Preferred Trapping Locations of Microscopic Particles Held in a Laser Beam via Photophoresis

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ABSTRACT

It has been known for decades that microscopic dust particles can become trapped near the focus of a continuous laser beam when surrounded by ambient gas such as air. In this photophoretic interaction, the laser heats the particle, which interacts with surrounding gas molecules. Trapped particles typically scatter significant laser light as they are suspended in midair and can be easily observed from the side of the beam. We report on the first on-axis images of photophoretically trapped particles together with the laser-beam profile responsible for the trapping. The radial structure of the laser is recorded using 1:1 imaging, where the 1 W beam must be strongly attenuated without introducing distortion. The trapped particle is weakly illuminated using a different wavelength, chosen to transmit through the filters used to attenuate the laser.

Keywords: Particle Trapping, Photophoresis

1. INTRODUCTION

Soon after the invention of the laser, Rawson and May reported seeing dust particles executing interesting motion in a laser beam.[1] They hypothesized that photophoresis was responsible for the behavior. In this photophoretic interaction, dust particles are heated by the laser, which alters their interaction with ambient air molecules. Rawson and May suspected that one side of the dust particle absorbed more light, becoming hotter and causing air molecules to rebound with extra momentum to impart a net force on the particle.

In 1981, Lewittes and Arnold observed that this phenomenon could lead to stable trapping of opaque particles near a laser focus.[2] They argued that opaque particles seek out intensity minima within a structured beam. The following year, Pluchino reported trapping multiple microscopic carbon particles in a laser operating in the TEM00 mode,[3] both before and after the focal plane. Pluchino was able to trap particles with the beam orientated in any direction, and he believed that light energy swirled around the micron-size particles to cause greater light energy to be absorbed on the back side, giving rise to the stability of the trapping. In 2002, Huisken and Stelzer, levitated metal particles surrounded by air with an upward directed laser beam.[4]

A series of student theses[5–12] at Brigham Young University investigated this phenomenon between 2002 and 2010. The effects of material, particle size, beam power, ambient pressure, gravity, and beam shape were studied.[13] More recently, we showed how trapped particles can be controlled and used to draw images for a volumetric display.[14–16]

A number of researchers[17–26] have demonstrated trapping of small absorptive particles surrounded by air near the focus of individual laser beams, typically with beam structure intentionally introduced. Most agree that the trapping phenomenon is governed primarily by a photophoresis force.[27–33] However, there is no consensus for explaining the stability of the trapping. If particles flee regions of high intensity, why are they not swept downstream by the laser, even from local minima inf a structured beam? If particles seek high intensity, why are they not observed in the most intense focal region of the beam?

To answer the question of how an opaque particle becomes stably trapped in a laser, we must first answer the question of precisely where within a structured beam trapped particles reside. To this end, we have measured on-axis images of photophoretically trapped particles in the context of the laser-beam profile responsible for holding them trapped. These images distinguish whether particles become trapped in local intensity minima, maxima, or the gradient between. This increased understanding may lead to the design of structured light beams with improved trapping stability for such applications as volumetric displays.

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2. IMAGING TRAPPED PARTICLES WITH THE BEAM

We trap particles in a 532 nm continuous laser beam that is spatially filtered to produce a smooth 12 mm diameter, near-Gaussian profile. We focus the 1-W beam using a spherical plano convex lens with focal length $f = 6.5$ cm. The focusing lens introduces spherical aberration, which results in diffraction structure in the approximately 1 mm region just before the tightest focus. We introduce cellulose particles (a few microns in diameter) into this region, some of which become suspended in the laser, stably trapped. The setup for imaging both the laser beam and a trapped particle is shown in Fig. 1.

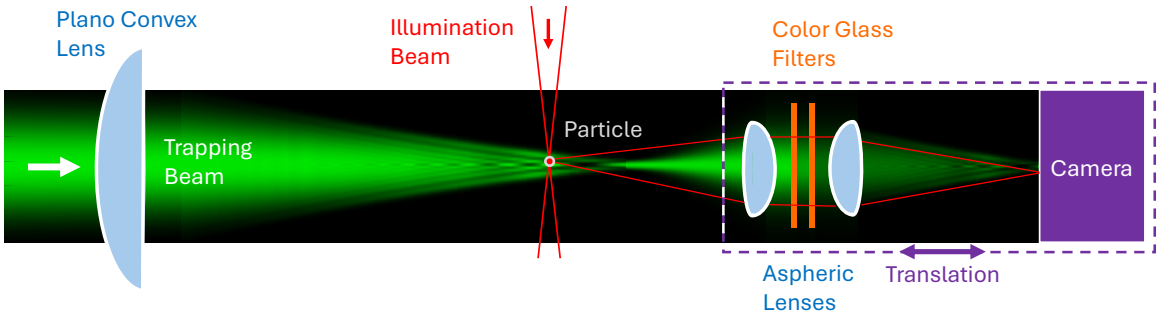


Figure 1. Side view of experimental setup for imaging trapped particles and the trapping beam.

The light scattered from the particle is much weaker than the surrounding beam, making it challenging to simultaneously see both the particle and the trapping beam when they are imaged onto the same camera. Moreover, the imaging optics must not introduce aberrations that distort the trapping beam structure, since the beam structure is what we wish to study. To distinguish the trapped particle from the much brighter surrounding beam, we laterally illuminate the trapped particle using a 15 mW, 610-nm laser beam focused loosely with $f/100$. The illumination wavelength is chosen to transmit well through color-glass filters, which strongly attenuate the trapping laser (with optical density ~ 10).

The radial structure of the laser is recorded using the imaging system shown in Fig. 1. To avoid thermal distortions, the imaging system must be sufficiently large to disperse the trapping laser power across the surface of the absorption filters. We employ two aspheric lenses with $f = 5$ cm in a 1:1 configuration.

We verified that the imaging system faithfully reproduces the laser beam structure by scanning a camera along the axis of the beam directly in the focus (with attenuation) and comparing with a similar scan produced using the imaging system. We found that aspheric achromat lenses introduce unacceptable additional spherical aberration, which alters the structure in the imaged beam. Instead, we used a pair of simple aspheric lenses that reproduce the beam profile without noticeable alteration.

Unfortunately, the focal length of the imaging system is different for the 532-nm trapping light and the 610-nm illumination light. We compensate by calibrating this difference and translating the imaging system parallel to the laser axis when taking pictures at each wavelength. To calibrate, we take a picture of a 2-μm pinhole back illuminated by each wavelength. We found that, to form a sharp image of the pinhole, we need to move the imaging system 1250 μm closer to the pinhole when back illuminated by 532 nm, compared to 610 nm. When moving such a distance, the translation stage must move parallel to the axis of the trapping laser beam to within two milliradians in order to avoid lateral shifts of the camera by more than a pixel width.

3. IMAGING TRAPPED PARTICLES WITH THE BEAM

Figure 2 shows images of two particles separately trapped at two locations before the tightest focus of the trapping beam. After trapping a particle, we translate the imaging system so that the particle is in focus for the 610-nm illumination wavelength. A picture is then taken of the trapped particle using a monochrome camera (with 1.8-μm pixel spacing) with and without the illumination laser turned on. These two images are subtracted to remove the out-of-focus trapping laser from the image of the particle. Next, we move the imaging system

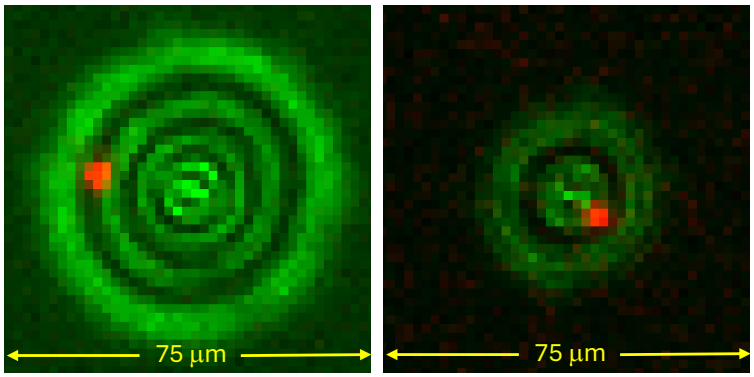


Figure 2. Images of beam with trapped particles 610 μm (left) and 380 μm (right) upstream of tightest focus. Red shows the location of the particle and green is the laser focus structure.

1250 μm closer to the focus so that the corresponding plane for the 532-nm trapping laser is in focus. With the illumination laser turned off, an image is taken of the trapping beam at this corresponding plane. The images of the particle and the surrounding trapping beam are then added (after applying pseudo color to each). The exposure time for each image is adjusted separately to put the two images on a similar brightness scale.

As seen in Fig. 2, in our setup, particles become photophoretically trapped at low-intensity locations within the structure of our spherically aberrated beam. This conclusion persists over many repeated trials of trapping and imaging particles, which become trapped at a wide variety of locations both radially and axially. The two images in Fig. 2 are of planes 230 μm apart. While it makes sense that heating the particle by the light could nudge the particle radially toward low-intensity regions, it remains unclear how the particle becomes stably trapped against axial motion. After all, even for our $f/5$ focusing, the laser energy flows in a single direction to within $\pm 6^\circ$. Further analysis is needed to fully explain the trapping stability.

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