

## Optical Mirror from Laser-Trapped Mesoscopic Particles

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Trapping of mesoscopic particles by optical forces usually relies on the gradient force, whereby particles are attracted into optical wells formed by landscaping the intensity of an optical field. This is most often achieved by optical Gaussian beams, interference patterns, general phase contrast methods, or other mechanisms. Hence, although the simultaneous trapping of several hundreds of particles can be achieved, these particles remain mostly independent with negligible interaction. Optical matter, however, relies on close packing and binding forces, with fundamentally different electrodynamic properties. In this Letter, we build ensembles of optically bound particles to realize a reflective surface that can be used to image an object or to focus a light beam. To our knowledge, this is the first experimental proof of the creation of a mirror by optical matter, and represents an important step toward the realization of a laser-trapped mirror (LTM) in space. From a theoretical point of view, optically bound close packing requires an exact solver of Maxwell's equations in order to precisely compute the field scattered by the collection of particles. Such rigorous calculations have been developed and are used here to study the focusing and resolving power of an LTM.

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*Introduction.*—The concept of a laser-trapped mirror (LTM) as originally formulated in [1] relies on the formation of a parabolic interference pattern in space—from two coherent counterpropagating laser beams—in which mesoscopic particles can be trapped [2], forming a membrane of optical matter [3]. By trapping a sufficiently large amount of particles, a quasicontinuum could be formed and would create a reflecting surface akin to a mirror. Such LTM-based telescope concept holds promise for permitting *in situ* construction of very large, self-healing, extremely low areal density telescopes without complex mechanical deployment and with aperture size potentially limited only by the available laser power. Remarkably, a 100-nm thick, 35-m diameter mirror would only weight about 100 g. However, creating and maintaining such optical membrane in space and understanding its focusing properties poses formidable scientific and engineering challenges, beyond the reach of current technology. This Letter, albeit not offering a full solution to the problem, proposes two fundamental advancements toward an LTM. First, we show experimentally that two-dimensional membranes can be formed by light and can be used as dielectric mirrors. Although our experiment was performed in water where damping stabilizes and cools the system, it is the first time that the imaging capability of an optical membrane, made of an arrangement of closely packed yet nontouching mesoscopic spheres, is shown. Second, theoretical and numerical studies extend the experimental work toward an actual parabolic optical membrane composed of mesoscopic particles

in order to study its focusing properties and resolving power. Implementing an exact solution of Maxwell's equations where all interactions between particles are accounted for, we show that the optically bound particles do exhibit similar properties to those of conventional telescope mirrors.

*Experimental realization of a reflecting optical membrane.*—The trapping of particles based on dipole force has mostly been used in atomic physics to slow down and to manipulate atoms as well as Bose-Einstein condensates [4,5]. At a much larger scale, the trapping of mesoscopic particles with nondipolar optical forces is also a well understood phenomenon which has been exploited in various forms such as trapping in a template [3,6–9], in counterpropagating Gaussian beams [10,11], in Fizeau-Tolansky fringes [12], or in Talbot self-images [13]. Currently, the most adequate medium to trap remains water because of its damping and cooling properties as well as its low viscosity, although trapping in air has also been achieved [14,15]. Beyond the physical sciences, optical forces have been used mostly in biology to study molecular motors, to unwind protein strands, to track movement in biological specimens, to sort, and to stretch cells [16,17]. Yet, most applications reported to date take advantage of single particle trapping: notwithstanding the fact that multiple particles can be trapped in parallel [3,9,17], they usually remain in individual traps with little to no interaction with one another.

The problem of creating stable two-dimensional close packing assemblies of mesoscopic trapped particles, akin to crystals or optical matter, remains little addressed and

yet represents a fundamental step toward an LTM. Albeit in water and at a small scale of about 150 particles, we hereby show that an optical membrane can be created and that this membrane can be used as a reflecting mirror to form an image.

The laser source used for the experiment is a diode pumped solid state Neodymium:Vanadate laser—intracavity frequency doubled—(Coherent, Verdi V-5) delivering up to 5 W in cw mode at 532 nm. The beam illuminates 3  $\mu\text{m}$  spherical polystyrene particles of refractive index 1.59 embedded in water within a glass cell. The waist of the quasi-Gaussian laser beam is wide, with a diameter of about 40  $\mu\text{m}$ , and the beam is vertically aligned, traveling from bottom to top. As a result of the scattering force (i.e., the component of the optical force in the direction of light propagation), the beads are pushed toward the top of the glass cell where they aggregate at the waist of the beam, experimentally set to coincide with the top of the cell. Simultaneously, the gradient force, albeit weak due to the size of the Gaussian waist compared to the particle size, drives the beads toward the center of the beam to form a membrane of closely packed particles, as previously described in [3]. The binding force [18], resulting from the interaction between beads, is responsible for the crystal-like organization of the membrane illustrated in Fig. 1. The mechanical stability of the structure has been observed to be excellent, in the order of hours, barring global rotations of the crystal due to convection effects. We have, therefore, proceeded to use the membrane thus created as a mirror, to image a two-dimensional object (a portion of a transparent ruler near the inscription “8”) illuminated with a He-Ne laser, as shown in Fig. 2. In order to filter out reflections from its external surfaces, the cell has been built with wedges both at the bottom and top. The reflections from the internal surfaces have been eliminated by recording two images, with and without the optical membrane as shown in Figs. 3(a) and 3(b), respectively, then subtracting them in order to digitally produce the image of the particle-only system, a small-scale LTM, shown in Fig. 3(c). The image was formed at 633 nm and the membrane is made of 3  $\mu\text{m}$  spheres trapped at 532 nm.

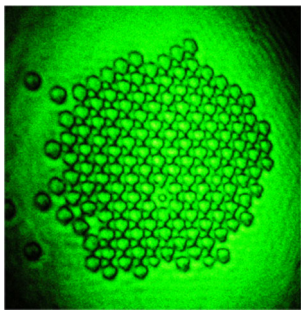


FIG. 1 (color online). Optical matter: a membrane of about 150 noncontacting beads is created based on the trapping and binding forces.

This result demonstrates the possibility of using optical membranes as mirrors, despite their inherent discontinuities and roughness on the order of a few wavelengths.

*Numerical simulations of an optical membrane focusing properties.*—Based on the experimental demonstration of the feasibility of a reflecting optical membrane, we have extended the concept numerically in order to demonstrate the optical properties that such membrane would exhibit. The deviations from the previous experimental configuration are (1) the reduced dimensionality of the problem whereby infinite cylinders—hence two-dimensional particles—are trapped transversally as opposed to three-dimensional beads, (2) the size of the one dimensional aperture, which is increased here to about  $52 \lambda_0$  (obtained as a trade off between imaging capabilities and computation time), and (3) the shape of the interference pattern, parabolic as conceptualize in [1] in order to achieve focusing with a single mirror. The reduced dimensionality allows us to develop an exact solution of Maxwell’s equation of the full-wave collective scattering from all the particles, accounting for all interactions, while reproducing most of the three-dimensional trapping properties, as we have extensively shown in the past [19,20]. For all simulations hereafter, we use an illumination wavelength of  $\lambda_0 = 1064 \text{ nm}$ , impinging upon dielectric rods of permittivity  $\epsilon = 2.53\epsilon_0$  and of radius  $a = 0.3 \lambda_0$ . The background is vacuum with a permittivity of  $\epsilon_0$ .

Within an LTM configuration, we start by showing that the collective scattering of a plane wave by a collection of two-dimensional particles organized in a parabolic shape does indeed focus light. Figure 4 illustrates the membrane behavior for a plane wave traveling from right to left.

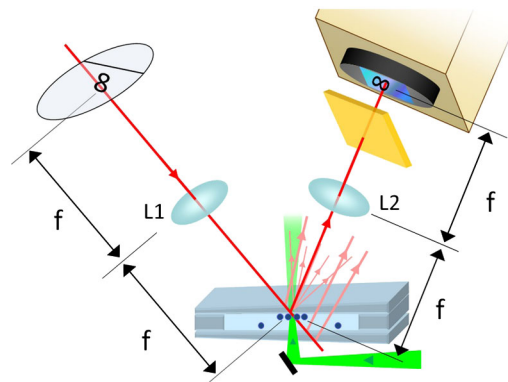


FIG. 2 (color online). Experimental setup to realize a small-scale LTM in water: polystyrene beads (not shown to scale) are trapped in the waist of a 532 nm laser beam, propagating from right to left then upward after hitting a mirror inclined at  $45^\circ$ , to create a reflective membrane. A He-Ne laser beam at 633 nm illuminates a portion of a transparent ruler with the number “8”. A folded  $4f$  optical system (afocal) made with lenses  $L1$  and  $L2$  shapes the beam reflected by the membrane to form an image onto the camera sensor. The optical system is designed to limit perturbations from unwanted reflections.

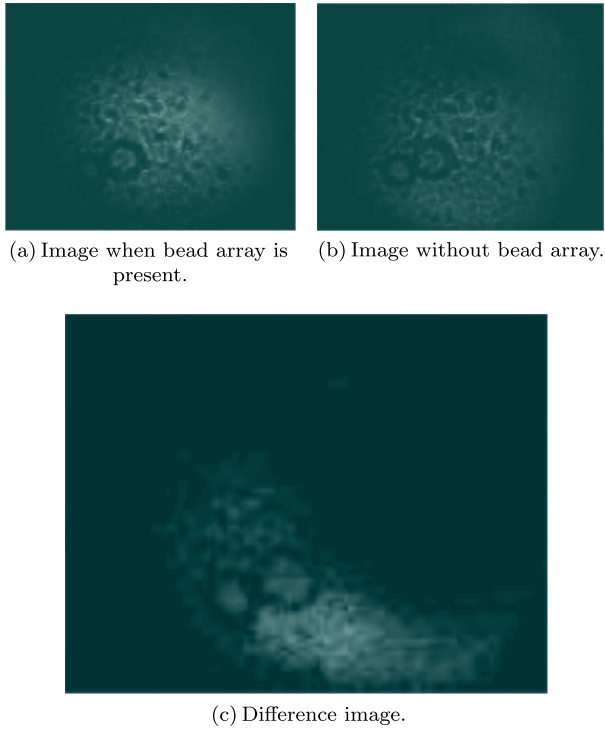


FIG. 3 (color online). Imaging with an LTM in water.

Ignoring the transmitted part—also computed exactly but not necessary for this application—we are interested in the field intensity distribution of the reflected part propagating from left to right, which we especially examine around the focal point. We reiterate here that this result has not been obtained from ray-tracing or geometrical optics, but is an exact solution to the electromagnetic scattering by all the particles arranged along the parabolic fringe. For the simulation, a series of 81 cylinders have been located in air (unit refractive index) on a parabola of equation  $y^2 = 2rx$  where  $r = 64 \lambda_0$  with a center to

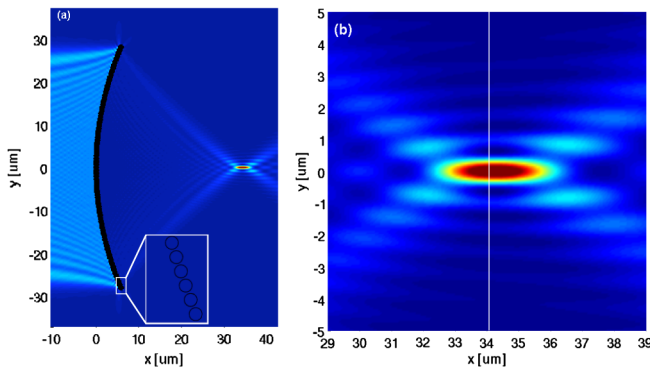


FIG. 4 (color online). LTM imaging capability for a single plane wave propagating from right to left along the axis of the dish: (a) entire view with inset zooming onto the membrane to show the particles of circular cross section, (b) zoom on the focusing region (the white line corresponds to the theoretical position of the focal plane).

center separation of about  $0.7 \lambda_0$ , yielding an aperture size of about  $52 \lambda_0$ . The mathematical focal plane distance is shown by the white line in Fig. 4(b) and corresponds to a coordinate  $x = r/2 \approx 34.0 \mu\text{m}$ , in good agreement with the full-wave simulation results. Although the large numerical aperture of this example, about 0.8, is practically unrealistic, our emphasis is to show that the exact computation of the scattered field reproduces reliably the expected physical phenomena at both qualitative as well as quantitative levels: in Fig. 4, the impinging wave, traveling from right to left, is partially transmitted through the membrane to the left, partially reflected, and focused to the right.

The resolution of the LTM is further quantified by its ability to resolve two incident plane waves impinging upon the dish at two symmetric angles with respect to the horizontal axis. The images and two dimensional power intensities similar to those of Fig. 4—not shown here—reveal an angular separation of about  $1.4^\circ$ . This value is once again in quantitative agreement with the Rayleigh criterion which stipulates that for an optical system, two sources are resolved when the maximum peak of one point spread function falls onto the first minimum of the other one. Indeed, the Rayleigh criterion defines the resolution as  $\Delta\theta = 1.22\lambda_0/D$  which, in our configuration, corresponds to  $1.22\lambda_0/(52\lambda_0) \approx 1.35^\circ$ .

Experimental results have underlined the difficulties of trapping several hundreds of particles in optical wells due to the binding force whose effect is added to the more traditional gradient and scattering forces which modify the position and the stability of the arrangement of particles. From a theoretical perspective, all these forces are included in the exact calculation based on the Maxwell's stress tensor [21,22], and are, therefore, an effect of the collective scattering of light by all the particles. As a result of more particles present in close proximity to one another, stronger scattering occurs which eventually perturbs the original (externally imposed) interference pattern, in turn modifying the location and regularity of the traps. It is, therefore, expected that with an increased number of particles, the parabolic trapping loci fundamental to the LTM is modified, resulting in roughness of the mirror (beyond the inherent roughness due to the fact that the surface is composed of mesoscopic circular particles and is, therefore, not smooth at the wavelength scale). In order to quantify the effect of such roughness on image quality, we have studied the resolution capability of the LTM dish of Fig. 4 to out-of-plane surface roughness, using two plane waves separated by  $2^\circ$  incidence as a reference. Various roughness amounts have been generated by randomly displacing the particles away from their ideal positions based on the modified parabola equation:

$$y^2 = 2rx + \gamma \frac{N}{100} a, \quad (1)$$

where  $a$  is the radius of the cylinders,  $\gamma$  a random number uniformly distributed between  $-1$  and  $+1$ , and  $N$  the

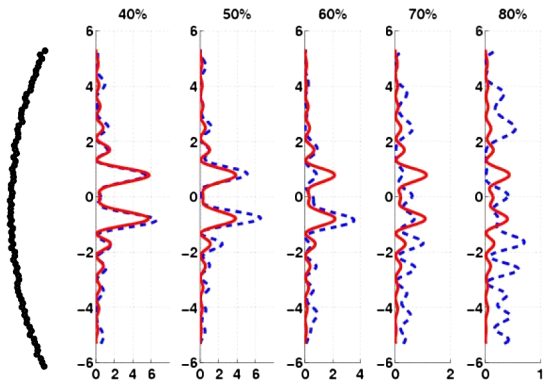


FIG. 5 (color online). Sensitivity of an LTM composed of 81 cylinders (yielding an aperture of approximately  $52\lambda_0$ ) shown on the left as function of surface roughness. The dish is imaging two incident plane waves at  $179^\circ$  and  $181^\circ$  for various dish roughnesses: 40%  $a \leftrightarrow 12\% \lambda_0$ , 50%  $a \leftrightarrow 15\% \lambda_0$ , 60%  $a \leftrightarrow 18\% \lambda_0$ , 70%  $a \leftrightarrow 21\% \lambda_0$ , 80%  $a \leftrightarrow 24\% \lambda_0$ . The one-dimensional plots represent the intensity at the focal plane (dotted blue line: result for a single realization; solid red line: result for a Monte Carlo integration over 100 realizations).

amount of randomness which is intuitively understood as the deviation in percentage of radius away from the ideal position in the positive or negative directions: a value  $N$  represents a variation in the out-of-plane direction of  $\pm N\%$  of  $a$ . In order to obtain averaged effects, the intensity distributions have been integrated in the image plane over 100 Monte Carlo realizations. The results are shown in Fig. 5 for various roughnesses, which are also expressed in terms of wavelength in the caption of the figure. This result shows the robustness of the LTM to resolve the two plane waves despite a deviation of  $\pm 80\%$   $a$  away from the ideal parabola, although in this case, the peak amplitudes are significantly lower than in the case of, *e.g.*,  $\pm 40\%$   $a$  and would require much more sensitive sensors.

*Conclusions and discussions.*—This Letter presents the first experimental demonstration of a water-immersed laser-trapped mirror, albeit at a small scale, which has been used as a reflective surface to image an object. The associated numerical studies have extended the LTM proof of concept by showing the focusing capabilities of a discontinuous optical membrane and by studying its resolution degradation for nonperfectly trapped particles. The major experimental limitations we are currently facing concern (i) the difficulty of stabilizing a membrane in three dimensions, away from the surface of our cell, and (ii) the size of the membrane which becomes unstable as more particles are trapped. Indeed, optical binding helps generate the crystal and gives self-healing properties to the membrane since the latter reorganizes itself after a disruption (*e.g.*, if one or more particles leave the assembly). However, optical binding is also the cause of dislocations in the crystal and can create instabilities. Ultimately, however, in a two-counterpropagating beam configuration where several parabolic fringes are defined, the problem of creating large

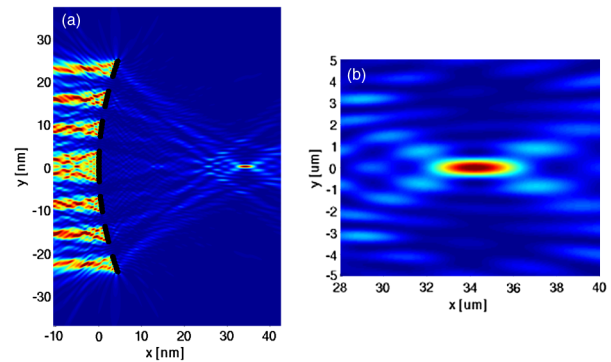


FIG. 6 (color online). Piecewise LTM: a discontinuous surface of trapped particles retains its focusing capabilities. The concept can be extended to particles trapped in multiple interference fringes since the latter are spaced by  $\lambda/2$  and have all the same focal point. The figure shows the intensity distribution resulting from an exact solution of Maxwell's equations in the presence of all the scatterers.

stable membranes can be overcome when, instead of trapping only in the central fringe of the interference pattern as originally proposed [1], trapping occurs in several fringes to create a piecewise LTM akin to a phased-array space telescope. The concept is illustrated in Fig. 6 for the particular case of single-fringe trapping but would work for multifringe trapping since all the parabolic interference patterns have the same focal point (possible decoherence effects due to the reflection from several surfaces could be compensated by operating at a wavelength of which the fringe separation is a multiple). This result strengthens yet further the self-healing property of the LTM since a disruption of the membrane would not have to be healed within the same fringe but could be compensated by particle redistribution in multifringes without performance degradation. These experimental and theoretical results, therefore, represent a step further toward the reality of an LTM in the controlled environment of a laboratory.

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