Wavelength-driven positioning of a trapped particle on a photonic crystal waveguide

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We demonstrate novel discrete positioning of a microparticle optically trapped on a tapered Si photonic crystal waveguide. Upon sweeping the wavelength in a range beyond pinch-off for transmission, we observe trapping at specific positions. When the wavelength is swept up, it hops towards the wider side of the waveguide. When it is swept down, it hops in the reverse direction, the stable trapping positions being the same. The spacing between the positions equals the lattice constant of the crystal. FDTD simulations and force calculations allow interpretation of the phenomenon, which arises from the special slow-light mode of the waveguide.

Introduction

In the field of biophotonic sensing optical manipulation of micro- and nanoparticles with on-chip photonic structures receives increasing attention [1], to overcome disadvantages of optical tweezers [2] such as big size and high costs. In this integrated photonics approach optical trapping and propulsion of particles are basic functionalities. Important examples of trapping devices giving static trapping sites are dual-waveguide traps [3], plasmonic evanescent field traps [4] and photonic crystal cavities [5,1]. Trapping and subsequent particle propulsion can be accomplished using the evanescent field of ridge waveguides [6] and slot waveguides [7]. In these structures the evanescent field gives rise to trapping via the gradient force, while propulsion is induced by the scattering force arising from scattering of the propagating waveguide mode at the trapped particle. A new playground in this context are photonic crystal waveguides in a photonic crystal slab. Such a waveguide is a line defect in the crystal. Its characteristics can be engineered to give special properties of the waveguide mode, such as slow light [8] and light localization [9]. These effects can be used for manipulation of a particle trapped on the waveguide. In this contribution we demonstrate and interpret novel wavelength-driven discrete positioning of a particle optically trapped on a tapered W1 waveguide in a Si photonic crystal slab.

Tapered photonic crystal waveguide

The device is fabricated in the 200 nm thick Si layer of silicon-on-insulator material, using e-beam lithography and dry etching. We use a triangular hole-type photonic crystal of lattice constant a=430 nm and r/a=0.3 (r=hole radius). The waveguide in the crystal is very similar to a W1 waveguide, the difference being that its width is accurately tapered down with 2 nm per 430 nm, giving a tapering angle of 0.26 degree. A 50 µm wide and 30 µm deep fluidic channel is built on the chip using a dry resist technique. Water with dispersed 1 µm diameter polystyrene beads can be flown perpendicularly and with a controlled velocity across the waveguide, so that a trapping situation is created. In Fig. 1 a scanning electron microscope (SEM) picture of the device is shown, limited to the central device region.

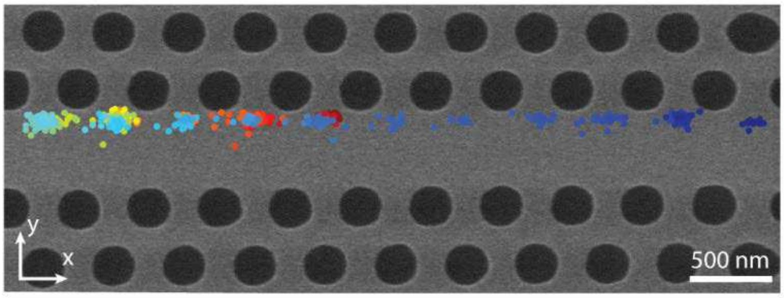

Fig. 1. SEM picture of the tapered W1 photonic crystal waveguide. Picture taken after underetching of the crystal. The waveguide tapers down in width from left to right with 2 nm per lattice constant (*a*=430 nm). The dots superimposed on the picture represent a 2D scatter plot of tracked positions of a trapped polystyrene bead, derived from the frames of a movie recorded while sweeping the wavelength down and up. The color of the dots indicates the time order in which they were taken (blue to red is initial to final).

From in-plane transmission measurements in water with TE-polarized laser light we find that the waveguide supports a range of wavelengths in the photonic band gap, with on the long wavelength side a pinch-off wavelength $\lambda_{p,0}$ of about 1560 nm. In the experiments we couple light of wavelengths just above $\lambda_{p,0}$ (1564-1604 nm) and with a power on the order of one mW into the broad waveguide entrance, so that it propagates into the taper.

Trapping and wavelength-driven positioning of particles

In a trapping experiment a steady water flow (≈5 µm/s) with beads is passed over the waveguide, while recording the top-view microscope observation. We can clearly observe optical trapping of an individual bead on the waveguide for wavelengths above $\lambda_{p,0}$ when it enters the evanescent field. Being trapped, the bead hovers at the trapping site with small excursions, indicating confined Brownian motion. When the laser is switched off, the bead is immediately released into the flow, confirming that we observe optical trapping and not adhesion to the surface.

We observe a very special sequence of trapping events upon sweeping the excitation wavelength, *viz.* an already trapped bead repeatedly hops to an adjacent stable trapping position for every 1.6 nm wavelength change. Hopping is towards the wide side of the waveguide with increasing wavelength and the narrow side with decreasing wavelength. When changing direction of the repositioning of the bead (*i.e.* sweep direction), the effect shows hysteresis in wavelength. Snapshots of a movie of a trapping sequence are given in Fig. 2. On the movie we perform a tracking analysis of the

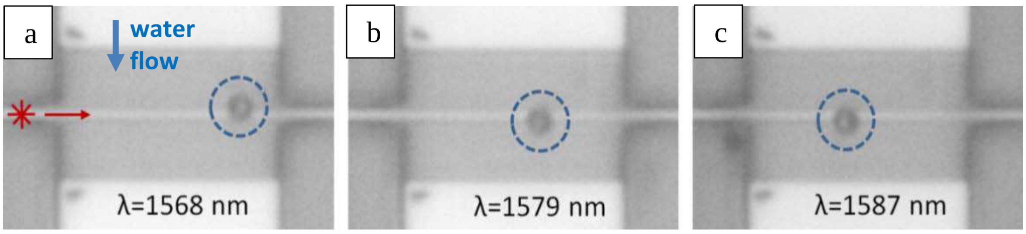

Fig. 2. Snapshots (a-c) of a movie of a trapping sequence of a polystyrene bead (encircled, *d*=1 µm) on the tapered waveguide, showing the systematic shift of the stable trapping position to the left (*i.e.* wider waveguide side) with increasing wavelength. For wavelengths in between the stated values the bead visited several intermediate sites. Water-flow direction is as indicated. In a) the trapping position is slightly offset with respect to the waveguide axis in the positive *y*-direction, in b) and c) in the negative *y*-direction.

particle position. A typical scatter-plot result is shown in Fig. 1, superimposed on the waveguide. The positions of the bead show up as small and clearly separated clouds of tracked positions. The clouds reflect confined Brownian motion of the bead in a trapping potential. To emphasize the discrete positioning, the data have been reduced in Fig. 3 to a plot of the particle's trapping position versus the frame number of the movie. The plateaus in Fig. 3 are equidistant, with a spacing to a high degree of accuracy (1%) equal to the lattice constant of 430 nm. We conclude that we measure wavelength-driven lattice-quantized positioning of the bead. In connection to Fig. 2, we further note that the trapping positions are displaced with respect to the centerline of the waveguide. This effect is not biased by the flow of the water as is apparent from the figure, where it can be seen that the stable trapping position can be on either side of the centerline.

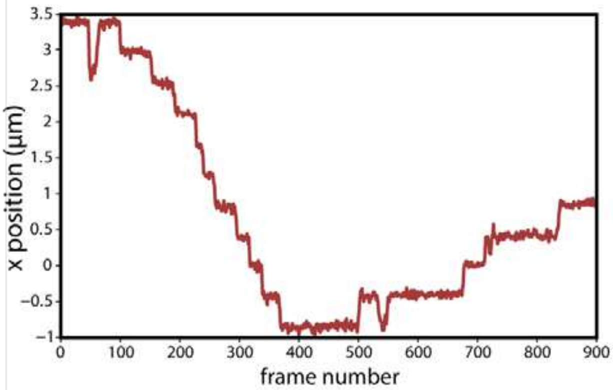

Fig. 3. Traced position of the trapped bead on the waveguide in the *x*-direction versus frame number of the movie (frame rate 30 fps, total time span 30 s), showing quantized positioning with a stepsize of 430 nm. In time, the wavelength was first swept up and then down, so that the bead moves to larger *x*-positions after a minimum.

Interpretation and discussion

To interpret these results, we perform finite-difference time domain (FDTD) simulations of the light in the waveguide, in dependence of the excitation wavelength. An example of a resulting mode in the waveguide for λ=1578 nm, represented by the electric field energy, is given in Fig. 4. It is seen that the light penetrates into the waveguide up to a stop point, where a local resonance occurs with properties similar to a resonance of a photonic crystal cavity. From calculations of the photonic band structure of the waveguide, which we model by a concatenation of constant width sections, we derive that the resonance arises as a result of operation of the waveguide in the slow-light regime. For each waveguide width a specific photonic band comes into play, in particular a mode of that band close to the Brillouin zone boundary, where $\mathrm{d}\omega/\mathrm{d}k\rightarrow 0$ (group velocity becomes very low). This mode can only penetrate into the waveguide up to a distance determined by the width-dependent band index of the mode. As a result of spatial compression of the slow light and reflection of the mode at the stop point, a resonance due to interference builds up. Via the width dependence of the bands, the resonance position depends continuously on wavelength. For the resonance we find from simulations a field (εE^2) enhancement factor of about 45 with respect to the value at the entrance of the waveguide. This property of field enhancement suggests a strong gradient force exerted on a particle, making it likely that trapping occurs at the position of the resonance, as we observe.

To understand the quantized positioning, we use the the Maxwell stress-tensor method to calculate the trapping force exerted on the bead. We simulate the force for 20 bead positions in the *xy*-plane 4 nm above the surface, near the symmetry axis (*x*,*y*=0) and for various wavelengths. We find a calculated stable trapping position or a potential

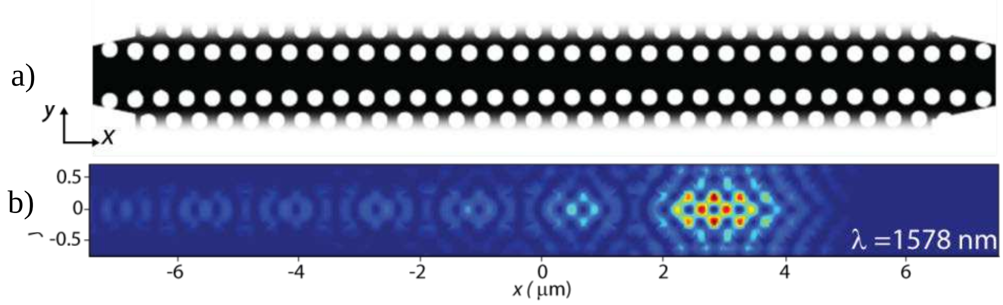

Fig. 4. (a) Cut from the geometry of the tapered waveguide device, as a guide for the mode profile below. (b) Mode profile εE^2 for $\lambda = 1578$ nm, showing the prominent resonance at the stop point. The sub-resonances occuring left from the main resonance are part of the total mode interference pattern

well near (*x*,*y*) = (0 nm, 110 nm), slightly shifted in the positive *y*-direction with respect to *y*=0. During a wavelength downsweep of 1.5 nm, the initial well is gradually weakened and a second well is created (double-well potential), finally giving a shift of the resonance region over one lattice constant. Upon completion of this shift, the gradient force pulls the particle in the newly created well at (*x*,*y*) = (430 nm, 110 nm). This result closely agrees with the observed quantized positioning.

Conclusion

In conclusion, we demonstrate wavelength-driven lattice-quantized positioning of a polystyrene bead trapped on a tapered photonic crystal waveguide. For every 1.6 nm wavelength change, the trapped bead is controllably moved over a distance of the lattice constant. This effect arises from a local resonance, built up from interference of an incoming and spatially compressed slow-light mode and its reflection. By calculating the wavelength-dependent optical force on the bead, we find that its interaction with the shifting resonance leads to stable trapping positions one lattice constant apart, as measured.

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