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Preferred Locations in a Laser Beam for Photophoretic Trapping of Microscopic Particles

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ABSTRACT

Photophoresis can trap opaque microscopic particles in a focused laser beam surrounded by a gas such as air. The particle is heated by the laser, and in turn, interactions with the ambient gas provide a stabilizing force that holds the particle in a specific region of the beam. The particles can stay trapped while the beam is moved side to side up to 2 m/s, enabling three-dimensional images to be traced out in a display application. Structure in the laser beam is associated with the trapping phenomenon, but the fundamental mechanism for stability of the trap remains mysterious. Particles prefer regions of the beam with diffraction features such as those that arise from spherical aberration. Nevertheless, the ability of near-unidirectional light, albeit light that undergoes focusing and exhibits structure, to provide a restoring force to trapped particles in the direction opposite to beam propagation needs to be explained. Through repeated trials of capturing particles in a well characterized beam, we map out the preferred locations for particle capture and correlate them with diffraction features of the beam. The specific beam locations that host trapped particles, when compared with neighboring regions that do not, can offer insight into the stability mechanism. We analyze the Poynting vector in the vicinity of trapped particles. The flow of light energy can provide important clues into the trapping mechanism.

Keywords: photophoresis, optical trapping, volumetric display

1. INTRODUCTION

Soon after the development of the laser, Rawson and May observed dust particles being propelled by the beam in a laser cavity.[1] They conclude that photophoresis was the cause of this behavior. In their words, "photophoresis is the net transfer of momentum to a particle with a temperature gradient due to gas molecules rebounding from the hotter side with greater momentum than from the colder side." Photophoresis in other contexts has been studied for over a century.[2–8]

In 1981, Lewittes et al. observed for the first time stable trapping of opaque particles near a laser focus.[9] They concluded that radiometric recoil of gas molecules from the hotter side of the particle was the mechanism responsible for levitation. They argued that particles were pushed into an intensity minima. They employed a beam featuring structure with intensity minima, directed upward to oppose the force of gravity. Soon after, Antonio Pluchino reported trapping of microscopic carbon particles in a laser[10] both upstream and downstream of the focus. Pluchino was able to trap particles with the beam orientated in any direction, even downward. Pluchino believed that "due to the particle being surrounded by regions of higher energy density and swirling energy flow" they could become trapped in the laser beam. Pluchino believed that the primary mechanism for trapping was extra light energy being absorbed on the 'shady' side of the particle.

In 2002, Huisken and Stelzer, levitated metal particles surrounded by air in an upward directed laser beam.[11] They suggested that the trapping phenomenon is governed by thermal creep, a form of photophoresis involving interdiffusion of hot and cold molecules near the edges of a Crooke's radiometer.

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Between 2002 and 2010, a series of students at Brigham Young University (BYU) investigated photophoretic trapping.[12–19] They examined the effects of material, particle size, beam power, ambient pressure, gravity, and beam structure, which are highlighted below. The BYU work was done using wavelengths 456 nm and 532 nm and powers up to a few watts. A variety of particles were readily caught and held indefinitely in a Gaussian laser beam focused with f/10 using a plano-convex spherical lens: tungsten, silver, aluminum, nickel, iron, magnesium oxide, charcoal, graphite, and cellulose (ranging in size from a few microns to ten or twenty microns).[13] Particles were sprinkled into the beam focus, where self selected particles became trapped, presumably based on size, shape, and local beam characteristics. Once trapped, particles stayed in the beam as it was moved by steering a mirror near the focusing lens. Particles could be held with as little as ten milliwatts of laser power, although power on the scale of a watt or more makes the initial trapping of a particle easier.[13] We also controlled ambient gas pressure and found that the trapping phenomenon can be sustained at pressures as low as a few torr and at pressures up to ten atmospheres.[16,18] The most stable trapping pressure was found to be about 200 torr. The trapping behaved similarly in helium or argon. The trapping behavior showed no apparent sensitivity to gravity;[14] in 2006, BYU students performed experiments onboard a NASA jet that provided zero gravity and $2g$ in 30-second intervals; no difference in trapping effectiveness was noticed at $0g$, $1g$, or $2g$. In other BYU experiments, a microscope objective was used to record zoomed-in movies of trapped particles.[15] Particles were seen to undergo rapid oscillations along the direction of laser beam, experiencing acceleration in excess of $10g$. Some asymmetric particles were seen to spin or tumble while being held stably in the laser beam.

Beginning in 2009, Shedov et al. published a series of experiments where particles in air were trapped and their movements controlled using various laser beams, including "vortex" and "bottle" beam profiles and counter-propagating geometries.[20–26] Other researchers[27–30] in the recent past have demonstrated trapping of small absorptive particles surrounded by air near the focus of individual laser beams, typically with beam structure intentionally introduced.

While most researchers agree that the trapping arises from a photophoresis force, it is less obvious how this force leads to stable trapping in a unidirectional beam, even if there are local intensity minima or maxima present. A variety of explanations have been offered for the trapping phenomenon. For example, in 2015, Redding[30] argued that asymmetries in particle shape and/or surface quality can cause an otherwise uniformly heated particle to accommodate interactions with gas molecules differently on different sides, which could lead to stable trapping. We note that this explanation is inconsistent with our observation of some asymmetric particles tumbling while being trapped. Because a mechanism for stable trapping is not immediately obvious, many researchers in the past, at least initially, have employed trapping schemes that use counter-propagating beams, a substrate to trap against, or arranged for the force of gravity to provide a balance against an assumed unstable photophoretic force.[11,12,21–24,27–32]

We recently demonstrated the ability to draw centimeter-scale patterns by sweeping a particle trapped in a laser focus through a volume of space.[33] Cellulose particles can become caught in a laser beam with sufficient stability to withstand mild breezes in the open air and to track with the beam at speeds up to 2 m/s. The generated images rely on visual persistence as laser light scatters from the particle while it is swept through the 3-D pattern. The potential interest in three-dimensional displays based on this scheme provides strong motivation to try to greatly increase the sweep speed for particles that remain stably trapped in the laser beam.

2. BEAM STRUCTURE

When opaque particles are trapped in the beam, we, like other researchers, observe that they are usually tethered to a particular location. This observation makes it plausible that local intensity structures (minima, maxima, or perhaps intensity gradients) play a role in the trapping. In this context, it is surprising that Pluchino,[10] our group,[17] and Zhang[27] came to the conclusion that a relatively smooth beam can trap particles. More recently, we realized that our 'smooth' beam used in the past was likely influenced by spherical aberration, and we have reexamined the extent to which structure in a laser beam is required to capture particles.

We observe that it is much easier to trap particles using a spherical lens than an aspherical lens. To explore this further, we calculated the diffraction pattern created when a Gaussian laser beam is focused using a spherical-planar lens using the technique originally developed by Ignatovsky and described in our recent article.[34] In Fig. 1 we plot a two-dimensional slice of this diffraction pattern in the x-z plane, where $+z$ is the direction of propagation and x is the direction of polarization for the beam. In this plot, we renormalize the intensity at every z position to highlight the structure of the beam. Notice that the upstream portion of the beam just prior to the focus contains significant structure. This is due to the fact that parts of the beam at different radii experience differing amounts of spherical aberration

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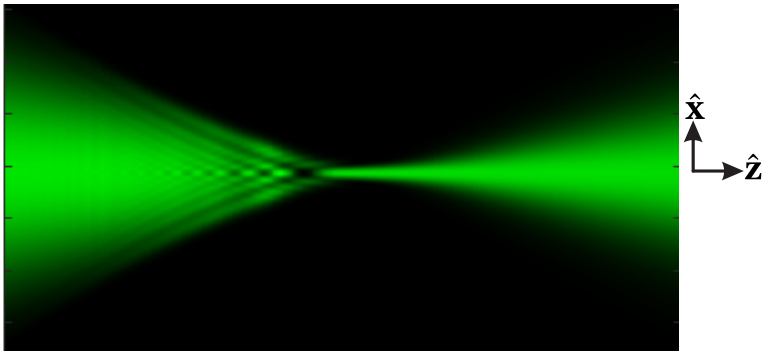


Figure 1. Calculated diffraction pattern in the x,z plane (where $+z$ is the propagation direction) for a Gaussian beam focused using a f/10 plano-spherical lens and 532 nm.laser light. Notice the interference structure upstream from the focus.

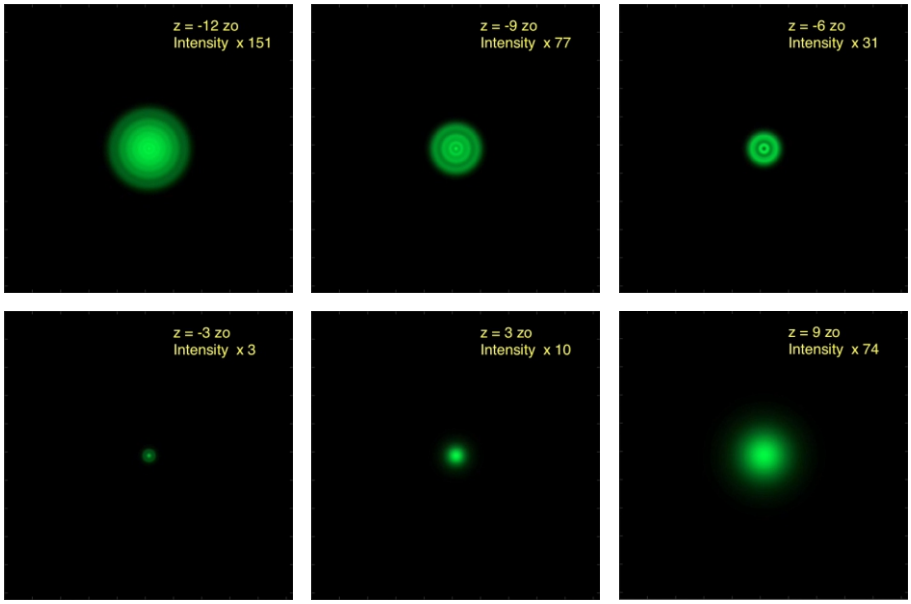


Figure 2. Calculated diffraction pattern in the x,y plane at various z positions. The same parameters are used as in Fig. 1. Again, the interference structure is apparent upstream from the focus, and washes out downstream of the focus.

and these portions interfere to create a diffraction pattern. Downstream of the focus, the interference washes out for a smooth beam profile. Figure 2 shows this same diffraction pattern plotted in the x-y plane at a variety of z positions.

We also directly measured the beam profile of a spatially-filtered 532 nm laser with a diameter of approximately 1 cm focused using a plano-convex f/10 lens. Figure 3 is an image of the Rayleigh scattering collected laterally from the beam using a 20× microscope objective positioned out the side of the laser beam. The shallow depth of field for this objective makes this image roughly comparable to Fig. 1. While the out-of-plane light washes out much of the interference structure, the general features of interference structure upstream of the focus and a smooth beam downstream of the focus is apparent. For Fig. 4 we placed a high-resolution CCD camera directly in the (attenuated) beam at various z positions before and after the focus. In these images the upstream structure and the downstream smooth beam is clear. As a control, we also made a series of measurements using an aspherical lens, shown in Fig. 5. While the aspherical lens displays some structure due to imperfections, the general pattern is much smoother than that of the spherical lens.

In a series of measurements, we found that particles were readily trapped in the focus made by the spherical lens, while it was very difficult to trap in the focus made by the aspherical lens (we were only able to trap one particle in

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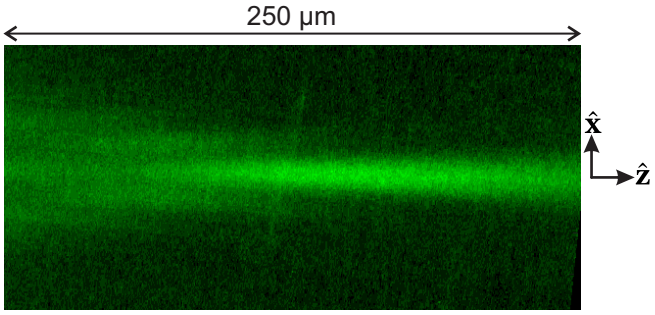


Figure 3. Measured Rayleigh scattering out the side of a laser focus produced by focusing a spatially filtered Gaussian beam with a plano-spherical lens.

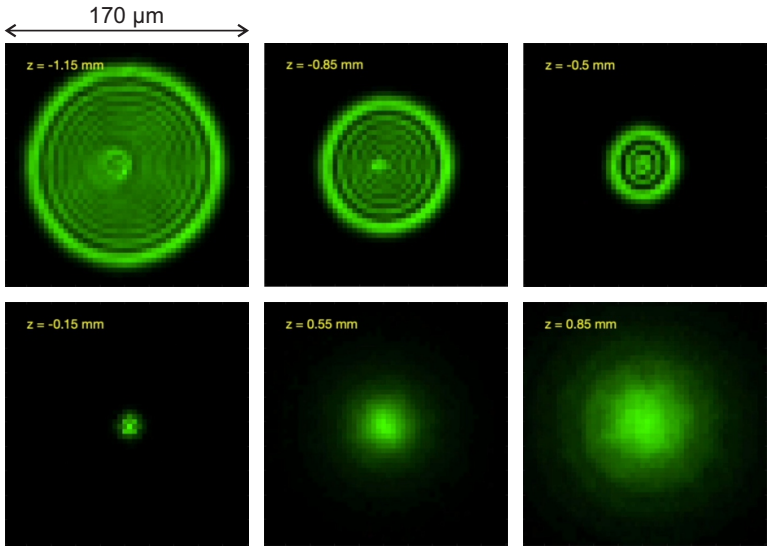


Figure 4. Directly measured diffraction pattern in the x,y plane at various z positions for a laser focused with a plano-spherical lens. Images were produced by placing the CCD camera directly in the attenuated laser beam.

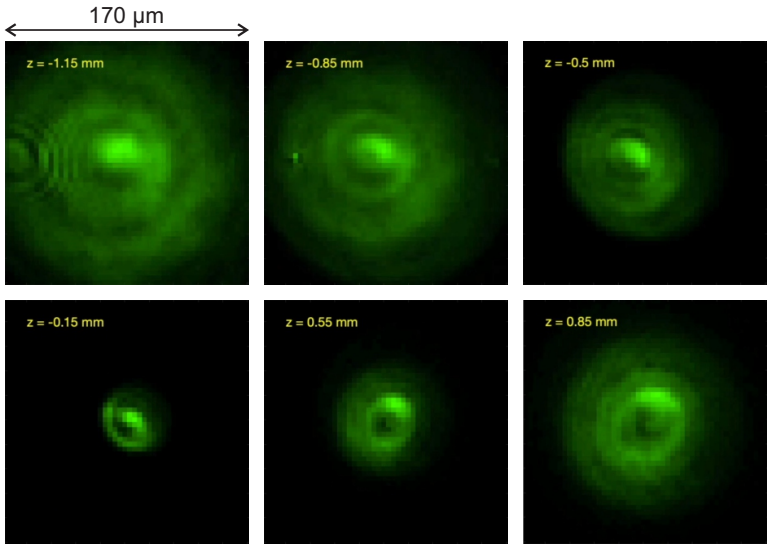


Figure 5. Directly measured diffraction pattern in the x,y plane at various z positions for a laser focused with an aspherical lens. Images were produced by placing the CCD camera directly in the attenuated laser beam.

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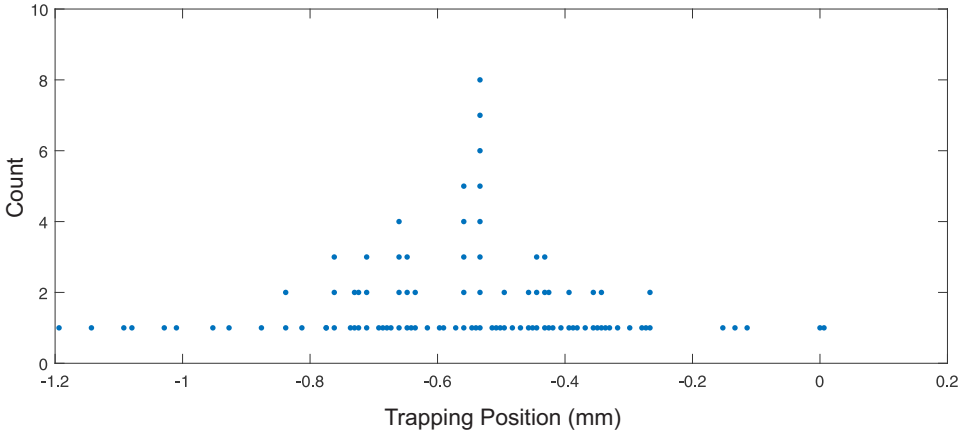


Figure 6. Histogram of the spatial location (in mm) of the trapping position for particles sprinkled into a laser focus. The laser focus is at 0 mm, and negative values represent the upstream direction.

many dozen attempts). Furthermore, we found that the particles trapped in the spherical focus always trapped in the upstream portion of the beam where the structure was apparent. We thus conclude, as did Shvedov and coworkers,[25] that the interference structure plays an important role in trapping.

3. TRAPPING LOCATION

Using a microscope objective and a CCD camera, we studied the motion and location of particles trapped in the beam characterized by Figs. 3 and 4 with 1 watt of power. Particles were imaged via scattered laser light using a 20× microscope objective positioned out the side of the laser beam. In various trials, we observed particles that were essentially stationary to within a few microns; particles that exhibited large, complicated orbits withexcursions on the scale of 150 μm; particles with orbits that appeared to circle in and out of the plane of the image, perhaps along a diffraction ring; particles whose position was metastable, hopping between adjacent well-defined stable positions along the z-axis of the laser; and sets of particles with fixed spacing between the particles on the scale of a hundred microns, that execute synchronous motion, i.e., in phase oscillations left to right. In other trials, we have occasionally seen particles that appear to rotate or tumble as they execute oscillations.[15] The particles were loaded by sprinkling dust through the focus, so that particle properties and trapping locations were self selected. The trapped particles we observed ranged in size from a few microns up to about 10 microns.

In a series of trials, we recorded the z position of the trapped particles. Figure. 6 plots the distribution of trapping locations in the beam for 100 trials where cellulose particles were sprinkled into the laser focus. Several particles typically became trapped on a given trial, in which case we recorded only the most upstream particle because of concerns that upstream particles might influence downstream trapping locations. A clear preference for trapping in certain regions of the beam is evident. We are working to correlate the preferred trapping locations with specific diffraction features in the beam.

4. SUMMARY

We have studied the behavior of trapped opaque particles near a laser focus with and without spherical aberration. While it is clear that the particles are acted upon by a photophoretic force, how the force leads to stable trapping remains unclear, even in a beam with high-contrast diffraction structure. We are investigating the vector fields in such a beam and calculating the Poynting vector to learn the details of energy flow in diffraction regions. The distinctive dynamics of the trapped particles outlined above may provide further insights into the mechanisms for stable trapping. Improved understanding of the mechanisms that lead to trapping may lead to opportunities to better engineer traps with customized properties.

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REFERENCES

[1] Rawson, E. G. and May, A., "Propulsion and angular stabilization of dust particles in a laser cavity," *Appl. Phys. Lett.* **8**, 93–95 (1966).

[2] Ehrenhaft, F., "On the physics of millionths of centimeters," *Phys. Z.* **18**, 352–368 (1917).

[3] Rosen, M. and Orr, C., "The photophoretic force," *J. Colloid. Sci.* **19**(1), 50–60 (1964).

[4] Rohatschek, H., "Direction, magnitude and causes of photophoretic forces," *Journal of Aerosol Science* **16**(1), 29–42 (1985).

[5] Rohatschek, H., "Semi-empirical model of photophoretic forces for the entire range of pressures," *J. Aerosol Sci.* **26**(5), 717–734 (1995).

[6] Davis, E. J., "A history of single aerosol particle levitation," *Aerosol Science and Technology* **26**(3), 212–254 (1997).

[7] Jovanovic, O., "Photophoresis—light induced motion of particles suspended in gas," *Journal of Quantitative Spectroscopy and Radiative Transfer* **110**(11), 889–901 (2009).

[8] Horvath, H., "Photophoresis-—a forgotten force ??," *KONA Powder and Particle Journal* **31**, 181–199 (2014).

[9] Lewittes, M., Arnold, S., and Oster, G., "Radiometric levitation of micron sized spheres," *Appl. Phys. Lett.* **40**(6), 455–457 (1982).

[10] Pluchino, A. B., "Radiometric levitation of spherical carbon aerosol particles using a Nd:YAG laser," *Appl. Opt.* **22**(12), 1861–1866 (1983).

[11] Huisken, J. and Stelzer, E. H. K., "Optical levitation of absorbing particles with a nominally Gaussian laser beam," *Opt. Lett.* **27**(14), 1223–1225 (2002).

[12] Bellville, B., "Single-beam laser traps for opaque or reflective particles." Senior Thesis, Brigham Young University (April 2002), https://physics.byu.edu/library/theses/2002.

[13] Bliss, C. L., "Optical levitation of intensity-fleeing particles in a single-beam laser trap." Senior Thesis, Brigham Young University (August 2002), https://physics.byu.edu/library/theses/2002.

[14] Painter, J., "Optical levitation of opaque particles in a laser beam: Zero-gravity experiment." Senior Thesis, Brigham Young University (August 2004), https://physics.byu.edu/library/theses/2004.

[15] Hendrickson, A., "Radiometric levitation of opaque particles in a laser beam." Senior Thesis, Brigham Young University (August 2005), https://physics.byu.edu/library/theses/2005.

[16] Lindsey, R., "Optical levitation of opaque particles in a laser beam at high and low pressures." Senior Thesis, Brigham Young University (August 2005), https://physics.byu.edu/library/theses/2005.

[17] Martin, M., "High-resolution imaging of a laser beam used to levitate opaque microscopic particles." Senior Thesis, Brigham Young University (August 2007), https://physics.byu.edu/library/theses/2007.

[18] Peterson, R., "Radiometric particle levitation in a laser beam at high ambient gas pressure." Senior Thesis, Brigham Young University (August 2008), https://physics.byu.edu/library/theses/2008.

[19] Black, D., "Spatial distribution of laser light absorption by small spheres undergoing mie scattering." Senior Thesis, Brigham Young University (April 2010), https://physics.byu.edu/library/theses/2010.

[20] He, H., Heckenberg, N., and Rubinsztein-Dunlop, H., "Optical particle trapping with higher-order doughnut beams produced using high efficiency computer generated holograms," *J. Mod. Opt.* **42**(1), 217–223 (1995).

[21] Shvedov, V. G., Desyatnikov, A. S., Rode, A. V., Krolikowski, W., and Kivshar, Y. S., "Optical guiding of absorbing nanoclusters in air," *Opt. Express* **17**(7), 5743–5757 (2009).

[22] Desyatnikov, A. S., Shvedov, V. G., Rode, A. V., Krolikowski, W., and Kivshar, Y. S., "Photophoretic manipulation of absorbing aerosol particles with vortex beams: theory versus experiment," *Opt. Express* **17**(10), 8201–8211 (2009).

[23] Shvedov, V. G., Desyatnikov, A. S., Rode, A. V., Izdebskaya, Y. V., Krolikowski, W. Z., and Kivshar, Y. S., "Optical vortex beams for trapping and transport of particles in air," *Appl. Phys A* **100**, 827–331 (2010).

[24] Shvedov, V. G., Rode, A. V., Izdebskaya, Y. V., Desyatnikov, A. S., Krolikowski, W., and Kivshar, Y. S., "Giant optical manipulation," *Phys. Rev. Lett.* **105**, 118103 (2010).

[25] Shvedov, V. G., Hnatovsky, C., Rode, A. V., and Krolikowski, W., "Robust trapping and manipulation of airborne particles with a bottle beam," *Opt. Express* **19**(18), 17350–17356 (2011).

[26] Turpin, A., Shvedov, V., Hnatovsky, C., Loiko, Y. V., Mompart, J., and Krolikowski, W., "Optical vault: A reconfigurable bottle beam based on conical refraction of light," *Opt. Express* **21**(22), 26335–26340 (2013).

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[27] Zhang, Z., Cannan, D., Liu, J., Zhang, P., Christodoulides, D. N., and Chen, Z., "Observation of trapping and transporting air-borne absorbing particles with a single optical beam," *Opt. Express* **20**(15), 16212–16217 (2012).

[28] Woerdemann, M., Alpmann, C., Esseling, M., and Denz, C., "Advanced optical trapping by complex beam shaping," *Laser & Photonics Reviews* **7**(6), 839–854 (2013).

[29] Wang, C., Pan, Y.-L., and Coleman, M., "Experimental observation of particle cones formed by optical trapping," *Opt. Lett.* **39**(9), 2767–2770 (2014).

[30] Redding, B., Hill, S. C., Alexson, D., Wang, C., and Pan, Y.-L., "Photophoretic trapping of airborne particles using ultraviolet illumination," *Opt. Express* **23**(3), 3630–3639 (2015).

[31] Sato, S., Harada, Y., and Waseda, Y., "Optical trapping of microscopic metal particles," *Opt. Lett.* **19**, 1807–1809 (Nov 1994).

[32] Rubinsztein-Dunlop, H., Nieminen, T., Friese, M., and Heckenberg, N., "Optical trapping of absorbing particles," *Advances in Quantum Chemistry* **30**, 469–492, Academic Press (1998).

[33] Smalley, D. E., Nygaard, E., Squire, K., Van Wagoner, J., Rasmussen, J., Gneiting, S., Qaderi, K., Goodsell, J., Rogers, W., Lindsey, M., Costner, K., Monk, A., Pearson, M., Haymore, B., and Peatross, J., "A photophoretic-trap volumetric display," *Nature* **553**, 486–490 (2018).

[34] Peatross, J., Berrondo, M., Smith, D., and Ware, M., "Vector fields in a tight laser focus: comparison of models," *Opt. Express* **25**(13), 13990–14007 (2017).

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