Optical trapping near a photonic crystal

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Abstract: We show that the photonic confinement induced by a photonic crystal can be exploited to trap nanoparticles. As demonstrated by the recent advances in the design and fabrication of photonic crystals slab structures, total internal reflection and multiple scattering can be combined to confine photons very efficiently. A consequence of this confinement is the existence of strong gradients of electromagnetic intensity in the near-field of the photonic structure. Hence, a nanoparticle placed in the vicinity of the crystal would experience an optical force which, with a proper design of the near-field optical landscape, can lead to trapping.

OCIS codes: (020.7010) Atomic and molecular physics : Trapping, (130) Integrated optics; (130.2790) Guided waves; (130.3120) Integrated optics devices; (140.3410) Laser resonators; (230) Optical devices; (230.5750) Resonators; (250.5300) Photonic integrated circuits; (260.5740) Resonance

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Since its inception [1], the concept of photonic crystal (PC) has been mainly associated with the control of the propagation and the spatial confinement of photons. The wide and growing interest around PCs stems from their ability to tailor the electromagnetic environment through the geometric features of the crystal [2, 3]. PCs can thus enhance or suppress spontaneous emission, or guide photons, often in ways that elude conventional, refractive optics. When it comes to photon confinement, one class of PC devices has been particularly fecund: photonic crystal structures inscribed in a slab waveguide. This type of structure associates total internal reflection with the photonic band-gap effect to achieve enhanced photon confinement, while preserving a great potential for integration in complex photonic architectures. Such structures have demonstrated a high capacity to confine light effectively within a small volume. In most studies involving a PC slab (PCS), the emphasis is often on the radiation dynamics associated with enhanced photon confinement. This is quite natural in regard of the very wide interest that the control of light-matter interaction has in the context of, for instance, single-photon sources or ultra-low threshold microlasers [4, 5, 6, 7]. However, there is another outcome of the ability of PCs to confine light which, albeit seldom considered, has nevertheless a large potential interest. Indeed, an enhanced spatial confinement of light means that strong variations of electromagnetic intensity can be achieved over a small region of space, thus creating large gradients of the electromagnetic field intensity, and therefore large optical forces. Hence, in the context of PCs, particularly in the slab geometry, photon confinement can lead to an enhanced

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mechanical coupling between light and matter. Let us point out that the potential use of PC structures for optical trapping was noted by Toader and coworkers who have shown that the electromagnetic modes of an inverse opal PC could be used to trap cold atoms using the gradient force[8]. In their case, the field confinement, and the concomitant trapping potential, result from a three-dimensional photonic band-gap effect. In the present work we are interested in a trapping geometry more suitable for integration within a planar architecture. The slab geometry, for which the localization of electromagnetic energy is the result of a combination of photonic band-gap effect and refractive confinement, satisfies this criterion.

The optical trapping of neutral particles has become a cornerstone not only of atomic physics, but also biology and chemistry [9]. In particular, the optical tweezers techniques used to trap and manipulate mesoscopic particles have been refined continuously over the years [10, 11, 12]. In this article we explore whether it is possible to trap nanoparticles (particles of a subwalength size) in the near-field of a photonic crystal. As a prototype configuration we consider a slab with refractive index 3.4 immersed in a fluid with refractive index 1.33. The slab with thickness $t = 0.467a$ is perforated with a triangular lattice of holes with period a and hole radius $r = 0.333a$. To localize light we introduce a defect in the photonic crystal by omitting one hole in the crystal pattern, thus creating a defect (i.e. localized) state in the bandgap (Fig. 1). We emphasize that the microcavity created by simply removing one hole, without any further refinement, has a quality factor typically of the order of 100, which is several orders of magnitude smaller than for the state-of-art PCS that have been reported [13, 14, 15]. We are thus dealing with a rather weak resonator, which beside its simplicity has the merit of allowing us to explore the worst-case scenario, and hence gain some insight in the general feasibility of the optical trapping of nanoparticles near a PC slab.

For the modeling, we use the finite, three-dimensional structure represented on Fig. 1. The calculations are done with the coupled-dipole method [16, 17]. The entire structure is discretized in space and the local-field is computed self-consistently. Details of the calculation are given in Ref. [18, 19]. We excite the cavity with an electric dipole along x. We vary the wavelength of the source and we plot the spectrum of the cavity by monitoring the total radiated power (or the decay rate of the source). As seen in Fig. 1, electromagnetic radiation by the source is drastically suppressed by the PCS, except near the cavity resonance at $\lambda_0 = 3.2a$.

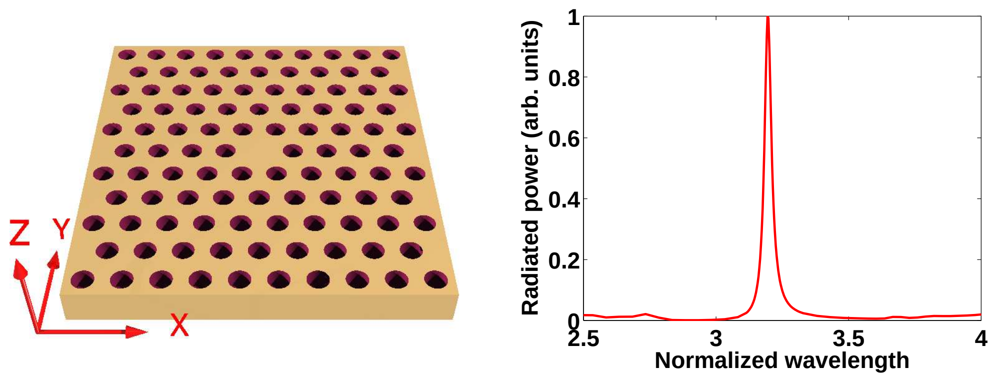

Fig. 1. Schematic of the finite photonic crystal microcavity used in the computation (left). Cavity spectrum (right). The wavelength is in units of a the lattice period of the PC.

Having located the cavity resonance we now explore the optical trapping capability of the optical mode of the cavity under external illumination. We consider the case of a plane wave illumination along a direction perpendicular to the slab (from bottom to top on Fig. 1). The

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electric field of the plane wave is polarized along the x direction. In order to probe the optical potential near the PC, we use a spherical particle with refractive index 1.5 and with radius $R_{\text{part}} = 0.039\lambda_0$. Given the size of the particle, we can use the dipole approximation to compute the time-averaged optical force experienced by the particle, provided that radiation reaction is accounted for [20, 21]. The CDM is used to compute the self-consistent local-field at a given wavelength. Once the local-fields are known, the optical forces and potentials are derived by propagating both the fields and their derivatives through the use of the appropriate field-susceptibility tensors [20]. Owing to both the size of the particle, the weak optical contrast between the particle and the surrounding fluid, and the modest quality factor of the cavity mode, we neglect the influence of the particle on the optical response of the cavity, i.e. we treat the particle as a passive probe. Note that in this regime, the optical potential is proportional to the volume of the particle. We assume an irradiance of 10 mW/μm^2 and room temperature (300 K).

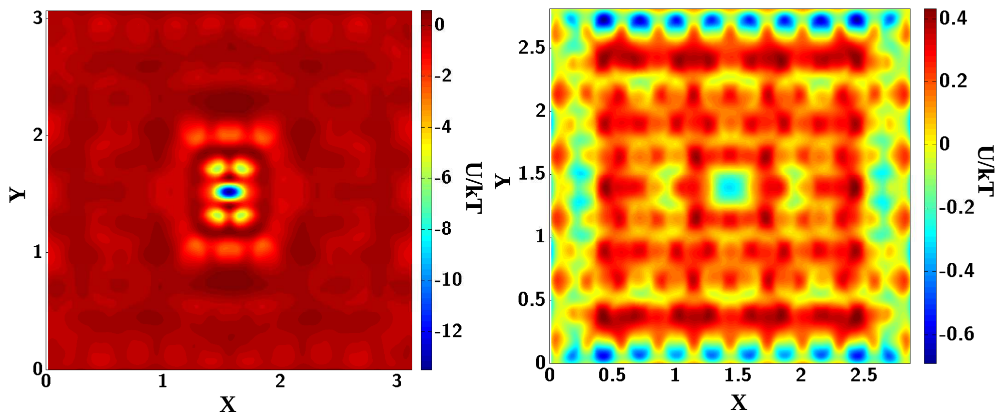

Fig. 2. Near-field maps of the optical trapping potential U for a nanoparticle with radius $R_{\text{part}} = 0.039\lambda_0$ in a plane located at $z = R_{\text{part}}$ above the photonic crystal. The lateral axes are normalized to the wavelength. Left: optical potential at the resonance wavelength λ_0. Right: optical potential off resonance at $1.09\lambda_0$.

Figure 2 shows maps of the trapping potential when the cavity is either on- or off-resonance. The maps are computed at a distance R_{part} from the surface of the cavity. When the illuminating beam has a wavelength that matches the resonance wavelength of the cavity, we obtain a well confined optical trap with a maximum depth of about 12 kT and a lateral size smaller than half a wavelength. This means that the particle can not only be efficiently trapped, but also be confined to a subwavelength area. Incidentally, we note that if we assume harmonic potentials, the variance of the spatial fluctuations of the trapped particle [22] is about 0.024 λ_0 and 0.014 λ_0 in the x and y directions respectively. This means that Brownian motion will not prevent the trapping. On the other hand, the optical trapping potential computed off-resonance, for the same irradiance, shows that no trapping is possible. The maximum potential depth achieved in this case is about 0.6 kT, 20 times weaker than the on-resonance, and this is mostly due to edge effects at the boundaries of the finite structure we used for the computation. The contrast in the trapping potential between the situations where the cavity is either on- or off- resonance, is easier to appreciate on a profile cut of the potential maps as plotted in Fig. 3. We can see that the trap is not symmetric along x and y. The optical forces lead to a tighter confinement along y than along x. This asymmetry is a reflection of the asymmetric polarization of the illuminating beam and the geometry of the cavity. We also note the presence of additional local minima

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of the potential on either side of the main trap in the y direction. However, trapping at these locations can be avoided by choosing an adequate irradiance for the pump.

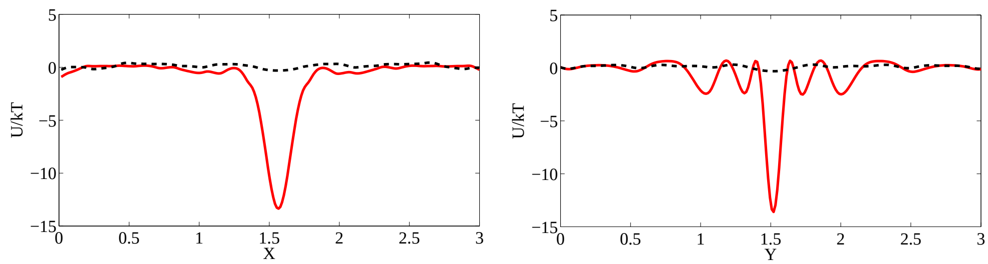

Fig. 3. Profile cuts along directions x and y over the center of the near-field maps of the optical trapping potential shown in Fig. 2. The distances are normalized to λ_0. Plotted in red solid lines are the trapping potential profiles for when the cavity is on-resonance, whereas the black dashed curves pertain to the off-resonance case.

The near-field nature of the optical trap is illustrated in Fig. 4 where we probe the vertical extension of the trapping potential. The trap is confined to the near-field of the cavity. The vertical confinement of the trapping zone is expected since the subwavelength confinement of light by the cavity is a testimony to the existence of strongly evanescent field components in the near-field of the cavity. Note that just like the tightness and the depth of the optical trap, the vertical reach of the trap can, to some extent, also be controlled by changing the irradiance of the pump.

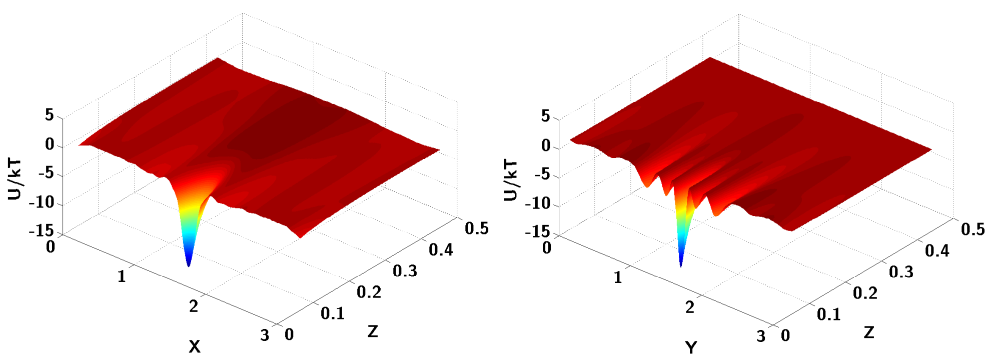

Fig. 4. Vertical dependence of the optical trapping potential U for a nanoparticle with radius $R_{\text{part}} = 0.039\lambda_0$ in a plane located at height z above the cavity, as a function of the lateral position of the particle along direction x (left) and y (right). All distances are normalized to λ_0, the resonance wavelength of the cavity.

Therefore, we see that despite the somewhat lossy nature of the resonator, efficient, near-field optical trapping of a nanometric particle should be possible under realistic pumping conditions. Of course, the idea presented in this paper is not restricted to a single defect in a PCS. Multiple optical nanotraps can be envisioned by considering, coupled-cavity systems [23], or the optical modes of a defect-free PCS, for instance, at critical points of the band diagram. In fact, the breadth of patterns associated with the optical modes of PCs opens new ways to, not only trap, but also foster the auto-organization of groups of nanoobjects [24] in the subwavelength regime. Indeed, while nanometric optical traps can be achieved by “sculpting” an evanescent wave created by total internal reflection with an external device [25, 26], PCSs achieve both : the slab supports a guided mode which has an evanescent tail above the slab while, at the same time, the photonic crystal molds the optical landscape in the near-field of the slab.

The present work is a first step in the exploration of the use of PCS for optical trapping and manipulation of nanoparticles. Further work will be needed to devise the most appropriate crystal configuration to achieve a given trapping geometry. In particular, cavities with high quality factors would be a good candidate in designing compact optical traps, however, for such cavities the influence of the particle on the resonance of the PCS may not be negligible anymore [27], requiring a careful assessment of the electromagnetic coupling between the particles and the PC. Hence, a balance must be reached so as to not allow the trapped particles to destroy the very PC resonance that supports the optical trap. For instance, if for PCS structures supporting modes with very large quality factors, having ensembles of nanoparticles passing through the holes of the crystal creates a disturbance of the crystal mode, polymer could be used to seal the holes without inducing too large an increase in the optical contrast compared to the case where the holes are filled with the fluid [28].

Another degree of freedom lies in the choice of the illumination configuration and polarization. Whereas we used normal illumination, the parallel wave vector of the excitation beam can be extended to larger components by using a configuration similar to the one used to create evanescent-wave mirrors for cold atoms [29] (or to the Kretschmann configuration used to excite surface plasmons in a thin metallic film). As demonstrated recently in the microwave regime, negative refraction can also be exploited to produce an optical trap [30]. However, the exploitation of negative refraction to achieve optical trapping at optical frequencies still bears technological challenges.

Finally, we should point out again that strong optical forces will occur whenever light is confined spatially. This means that metallic slabs are also a good candidate for generating optical traps at the subwavelength level. A single hole in a metal sheet can for instance lead to trapping [31]. However, periodic arrays of holes in a metallic slab should support more interesting trapping configuration [32]. These structures would also have the advantage that plasmon resonances can be used to enhance the selective trapping of metallic nanoparticles [33].

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