Regular oscillations and random motion of glass microspheres levitated by a single optical beam in air

Jeremy Moore,[1,2,5] Leopoldo L. Martin,[3,4,5] Shai Maayani,[3] Kyu Hyun Kim,[1] Hengky Chandrahalim,[1] Matt Eichenfield,[4] Inocencio R. Martin,[4] and Tal Carmon[1,3,*]

[1]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[2]*Sandia National Laboratories, Albuquerque, NM 87185, USA*
[3]*Technion-Israel Institute of Technology, Department of Mechanical Engineering, Haifa 32000, Israel*
[4]*La Laguna University, SC de Tenerife 38206, Spain*
[5]*These authors contributed equally*
[*]*tcarmon@technion.ac.il*

Abstract: We experimentally reporton optical binding of many glass particles in air that levitate in a single optical beam. A diversity of particle sizes and shapes interact at long range in a single Gaussian beam. Our system dynamics span from oscillatory to random and dimensionality ranges from 1 to 3D. The low loss for the center of mass motion of the beads could allow this system to serve as a standard many body testbed, similar to what is done today with atoms, but at the mesoscopic scale.

©2016 Optical Society of America

OCIS codes: (350.4855) Optical tweezers or optical manipulation; (020.7010) Laser trapping; (350.3950) Micro-optics.

References and links

1. K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle, "Bose-Einstein condensation in a gas of sodium atoms," Phys. Rev. Lett. **75**(22), 3969–3973 (1995).
2. M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, "Observation of Bose-Einstein condensation in a dilute atomic vapor," Science **269**(5221), 198–201 (1995).
3. S. Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable, "Experimental observation of optically trapped atoms," Phys. Rev. Lett. **57**(3), 314–317 (1986).
4. C. Cohen-Tannoudji, "Manipulating atoms with photons," Phys. Scr. **1998**(1), 33 (1998).
5. S. Chu, "The manipulation of neutral particles," Rev. Mod. Phys. **70**(3), 685–706 (1998).
6. W. D. Phillips, "Laser cooling and trapping of neutral atoms," Rev. Mod. Phys. **70**(3), 721–741 (1998).
7. J. Baugh, O. Moussa, C. A. Ryan, A. Nayak, and R. Laflamme, "Experimental implementation of heat-bath algorithmic cooling using solid-state nuclear magnetic resonance," Nature **438**(7067), 470–473 (2005).
8. D. E. Chang, C. A. Regal, S. B. Papp, D. J. Wilson, J. Ye, O. Painter, H. J. Kimble, and P. Zoller, "Cavity opto-mechanics using an optically levitated nanosphere," Proc. Natl. Acad. Sci. U.S.A. **107**(3), 1005–1010 (2010).
9. T. Li, S. Kheifets, and M. G. Raizen, "Millikelvin cooling of an optically trapped microsphere in vacuum," Nat. Phys. **7**(7), 527–530 (2011).
10. J. Gieseler, B. Deutsch, R. Quidant, and L. Novotny, "Subkelvin parametric feedback cooling of a laser-trapped nanoparticle," Phys. Rev. Lett. **109**(10), 103603 (2012).
11. N. Kiesel, F. Blaser, U. Delić, D. Grass, R. Kaltenbaek, and M. Aspelmeyer, "Cavity cooling of an optically levitated submicron particle," Proc. Natl. Acad. Sci. U.S.A. **110**(35), 14180–14185 (2013).
12. T. Li, S. Kheifets, D. Medellin, and M. G. Raizen, "Measurement of the instantaneous velocity of a Brownian particle," Science **328**(5986), 1673–1675 (2010).
13. S. M. Block, L. S. Goldstein, and B. J. Schnapp, "Bead movement by single kinesin molecules studied with optical tweezers," Nature **348**(6299), 348–352 (1990).
14. K. Svoboda and S. M. Block, "Optical trapping of metallic Rayleigh particles," Opt. Lett. **19**(13), 930–932 (1994).
15. P. Zhang, J. Prakash, Z. Zhang, M. S. Mills, N. K. Efremidis, D. N. Christodoulides, and Z. Chen, "Trapping and guiding microparticles with morphing autofocusing Airy beams," Opt. Lett. **36**(15), 2883–2885 (2011).
16. A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, "Observation of a single-beam gradient force optical trap for dielectric particles," Opt. Lett. **11**(5), 288–290 (1986).
17. M. M. Burns, J. M. Fournier, and J. A. Golovchenko, "Optical binding," Phys. Rev. Lett. **63**(12), 1233–1236 (1989).
18. A. Constable, J. Kim, J. Mervis, F. Zarinetchi, and M. Prentiss, "Demonstration of a fiber-optical light-force trap," Opt. Lett. **18**(21), 1867–1869 (1993).

#252555 Received 13 Nov 2015; revised 15 Jan 2016; accepted 15 Jan 2016; published 3 Feb 2016
© 2016 OSA

19. S. A. Tatarkova, A. E. Carruthers, and K. Dholakia, "One-dimensional optically bound arrays of microscopic particles," Phys. Rev. Lett. **89**(28), 283901 (2002).
20. W. Singer, M. Frick, S. Bernet, and M. Ritsch-Marte, "Self-organized array of regularly spaced microbeads in a fiber-optical trap," J. Opt. Soc. Am. B **20**(7), 1568–1574 (2003).
21. N. K. Metzger, E. M. Wright, W. Sibbett, and K. Dholakia, "Visualization of optical binding of microparticles using a femtosecond fiber optical trap," Opt. Express **14**(8), 3677–3687 (2006).
22. W. T. Irvine, M. J. Bowick, and P. M. Chaikin, "Fractionalization of interstitials in curved colloidal crystals," Nat. Mater. **11**(11), 948–951 (2012).
23. M. Guillon, O. Moine, and B. Stout, "Longitudinal optical binding of high optical contrast microdroplets in air," Phys. Rev. Lett. **96**(14), 143902 (2006).
24. A. M. Lipaev, V. I. Molotkov, A. P. Nefedov, O. F. Petrov, V. M. Torchinskii, V. E. Fortov, A. G. Khrapak, and S. A. Khrapak, "Ordered structures in a nonideal dusty glow-discharge plasma," J. Exp. Theor. Phys. **85**(6), 1110–1118 (1997).
25. W. T. Juan, Z. H. Huang, J. W. Hsu, Y. J. Lai, and L. I, "Observation of dust Coulomb clusters in a plasma trap," Phys. Rev. E **58**(6), R6947–R6950 (1998).
26. T. M. Grzegorczyk, B. A. Kemp, and J. A. Kong, "Trapping and binding of an arbitrary number of cylindrical particles in an in-plane electromagnetic field," J. Opt. Soc. Am. A **23**(9), 2324–2330 (2006).
27. K. Dholakia and P. Zemánek, "Colloquium: gripped by light: optical binding," Rev. Mod. Phys. **82**(2), 1767–1791 (2010).
28. J. Ng, Z. Lin, C. Chan, and P. Sheng, "Photonic clusters formed by dielectric microspheres: Numerical simulations," Phys. Rev. B **72**(8), 085130 (2005).
29. A. Ashkin and J. M. Dziedzic, "Optical levitation of liquid drops by radiation pressure," Science **187**(4181), 1073–1075 (1975).
30. D. G. Enzer, M. M. Schauer, J. J. Gomez, M. S. Gulley, M. H. Holzscheiter, P. G. Kwiat, S. K. Lamoreaux, C. G. Peterson, V. D. Sandberg, D. Tupa, A. G. White, R. J. Hughes, and D. F. James, "Observation of power-Law scaling for phase transitions in linear trapped ion crystals," Phys. Rev. Lett. **85**(12), 2466–2469 (2000).
31. P. Bak, C. Tang, and K. Wiesenfeld, "Self-organized criticality: an explanation of the 1/f noise," Phys. Rev. Lett. **59**(4), 381–384 (1987).
32. A. Ashkin, "Optical trapping and manipulation of neutral particles using lasers," Proc. Natl. Acad. Sci. U.S.A. **94**(10), 4853–4860 (1997).
33. M. D. Summers, J. P. Reid, and D. McGloin, "Optical guiding of aerosol droplets," Opt. Express **14**(14), 6373–6380 (2006).
34. M. Zhang, G. S. Wiederhecker, S. Manipatruni, A. Barnard, P. McEuen, and M. Lipson, "Synchronization of micromechanical oscillators using light," Phys. Rev. Lett. **109**(23), 233906 (2012).
35. T. A. Nieminen, V. L. Loke, A. B. Stilgoe, G. Knöner, A. M. Brańczyk, N. R. Heckenberg, and H. Rubinsztein-Dunlop, "Optical tweezers computational toolbox," J. Opt. A, Pure Appl. Opt. **9**(8), S196–S203 (2007).
36. T. Beatus, R. H. Bar-Ziv, and T. Tlusty, "The physics of 2D microfluidic droplet ensembles," Phys. Rep. **516**(3), 103–145 (2012).
37. D. W. Sesko, T. Walker, and C. E. Wieman, "Behavior of neutral atoms in a spontaneous force trap," J. Opt. Soc. Am. B **8**(5), 946–958 (1991).
38. T. Carmon, H. Rokhsari, L. Yang, T. J. Kippenberg, and K. J. Vahala, "Temporal behavior of radiation-pressure-induced vibrations of an optical microcavity phonon mode," Phys. Rev. Lett. **94**(22), 223902 (2005).
39. J. D. Thompson, B. M. Zwickl, A. M. Jayich, F. Marquardt, S. M. Girvin, and J. G. E. Harris, "Strong dispersive coupling of a high-finesse cavity to a micromechanical membrane," Nature **452**(7183), 72–75 (2008).
40. M. Eichenfield, R. Camacho, J. Chan, K. J. Vahala, and O. Painter, "A picogram and nanometer scale photonic crystal opto-mechanical cavity," arXiv preprint arXiv:08122953 (2008).

1. Introduction

At the molecular scale, traps can contain many atoms, serving as a testbed for studying quantum phenomena. Such atom ensembles benefit from the relative ease of dealing with the condensate [1–3] as a whole rather than individually engineering a single atom. Additionally, the signal that emerges from many-atoms can be strong enough, while noise is reducible by a variety of cooling techniques [4–7].

Trapping experiments with a single optically levitating sphere were suggested for quantum studies at room temperature [8] as its center-of-mass motion is coolable [9–11] while being minimally coupled with the thermal environment [8].

Optical traps are also sensitive enough to measure Brownian motion [12] and molecular forces [13] as well as holding particles as small 5 nm in size [14] and operating with non-diffracting beams [15]. Extending the original idea of suspending single silica beads in a single beam vertical trap of Ashkin et al [16] to an optical trap that contains many microspheres, is attractive and has often been studied in a viscous environment [17–22] and with multiple-minima traps [18, 20, 23] where each particle clings to a fringe, as well as in many charged particle ion traps and plasmas [24,25]. Additionally, the subject of optical

#252555 Received 13 Nov 2015; revised 15 Jan 2016; accepted 15 Jan 2016; published 3 Feb 2016
© 2016 OSA

binding, there light mediated interaction of optically trapped objects, has also been the subject of extensive work [26, 27].

We here investigate the dynamics of a many particles trapped in a single optical beam as theoretically suggeste in [28] and first experimentally demonstrated in [29]. Such systems might benefit studies of phase transition including zigzag-to-linear [30] and self-organization [31]. One might intuitively expect that many solid particles in a single 3D optical trap will move up the gradient to stick to each other near the well center. Contrary to this expectation, we experimentally report here on a long-range, low-dissipation optical binding where the particles are suspended against gravity by the optical trapping force. The repulsion between particles originates from their mutual scattering of light that modifies the initially smooth trap.

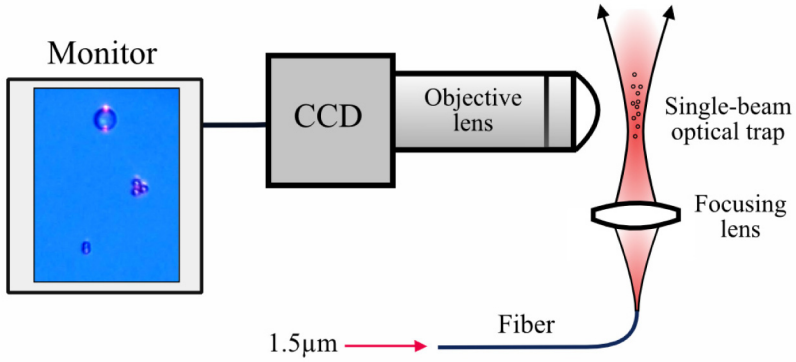

Fig. 1. Experimental setup: silica microspheres are suspended above a single Gaussian beam and give rise to many microspheres trapped near the beam focus.

2. Materials and methods

The experimental setup is shown in Fig. 1. The optical trap uses a 1.5 μm laser that is coupled to a GRIN lens (AR coated, focal length 2 mm, diameter 1.8 mm) via a single-mode optical fiber as suggested in [18, 20] for providing a beam that is smooth along the transverse direction. The beam is also kept smooth along the longitudinal direction as no counter-propagating beams are involved. This is done by keeping the region above the trapping region free from reflectors, only the lab ceiling, which is sufficiently high and scatters the light efficiently.

The combination of AR coating, single mode fibers and open region above guarantees the beam smoothness, as an extra caution this was experimentally checked by scanning along the focus a camera of pixel size 8.4 μm x 9.8 μm, smaller fringes would have been accompanied by scattering at angles larger than 9 degrees, which was not observed in our system. Additionally, we monitored the beam with an IR card at its far field. In all of these cases we could see no irregularities in the beam. All of the above are sufficient to rule out small-scale speckles and fringes.

We estimate that modulation or deviation of the beam from a Gaussian shape is less than 2%. We then suspend the silica particles by first holding them on a glass coverslip and then releasing them by applying a mechanical shock on the coverslip about 5 cm over the lens focus, this distance allows the sphere to reach the terminal velocity.

To minimize thermal effects, a combination of a 1.5 μm laser wavelength and fused silica spheres was chosen. The low absorption of silica at this wavelength (0.2 dB/km) makes that only one part in 10^7 of the laser light is absorbed, considering the worst case (single sphere sitting at the focus under 100 mW irradiation) and a simple steady state heat conduction in air at room temperature, produces a negligible thermal effect, with an upper limit of temperature rise about 0.05 K.

#252555 Received 13 Nov 2015; revised 15 Jan 2016; accepted 15 Jan 2016; published 3 Feb 2016
© 2016 OSA

The optically trapped particles are viewed from the side with a microscope and video camera, manually positioned by an XYZ stage. As background illumination, several blue LEDs were employed.

3. Results and discussion

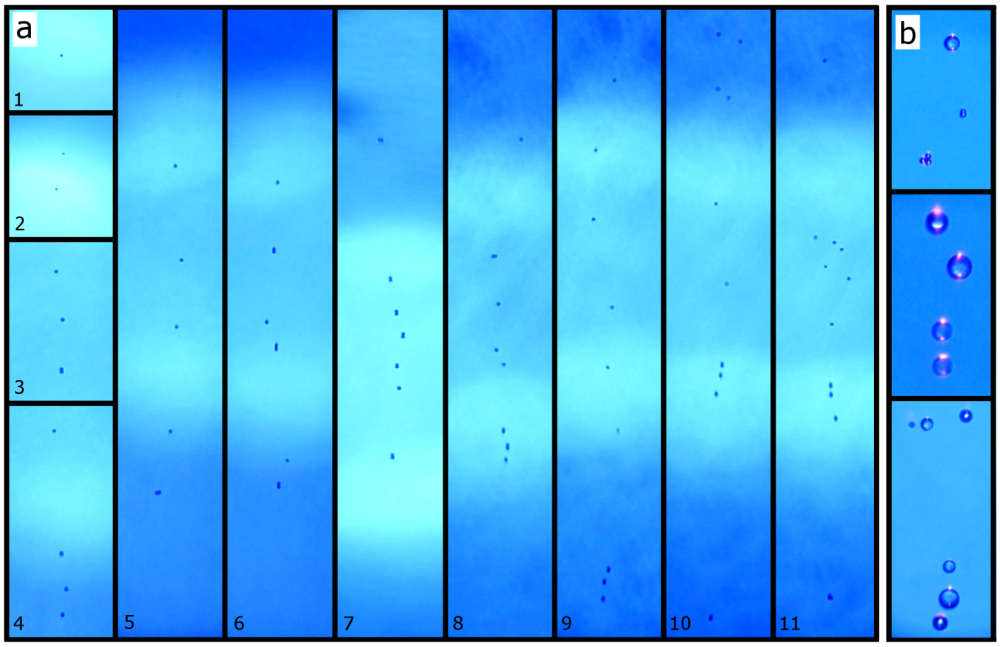

Fig. 2. Clustering of many particles as side viewed for 7 μm silica spheres suspended in air. (a) The number of particles grows from 1 to 11 as they keep falling (see Visualization 1). (b) Zooming-in reveals that multi-sized and multi-shaped particles can also optically bind. Red scattering is from a low-power probe beam (see Visualization 2). Scale bar is 50 μm in all images and beam waist is about 1 sphere diameter. With 11 particles the particle group center of mass was 240 μm above the beam waist.

Clustering of many particles - is observed in the trap at a power of 0.5 W with 7 μm spheres and a beam waist of approximately 1 sphere diameter (Fig. 2 and Visualization 1). Clustering is versatile in that it also occurs when non-spherical particles (which are formed from physically attached spheres) are suspended and clustered, as shown in zoomed-in in Fig. 2(b) and Visualization 2. Trapped objects remain suspended up to several hours, even with large numbers or highly dynamic behavior. Our experiments show that the center of mass of the particles is above the waist. As explained in [32], particles tend to settle at this region since it suggests 'increase in axial scattering force with decreasing height and transverse confinement of the gradient force'.

Temporal dynamic arrangements - created by the interaction of trapped particles range from simple, harmonic motion, to complex and disordered behavior when the particle number increases. Starting with two spheres, periodic oscillations are observed (Fig. 3). Figure 3(a) shows photographs of the two objects over one half period of oscillation. We observed such periodic motion lasting up to several minutes. The vertical (along the laser propagation direction) separation of the two spheres is shown in Fig. 3(b) (red) over a period of 4 s. The vertical position of the center of mass of the two spheres is also shown in Fig. 3(b) (blue). As will be calculated later (Fig. 4(c)), the lower sphere is significantly modifying the field in the upper sphere region, suggesting that oscillation is due to binding between the two

#252555 Received 13 Nov 2015; revised 15 Jan 2016; accepted 15 Jan 2016; published 3 Feb 2016
© 2016 OSA

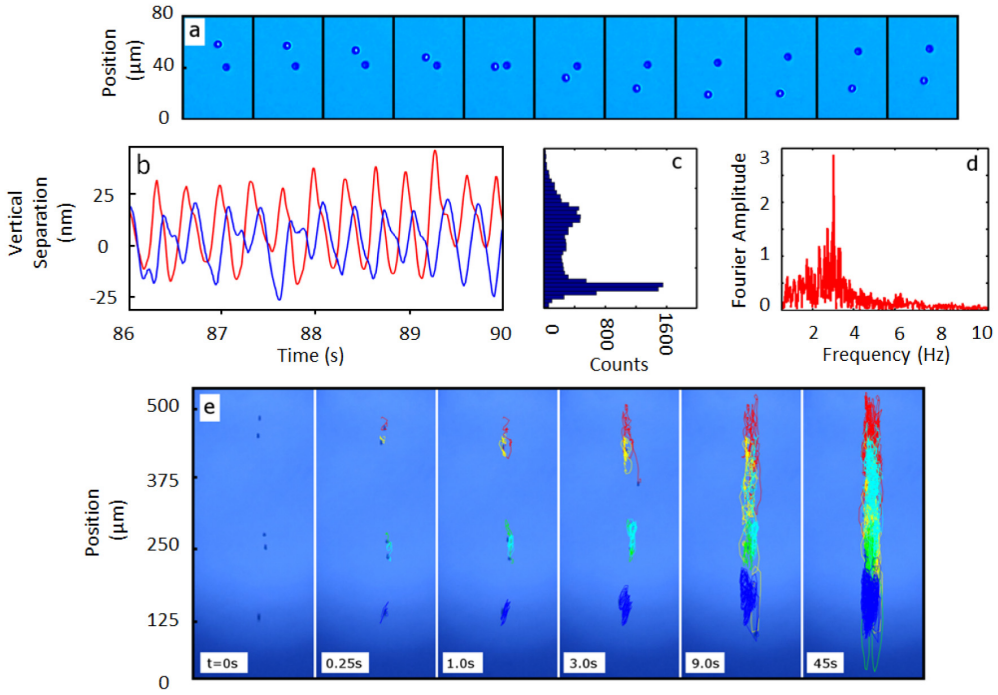

Fig. 3. Dynamics of oscillating microspheres in an optical Gaussian trap (beam waist 0.8 microsphere diameters). Two 7 μm silica microspheres (a) photographed over one half-period of oscillation (see Visualization 3) (b) partial time domain plot of the vertical separation (red) of the objects where changing the sign represents that the two particles were switching positions, and the vertical position of the center-of-mass of the two spheres (blue) (c) histogram of particle positions over 100 s of oscillation, showing two preferred spacings, and (d) Fourier transform of vertical separation data, oscillation is approximately 3 Hz. Non-periodic dynamics: (e) Time evolution of the trajectories for five trapped objects in a beam of waist 0.8 diameters. The particles initially move in small, random orbits near their original positions, but over time exchange places to form new configurations, eventually covering almost completely and area of 40 μm × 450 μm (see Visualization 4).

microspheres. Furthermore, such oscillation was never observed when a single sphere was populating the trap.

Figure 3(c) shows a histogram of the vertical position of the objects over 100s. Two discrete positions where the objects are likely to be found are evident. The oscillation frequency of the vertical separation is about 3 Hz (Fig. 3(d)), and so the histogram represents 300 oscillation periods. The distance between the two preferred positions is 35 μm, which is much larger than either the optical wavelength or the particle radius. The quality factor, where $Q = \nu/\Delta\nu$ is the frequency of the Fourier spectrum is approximately 70. The quality factor describes the energy stored in the system divided by the energy lost in one cycle. The measured Q = 70 shows that our system is operating at the underdamped regime, and the energy is dissipated by Brownian motion in air. The damping factor obtained for a 7 μm sphere in air by the kinematic theory of gases is 2.5 while our measured damping is 0.26 This is in contrast with the interaction of overdamped particles trapped in liquid media [17].

Disordered random motion is observed for larger numbers of interacting objects. Figure 3(e) shows such random paths traced by five trapped objects over the course of 45 s. Each colored line shows the path traced by one object, up to the time indicated on the image. It can be seen that the trapped particles initially move in small areas near their original positions. However, over time the objects move far from these locations, interchanging locations many times and forming new configurations. After less than one minute, an area of 40 μm × 450 μm has been covered almost completely by the trajectories of the five trapped objects.

#252555 Received 13 Nov 2015; revised 15 Jan 2016; accepted 15 Jan 2016; published 3 Feb 2016
© 2016 OSA

Our experimental results are accompanied by a model to give qualitative insight on the observed phenomena. A Comsol-based finite element mode was chosen for the static simulations since it allows dealing with arbitrary shapes and positions for any number of particles while considering multi-reflections. In what follows, we will increase the beam waist and see how the dimensionality of the system changes.

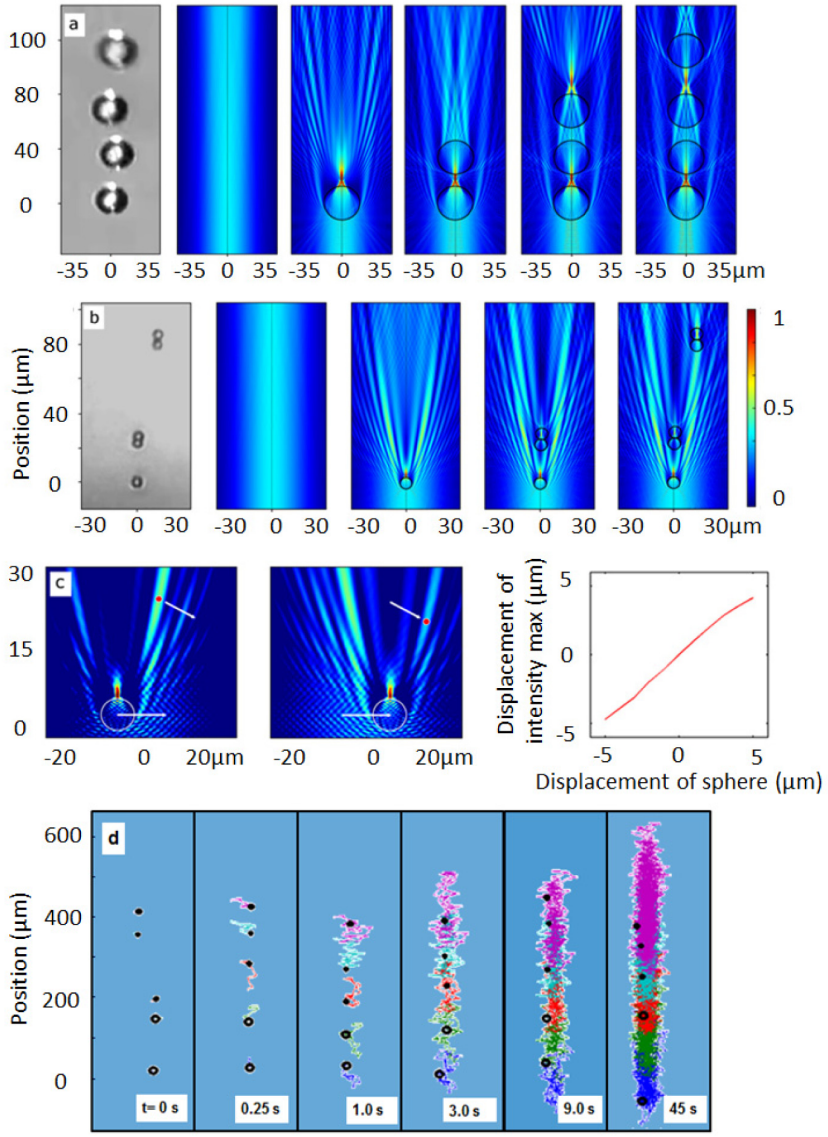

Fig. 4. Experimental results and modeling of (a) Silica microspheres, diameter 25 µm, 1D confined to a Gaussian beam trap (waist 0.8 microsphere diameters). Adding objects creates new intensity maxima, resulting in potential wells for trapping additional objects. (b) One spherical and two non-spherical objects in a weakly focused Gaussian beam (waist 4 microsphere diameters) trap where the structure turns 3D. (c) Long-range interaction of trapped particles. A 10 µm motion of a trapped particle results in a similar sized movement of the potential well at a distance of 4 diameters, or 18 wavelengths. (d) Dynamic simulation of trapped particles in an NA = 0.1 and 0.5 W, Gaussian beam where particle diameters from top to bottom are 5.6, 5.6, 7, 10.5 and 10.5 µm (see Visualization 5), as in the above experiment (Fig. 3.e).

#252555 Received 13 Nov 2015; revised 15 Jan 2016; accepted 15 Jan 2016; published 3 Feb 2016
© 2016 OSA

1D behavior - was experimentally observed, as in [33] when the beam waist was 80% of the sphere diameter. Figure 4(a) shows an experimental photograph of 4 microspheres, nominally 25 μm in diameter, confined to the optical trap at an optical power of 0.5 W. Figure 4(a) also shows the calculated intensity distribution produced by multiple scattering of light by the microspheres. As expected, because of multiple reflections and gravity, trapped objects can be displaced from the intensity maxima. From a general view, the resulting configuration resembles a 1D crystal and might be studied in the future as coupled oscillators [34] where the coupling mechanism is via mutual scattering.

When the beam waist is opened, a phase transition to 3D configuration is observed; this phenomena might be relevant to zigzag-to-linear 25 phase transition studies. Figure 4(b) describes the intensity pattern produced when the beam diameter is increased to 4 bead diameters. An off-axis intensity maximum is formed (Fig. 4(b) right), followed, as expected, by a particle settling there.

A major feature of the experimentally observed binding is that motion of one particle is long-range affecting the motion of another. In accordance with a typical situation seen in our experiment, we calculate in Fig. 4(c) that a 10 μm motion of one particle results a similar-size motion of the potential well at a distance of about 4 diameters away (= 18 wavelengths). In Fig. 4(d) (and Visualization 5), a simulation that combines the optical potential and gravity with the dynamics was performed. It was assumed (in Fig. 4(d)) that each sphere functions as a ball lens that focuses the light that hits it into a new Gaussian beam. The multiple forces that the Gaussian beams apply (the first from the GRIN lens with NA 0.1 and the secondary from the spheres beneath with NA 0.5) computed using the software "Optical tweezers computational toolbox" [35] serve as an input to a dynamic (including gravitational force) model that shows the expected motion. The dissipation was taken from the experimentally-measured mechanical quality factor, and the kinetic energy of the system was kept comparable with the thermal energy, k_BT, by accordingly adding random velocities to each sphere. Limited by our computational resources, this model neglects interference effect between the Gaussian beams involved. Still, this multi-physics simulation (Fig. 4(d) was estimates dynamics similar to what we experimentally observed (Fig. 3(e)).

An important enabler here relates to the fact that particles are not sticking to each other as evident from watching the trapped microspheres for many hours. This repulsion stands in agreement with previous observations of two-sphere system in a 2D aquatic environment [17]. Such repulsion originates from multi-reflections between particles as calculated in Fig. 4(a) and shown, for example, in the form of the intensity modification between the first two particles. Another repulsion mechanism originates from the dark fringes between the trap's minima. These dark fringes are inherent to coherent light scattering and function as a wall that separates particles (Figs. 4(a)-4(c)). Particle separation here might resemble repulsion in other many-body systems in nature including droplets in fluids [36] and atoms [37].

The final position and movement of the particles are determined by a manifold of well-known and reproducible parameters like the laser power and numerical aperture, but the initial position and speed of the particles (which are random within some degree) have a strong effect on the final configuration and dynamics of the trapped cluster above. We can qualitatively assert that most of the experiments resulted in a series of static particles in numbers between 1 and 5 (moving only within Brownian limits) like shown in Fig. 2 while about 10% of the experiments gave some degree of random motion like the one shown in Fig. 3(e) when the particle number increases between 4 and 10 and in rare cases, about 5% of the experiments, a periodic motion like the one shown in Fig. 3(a) was observed.

As for future experiments, an interesting question is what will happen in vacuum when the trap is turned off. As an example, we will take thirty 1 μm spheres trapped at 300 K in a 10 μm region and calculate their dynamics after the trap is turned off. About 5 ms after release, only half of the particles (the slow ones) will stay at a free-falling 10 μm region while their average temperature decreases to 200 K.

#252555 Received 13 Nov 2015; revised 15 Jan 2016; accepted 15 Jan 2016; published 3 Feb 2016
© 2016 OSA

3. Conclusion

In conclusion, we believe that our many particle optical trap can impact light-matter studies by providing a many-body test bed that is coolable [11] and almost free from clamping-loss or material-dissipation of mechanical energy [38–40]. A variety of particles shapes and sizes that we demonstrate to be dynamically trapped along the transverse and longitudinal dimensions is achieved by our relatively simple experiment where only one Gaussian beam is involved. It is expected that increasing the optical intensity and adding a counter propagating beam of transverse polarization, will bring us closer to the high frequencies where cooling [11] is likely (e.g. by placing the trapped microspheres in a blue-detuned resonator).

By using nano-particles [14], which calculation [28] and experiments [14] suggests possible, will allow less dissipation by light [8] (in vacuum) to further increase isolation from thermal environment. While systems such as BEC and ion traps are widely studied, our still unexplored light-matter system might serve as a many-body testbed benefitting from isolation [28] and coolability [11].

#252555 Received 13 Nov 2015; revised 15 Jan 2016; accepted 15 Jan 2016; published 3 Feb 2016
© 2016 OSA