50 to 450 (Fig. 2) [7]. Further improvement of cavity Q-factor can be readily achieved by increasing the number of 1-d holes in the waveguide. 3-d FDTD simulations are performed to determine the field distribution in this structure when the nanoparticle position is varied. The power input to the waveguide is taken as 100mW. A polystyrene particle (refractive index $n = 1.59$) with a radius of 10 nm and immersed in water ($n = 1.33$) is used in our simulation.

Fig.2 shows that the optical gradient force is increased 4 times compared to a plain SOI waveguide of the same size without the PhC cavity structure. The gradient force along the y axis is calculated by integrating the Maxwell stress tensor over the particle surface. A further 32-fold enhancement of trapping force is obtained by incorporating the taper structure and a nanoslot due to the increased resonant cavity enhancement effect and the high field intensity confined in the nanoslot.

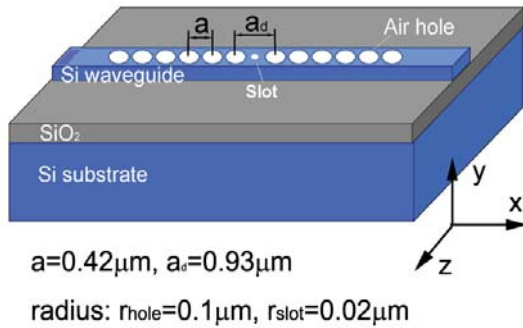


Fig.1 Schematic illustration of a nanoslot waveguide photonic crystal cavity.

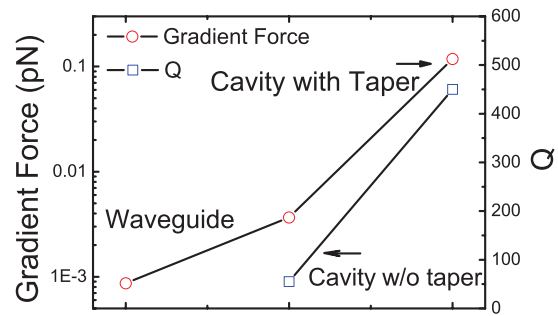


Fig.2 Cavity Q and corresponding optical gradient force in a plain waveguide, a waveguide PhC cavity w/o taper structure and a waveguide PhC cavity with a taper.

Figure 3(a) plots the E_z field component and gradient force distribution on the y - z plane across the nanoslot. High field intensity has been confined in the nanoslot. In Fig. 3b, the gradient forces is calculated based on the dipole approximation, applicable for Rayleigh particles with diameters much smaller than the wavelength ($d \ll \lambda$) [8]. Figure 3(b) shows gradient force distribution around the nanoslot. The gradient trapping force (F_y) is enhanced 135 and 32 times, compare to a plain waveguide and a waveguide PhC cavity without the slot, respectively. As shown in Fig. 3c, such a dramatic enhancement leads to a > 10 kT trapping potential even for particles with sizes down to 10 nm (comparable to that of single protein/DNA molecules), which would allow the stable trapping of a single macromolecule inside the nanoslot cavity despite the presence of Brownian motion. Optical damage to the trapped molecule should remains relatively low at such a power density, according to a previous study [9].

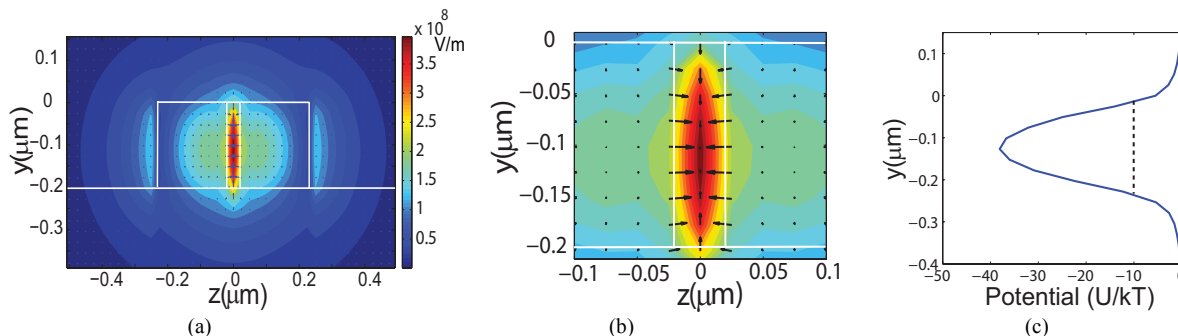


Fig.3 (a) E_z field distribution in the plane $z=0$, (b) gradient force around the nanoslot, (c) trapping potential well along y -axis normalized to kT . The broken line indicates the criterion of stable trapping (10kT).

We quantitatively evaluate the field perturbation and resulting resonant modification due to trapping of a single particle/molecule inside the nanoslot cavity for *in-situ* single particle detection [10]. Our results indicate that the optical trapping cavity also serves as a highly sensitive particle detection device suitable for rapid manipulation and analysis of molecules. The resonant peak shift due to the particle could be used to detection. We find a 0.5 nm resonance peak shift after trapping the nanoparticle in the center of slot. We will also discuss initial experimental results to verify our design concepts.

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