Dynamic control of defects in a two-dimensional optically assisted assembly

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Abstract. In this paper we demonstrate controlled loading of a closely packed array of optical traps. We also describe the technical advantages of our method of filling the trap array (which makes use of an independent, steerable trap created by a separate objective lens), as well of our specific implementation of array generation by multi-beam interference. Microscopic polystyrene spheres are trapped and subsequently assembled into sites on a two-dimensional optical lattice, which is formed from the interference of two pairs of coherent laser beams via an optical setup that allows for simple, continuous variation of lattice parameters over a very wide range. Individual particles in the initial assembly are dynamically manipulated with the independent laser beam, which offers the freedom to generate either defect-free lattices or a lattice with designer defects. As examples we demonstrate the assembly of a defect-free square lattice and a lattice with a single vacancy.

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Using optical forces, one can trap, levitate and manipulate particles with sizes from tens of nanometres to tens of micrometres. For example, when a laser beam is tightly focused on a small particle that has a higher refractive index than that of its surroundings, the beam will produce a gradient force on the particle directed towards the beam waist and a radiation force along the laser propagation direction. The gradient force attracts the particle to higher intensity regions and the radiation force pushes the particle in the direction of propagation. This particular trapping geometry is called optical or laser tweezers [1, 2]. In this paper, our traps are not, strictly speaking, optical tweezers, as they do not contain strong gradients along the direction of the optic axis, but the methods of array generation and controlled filling of trap arrays are generalizable. While the vast majority of laser trapping work in various subfields of biology, physics and materials science has focused on manipulating either one or two particles with optical tweezers, techniques for assembling multiple particles into one-dimensional (1d), 2d and 3d ordered arrays are now rapidly developing. In 1990, Burns et al [3] used the standing optical field resulting from the interference of several beams to trap polystyrene spheres, thereby producing a 2d colloidal crystal. Following this seminal work, several methods have been used to generate trap arrays including: interferometric optical tweezers, including 3d assembly using four beams [4]–[7]; surface organization through evanescent fields [8]; computer-generated diffraction patterns [9, 10]; spatial light modulators [11]–[13]; scanning laser tweezers employing galvano-optic mirrors [14] or piezoelectrics [15, 16]; and acousto-optical deflectors [17, 18]. Optical lattices are also used in atom optics [19], [20, 21]. However, when generating closely packed 2d patterns using these methods, it can be awkward to manipulate a specific particle, and unwanted defects can be generated.

In the work reported here, we combined single particle manipulation and reconfigurable, 2d optical interference trapping to make 2d colloid patterns with ‘designer’ features. That is, to supplement self-organization on to the optical substrate standing wave potential (produced by the interference of several beams), we introduced a single, independent, counterpropagating helper beam that can be used to individually manipulate selected particles. This gives us a flexible tool to design 2d patterns without defects, or arrays with pre-selected defect sites.

Certainly, defects in colloidal crystals are important and of continuing interest [22, 23]. For example the technique presented here offers significantly greater freedom to perform systematic, controlled investigations of the interactions of fivefold and sevenfold defects, as a function of their separation. Specifically, it is the combination of the weak, pre-determined array of traps with the independent helper beam that gives enhanced control. Another advantage of this setup is that simply by translating the prism mirrors M1 and M2 (see below), we can adjust, in situ, the unit-cell dimensions of the square (or rectangular) substrate potential, without the complicated variation in trap strengths that results from the use of some alternative methods [24].

A standing wave produced by the interference of two coherent laser beams has a spacing given by \( d = \lambda / \left[ 2 \sin (\theta / 2) \right] \), where \( \lambda \) is the laser wavelength, and \( \theta \) is the angle between the two beams. In our earlier work [25], we showed that one can adjust the spacing dynamically with a novel \( \theta / 2 \theta \) rotation system. Here, we demonstrate another method to change the spacing. When collimated light is incident normal to a lens, the light will be concentrated at the focal point of the lens. Similarly, when two parallel, collimated laser beams, symmetrically displaced with respect to the lens axis, are incident on a lens, they too will meet at the focal point and generate a standing wave in the vicinity of the beam waists, with a spacing governed by an angle \( \theta \) that depends on the focal length and the separation of the two beams. If now the separation between the two parallel input beams is altered, \( \theta \) will be changed which, in turn, alters the spacing of
the standing wave pattern. In our experiments, we used this strategy to change the spacing of the standing waves \textit{in situ}.

For a 2d colloid pattern, we do not need to consider the force along the light propagation direction in order to understand the optically induced crystallization of the colloid. We only need to consider the gradient force in the plane of the standing wave.

For single-laser conventional tweezing (which corresponds to our helper beam), the optical gradient force on a spherical particle in the paraxial Rayleigh limit is taken to be [26]

\[ F_{\text{grad}}(\vec{r}) = \frac{2\pi n_2 a^3}{c} \left( \frac{n_1^2 - n_2^2}{n_1^2 + 2n_2^2} \right) \nabla I(\vec{r}), \tag{1} \]

where \( n_1 \) is the refractive index of the particles, \( n_2 \) is the refractive index of the medium, \( a \) is the radius of the particles and \( I(\vec{r}) \) is the light intensity.

The intensity distribution arising for two perpendicular standing waves, in our case, formed from the weakly focused Gaussian waves, contains the form

\[ \cos(2k_x x) + \cos(2k_y y) + 2 \exp \left( -\frac{2(x^2 + y^2)}{w^2} \right), \tag{2} \]

where the first part arises from the interference (in a planar wave approximation) and the second part is the normal Gaussian beam profile.\(^6\)

The particles employed in the experiment described below only approximately satisfy the Rayleigh limit and formally the effective intensity they experience would involve a convolution; hence the form given in [2] provides only a qualitative guide which, however, is suitable for our purposes here. (For a discussion of finite size effects, see [6].)

The polystyrene colloid used in our experiment, which is monodisperse to better than 4\%, was purchased from Interfacial Dynamics Corporation (IDC) and was negatively charged. After dilution with de-ionized water, a small sample was sealed between two no. 2 microscope cover glasses (Fisherbrand 12-540A 18 × 18). The resulting fluid layer was approximately 80 \( \mu \)m thick, which is set by a spacer created by punching a hole in double-sided Scotch\(^ \text{TM} \) tape, which also sealed the sample volume, thereby preventing capillary or evaporative flows. The cover glass surfaces in contact with the liquid were washed with de-ionized water after they were first soaked and cleaned with ethanol. This helps to prevent the spheres sticking to the glass.

Figure 1 shows a schematic diagram of our setup. We use the TEM\(_{00}\) mode of an argon laser (Spectra-Physics model 164) operating at 514.5 nm with 1.5 W to produce the optical standing-wave substrate potential. The coherence length of the argon laser is roughly 16 cm. A krypton laser (Spectra-Physics model 164), operating at 647.1 nm and with the output set at approximately 20 mW, is used to generate the independent helper beam.

Here, three non-polarizing 50:50 beam splitters are utilized. The output of the argon laser is split into two beams by the first beam splitter and then, by the two subsequent beam splitters, into four beams, B1, B2, B3 and B4, all having the same intensity. B1 and B2 reflect from the second pair of beam splitters in the vertical direction and (after being redirected by additional mirrors) are subsequently reflected off an external prism mirror M1; B3 and B4 are derived from the transmitted beams of these same two beam splitters and ultimately fall on prism mirror M2. By careful alignment the two beams reflecting from M1 lie in the vertical plane, while the pair

\(^6\) All equations given here assume \( a \ll x, y \ll w \), which holds for weakly focused Gaussian beams.
Figure 1. A schematic of the laser trapping setup that combines a four-beam interferometer with a 'steerable helper' tweezers. L1 and L2 are lenses; M1–M4 are mirrors; B1–B4 show the four beams (that form the standing wave); D is a diachronic mirror; and F&A are the filter and attenuator.

reflecting from M2 lie in the horizontal plane. Simply by translating mirror M1, the separation between the B1 and B2 pair can be continuously changed; likewise, translating M2 alters the separation between B3 and B4. With proper overall alignment this setup generates four parallel beams that lie on the centres of the edges of a rectangle; for the case of equal separations this quadrilateral is a square, which is the geometry utilized for the present discussion.

A Fuji Fujinon-TV 1:1.4/50 camera lens is used to focus the four beams. The diameter of the lens is large enough to accept all four beams and it is installed on a 3d translator that positions the lens so that the beams overlapped each other at the focal point. The beams B1 and B2, composing the first pair, have the same path length and are therefore coherent; they form a horizontal standing wave. B3 and B4, the beams in the second pair, also have identical path lengths, which however may differ from that of the first pair; they form a vertical standing wave. If the path length difference between the first and second pair exceeds the coherence length of the laser, there will be no mutual interference between the two pairs; this is the mode utilized here. An additional long focal length lens can also be inserted to better control the beam overlap.

The extent of the resulting standing wave pattern was around 25 µm. During the experiment, the colloidal spheres are pushed against the cover glass on the far side of the beam by the radiation pressure; the gradient force associated with the optical lattice then traps the spheres at this surface on the intensity maxima. Again, the standing wave spacing can be changed in situ, as noted above, by moving mirrors M1 and M2. For a standing wave pattern with fourfold symmetry, the smallest lattice constant we can reach is approximately 1 µm, while the largest is 4 µm.

The microscope that imaged the system is formed from an infinity-corrected Mitutoyo long-working-distance 50× objective lens whose numerical aperture (NA) is 0.55 and two additional lenses. The microscope is connected to a CCD (for real time viewing) and a video recorder (allowing extended analysis at a later time). To keep the colloid clearly imaged on the CCD, we fix the distance between standing wave pattern and the microscope.

The helper beam is applied to the sample through the microscope, using lens L2 and the Mitutoyo objective to focus the helper beam. After focusing, the spot size is approximately that of a single sphere, here 2–3 µm. The helper beam is then steered in the sample plane by adjusting the two mirrors M3 and M4, and the region that can be scanned is much larger than the extent of the standing wave pattern.
Figure 2. Assembling a lattice with a central defect. (a)–(d) Moving a sphere (indicated by the arrow) to a designated site. (e)–(i) Moving another sphere to a different designated site. (j) A lattice assembled using the helper beam with a defect in a designated site.

The 45° dichroic mirror D (Thorlabs), which is used to couple the helper beam into the microscope, is 90% reflective for the krypton beam, however it transmits 85% of the 514.5 nm argon; most of the krypton beam is then utilized to trap particles while still allowing enough scattered light to reach the CCD for viewing. Filter F1, a notch filter with a bandwidth 10 nm, is essential to reduce the intensity of argon to a level that does not saturate the CCD. With an additional attenuator we can simultaneously image the particles, the interference pattern, and the position of the helper beam.

When manipulating a single particle, we must adjust the krypton laser intensity so that the opposing radiation forces from the two counterpropagating lasers can be balanced; otherwise the particle will be pushed away from the glass surface (by radiation pressure) and lost. At the same time, the extra gradient force applied by the helper beam is large enough to overcome the trapping force applied by the standing wave so as to allow the translation of single particles.

Figure 2 shows some of our results. In this series of frames, we constructed a central defect amid several spheres. The $x$ and $y$ periods of the optical potential are approximately 2.5 $\mu$m. The sphere size in this particular experiment is 2 $\mu$m. We first trapped several spheres with the argon laser. We then slowly translate the sample in the horizontal plane in order to capture (collect) additional particles suspended in the solution. During this process the trapped spheres largely remain in the illuminated region and fixed on maxima of the interference pattern (figure 2(a)).
After assembling a sufficient number of particles, the helper beam is then used to rearrange them as desired; figures 2(a)–(i) show successive steps in positioning two such particles. In each of these frames, the helper beam has been removed so that the particles can be seen more clearly. In the final picture (figure 2(j)), we show our ‘designer’ lattice, the standing wave and the helper beam simultaneously.

Figure 3 shows a defect-free 5 × 5 lattice with 3 µm spheres assembled on a 3 µm period square standing wave pattern using this setup. The substrate potential in these frames is the same as that in figure 2. When trapping the spheres without the aid of a helper beam, the self-assembled lattice always had defects (as seen in figure 3(a)). Figure 3(a)–(e) show the process of aligning spheres into a 5 × 5 lattice. We then moved the extra sphere away from the lattice to form a defect-free square lattice (figure 3(f)). Here, the helper beam functioned as a ‘cleaner’ to remove unwanted particles.

In conclusion, we have described a setup that uses an intense (argon) laser to generate a tailored, reconfigurable, 2d standing wave for trapping particle arrays and a second, independent (krypton) laser for trapping and manipulating individual particles within that array (the helper beam). The 2d array provides a reconfigurable optical substrate potential and the helper beam gives us a tool to assemble spheres within this potential. This combination may be viewed as an extension of one-beam laser tweezing in that individual particles previously positioned by the tweezers (the helper beam) remain where deposited as additional particles are assembled to construct an arbitrary pattern. For the case of a lattice of particles considered here, we are free to assemble defect-free lattices or ones with specific defects. More generally one has a tool to create model systems for studies of many-body interactions as well as a novel scheme for material processing and manufacturing.

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