# Selective trapping of multiple particles by volume speckle field

**Vladlen G. Shvedov**[1,2,3]**, Andrei V. Rode**[1]**, Yana V. Izdebskaya**[2,3]**, Anton S. Desyatnikov**[2]**, Wieslaw Krolikowski**[1]**, and Yuri S. Kivshar**[2]

[1]*Laser Physics Center, Research School of Physics and Engineering, The Australian National University, Canberra ACT 0200, Australia*
[2]*Nonlinear Physics Center, Research School of Physics and Engineering, The Australian National University, Canberra ACT 0200, Australia*
[3]*Department of Physics, Taurida National University, Simferopol, Crimea, Ukraine*

*vgs124@physics.anu.edu.au; avr111@physics.anu.edu.au*

**Abstract:** We suggest a new approach for selective trapping of light absorbing particles in gases by multiple optical bottle-beam-like traps created by volume speckle field. We demonstrate stable simultaneous confinement of a few thousand micro-particles in air with a single low-power laser beam. The size distribution of trapped particles exhibits a narrow peak near the average size of an optical speckle. Thus, the speckle-formed traps act as a sieve with the holes selecting particles of a similar size.



**OCIS codes:** (350.4855) Optical trapping, optical manipulation

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## 1. Introduction

Since the pioneering work of Ashkin [1] optical trapping and manipulation of particles by laser beams became indispensable tool in different fields of science. Most of the concepts for optical control [2, 3] and sorting [3–6] of microscopic particles are based on the radiation pressure of light. At the same time, the radiation pressure acting on airborne absorbing particles [7], in contrast to transparent aerosols [8–10], can be diminished by photophoretic forces [11].

The idea of utilizing inhomogeneous laser-induced heating in gases and employing photophoretic forces for trapping of particles was suggested some years ago [12–14]. Photophoretic forces are caused by interaction of molecules of the surrounding gas with the heated surface of a particle. Gas molecules reflected from a hotter side of the particle acquire higher speed than those reflected from a colder side and, as a result, the particle acquires a net momentum [15]. In spite of those earlier ideas, stable trapping of absorbing particles in air has been achieved only recently in a new trap created by two counter-propagating optical vortex beams [16, 17]. The corresponding light intensity distribution retains an axial symmetry with vanishing intensity at the beam center creating a stable attractive potential for absorbing particles. The distinct feature of this trapping geometry is that particles are trapped in the region of the minimum intensity of

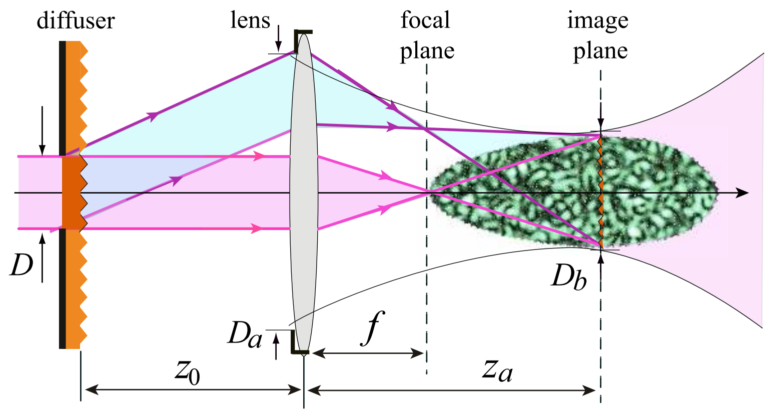


Fig. 1. Experimental setup. The diaphragm $D$ on the diffuser is imaged by the lens to a cigar-shaped trapping region as shown by a (green) image of the speckled intensity pattern.

light; this ensures their low heating and weak perturbation.

Recent development of holographic traps [18, 19] and the concept of an optical bottle beam [1] with a vanishing intensity surrounded by light in all three dimensions [20–22] have attracted a lot of attention as a hollow area of such beams can be employed for simultaneous trapping of a large number of particles and atoms [23].

In this paper, we demonstrate that a speckle pattern [24] generated by a coherent laser beam forms an ideal three-dimensional web of multiple traps that may be employed to capture a large number of micron-sized particles. We present the experimental results on simultaneous photophoretic trapping of several thousands of carbon particles in randomly distributed speckles. Our results show clear advantages of this new three-dimensional trapping strategy that combines the confinement of massive numbers of airborne particles by a single laser beam with the ability to select the size of captured particles in narrow margins.

The paper is organized as follows. In Sec. 2 we outline our experimental approach for selective trapping of absorbing particles in air. Section 3 summarizes the results on the optical trapping by speckle fields that allow us to realize multiple low-intensity optical bottle-beam traps with stable confinement of a few thousand airborne micro-particles with a single low-power laser beam. Finally, Sec. 4 concludes the papers and gives some further perspectives for the development of the method.

## 2. Experimental approach

In our experimental setup, shown in Fig. 1, a beam from cw laser (Verdi 5, Coherent, $\lambda = 532$ nm) illuminates a ground glass diffuser (Thorlabs DG10-1500) with the diffusion angle $2\alpha = 6^\circ$ FWHM. The imaging lens with a focal length of $f = 25$ mm and aperture $D_a = 23$ mm is placed at the distance $z_0 = 140$ mm from the diffuser. Similar to a partially coherent vortex beam [25], the overall intensity distribution after the lens is cigar-shaped, as can be deduced from scattered light in Fig. 2(a). As a result, the laser spot of the diameter $D = 2.6$ mm at the diffuser is reduced to $D_b = 570$ m in the image plane [Fig. 2(b)] located at a distance $z_a = 30.4$ mm from the lens, with the transmitted power of $P = 115$ mW. The trapping volume is enclosed inside a glass cuvette filled with carbon particles. It consists of many three-dimensional bright speckles separated by the dark "micro-bottle traps". The trapping area is imaged from the side [Fig. 2(a)] and along the beam axis [Fig. 2(b)], using white light passing through a notch filter.

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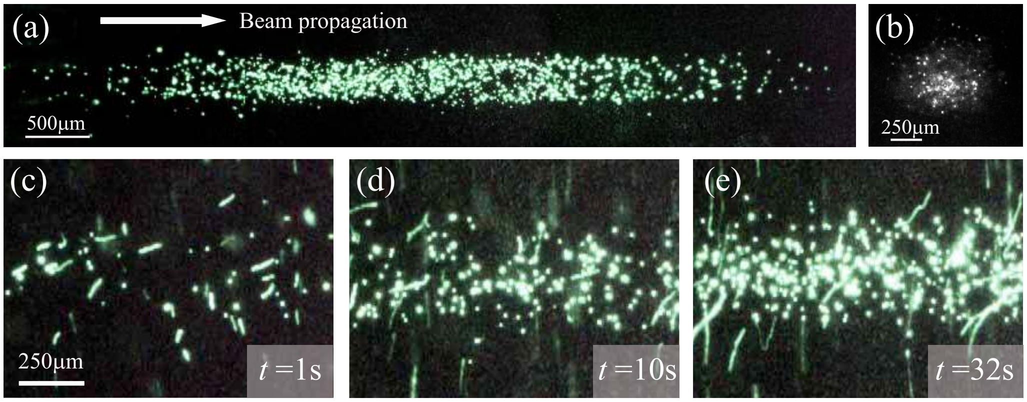


Fig. 2. Geometry and dynamics of particle trapping. (a) Image of the laser light scattered from the particles trapped in the speckled bottle beam, the axial view in (b) is obtained with the help of additional white-light illumination. A few thousands particles are captured simultaneously in the cigar-shaped trapping region of length $L = 6.5$ mm and diameter $D_b = 570$ m. (c-e) Temporal evolution of the selective optical trapping, see Media 1. The trap is being gradually populated with particles captured in the dark regions of the speckle pattern. The inverse process, i.e. the clearing of the trap from particles when power is gradually reduced, can be seen in Media 2.

For optical trapping we use agglomerated carbon nanoparticles, the so-called carbon nanofoam [26,27]. The nanofoam typically consists of particle agglomerates of irregular shape and size in the range from few nanometers (single nanoparticle) up to 100 micrometers with no apparent preferential size. When nanofoam is introduced into a glass cell, most of carbon particles initially suspended in air settle down on the cell walls within 30 minutes to an hour. When the laser beam is switched on, as seen in Figs. 2(c-e) and Media 1, the suspended particles entering the trapping area are reliably captured at the random speckle locations. When the population of the trap is saturated, as in Fig. 2(e), the particles remain trapped for practically unlimited time, up to 24 hours in our experiments. When laser power is reduced, some particles are released from the trap, the dynamics is shown in Media 2. The remaining particles are trapped firmly at any fixed power above the threshold $P_{\min}$ as long as the laser is on. In a representative experiment shown in Fig. 2 the trap is totally cleared of particles at $P_{\min} = 28.9$ mW.

The trapped particles are collected for further analysis on a silicon substrate. To avoid contamination of the sample and ensure that the particles on the substrate come from the trap only we collect particles when any free particles suspended in air are absent, usually about an hour after the laser trapping started. The particles collected on the substrate are subsequently analyzed with a scanning electron microscope (SEM); typical SEM images are shown in Figs. 3(a-c). Random sampling of 100 trapped particles under SEM reveals that the average linear size is $\langle d \rangle = 2.0$ m with standard deviation 0.6 m, and a corresponding size distribution is presented in Fig. 3(d). About 80% of particles are within the confidence interval of $d = 2.0 \pm 0.6$ m.

## 3. Optical trapping by speckle fields

In a striking contrast with our previous experiments [16, 28], where the variation of trapped particles size extended over three orders of magnitude, $d = 0.1 - 100$ m, the distribution in Fig. 3(d) indicates a selective mechanism of the trapping by a speckle beam. Below we present a theoretical analysis, which shows that the speckle fields acts as a sieve, with the most efficient trapping of particles of a size similar to the characteristic transverse size of individual speckles.

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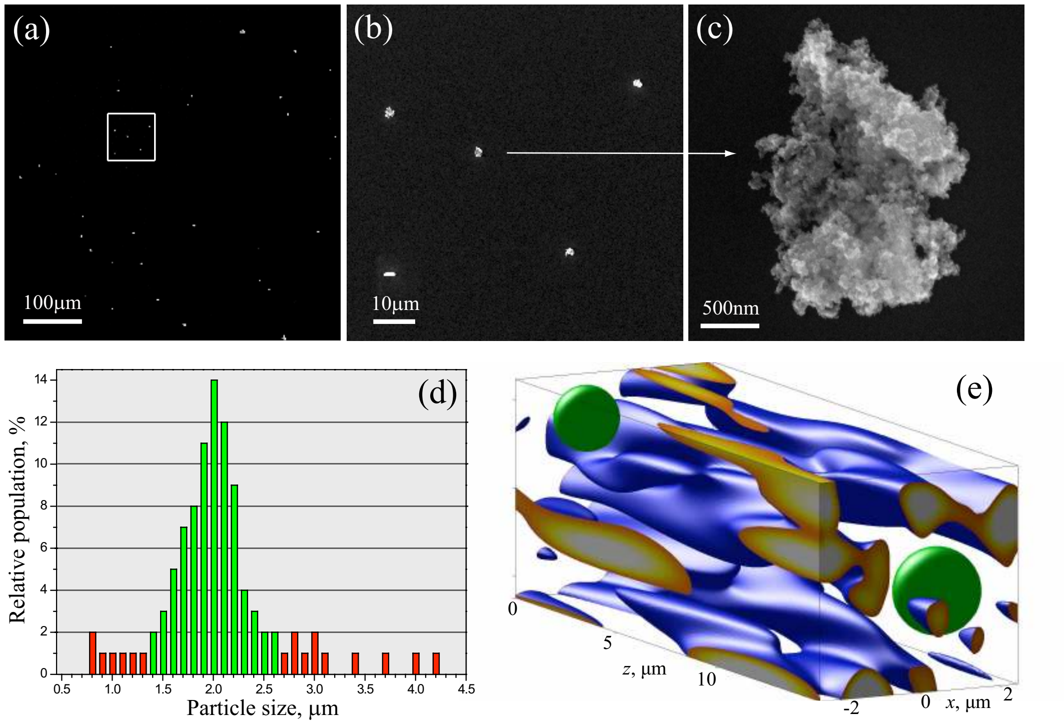


Fig. 3. Analysis of the particles from the speckle trap. (a-c) Scanning electron microscope images of agglomerates of carbon nanoclusters collected from the trap: the area with five particles marked by a white square in (a) is magnified in (b) and the arrow shows one of the particles in (c). (d) A histogram with the size distribution of trapped particles. The green color represents the standard deviation range. (e) Computer modeling of speckle intensity distribution for a small volume, $5 \times 5 \times 15\ \ \text{m}^3$, inside the trapping region. Blue surfaces enclose high-intensity speckles; voids correspond to the dark (low-intensity) bottle-traps; the green spheres represent trapped particles of diameters 1.5   m (left) and 2   m (right).

First, we recall the theoretical background of speckle pattern formation [24] as the interference of random coherent wavefronts formed by reflectance off or scattering by an irregular surface of the incident wave. In our experiments, the spatial structure of the diffraction pattern is determined by the aperture of the exit pupil of the optical system [29], the lens diaphragm of the diameter $D_a$ in our case. The averaged speckle sizes in the transverse, $\langle \varepsilon_\perp \rangle$, and longitudinal, $\langle \varepsilon_z \rangle$, directions, determined by the first zeros of corresponding correlation functions [24], are given by

$$\langle \varepsilon_\perp \rangle = 2.44\,\lambda \left( \frac{z_a}{D_a} \right) = 1.7 \quad \text{m} \quad \text{and} \quad \langle \varepsilon_\parallel \rangle = 16\,\lambda \left( \frac{z_a}{D_a} \right)^2 = 14.9 \quad \text{m}. \tag{1}$$

For direct comparison, we numerically model the speckle pattern as a coherent superposition of 1000 plane waves with equal amplitudes, random phases, and transverse wave-vectors $\mathbf{k}$ distributed randomly inside the circle, $|\mathbf{k}| < k_{\max}$. The radius of the disk-shaped angular spectrum is determined by the angular radius of the aperture as seen from the observation plane, namely $k_{\max} = k_0 D_a / 2 z_a = 0.3783 k_0$, here the wavenumber $k_0 = 2\pi/\lambda$. As seen in Fig. 3(e), the characteristic transverse and longitudinal sizes of cigar-shaped speckles and their dark counterparts, the micro-bottle traps, agree well with the average estimates in Eq. (1). The threshold trapping

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power in a single speckle $p_{\min}$ can be estimated as $p_{\min} = P_{\min}/N = 0.3$ W, here $P_{\min}$ is the measured above total threshold beam power and $N$ is the number of speckles in the transverse plane, $N = D_b^2/\langle\varepsilon_\perp\rangle^2 \simeq 1.1\times10^5$.

Next, we examine the balance of forces acting on the particle, required for stable three-dimensional trapping in air. In particular, we assume that transverse photophoretic force compensates gravitation, $F_\perp > mg = 4.1\times10^{-16}$ N, here $m = \pi\rho d^3/6 = 4.2\times10^{-14}$ g is the mass of a spherical particle with the diameter $d = 2$ m and mass-density of nanofoam, $\rho = 10$ mg/cm$^3$ [30]. Since, on average, each dark speckle is associated with an optical vortex [31], we can simulate the transverse intensity envelope of a micro-bottle by a vortex beam profile used in Ref. [17] to calculate the transverse photophoretic force, $F_\perp \simeq 8\kappa pR\langle d\rangle^3/3\langle\varepsilon_\perp\rangle^4$. Here $p$ is the laser power in a single speckle, $R$ is the shift of the particle centre from the point of zero intensity, and $\kappa = 8.5\times10^{-7}$ s/m is the parameter describing transfer of momentum from air molecules to carbon nanofoam [17,32]. According to our calculations in Ref. [17] the force $F_\perp$ attains its maximum for particles at the distance $R \simeq \langle\varepsilon_\perp\rangle/4$. It follows that the optical power required to balance gravitation is $p > 3.6$ nW, two orders of magnitude lower than the experimental threshold power $p_{\min}$. The reason for this discrepancy lies in the presence of disturbances stronger than he gravitational force, such as interaction between particles, via local perturbations of the laser field induced by the particles themselves [33], as well as convective air flows. The latter can move particles easily upward, as clearly seen in Media 1 and Media 2.

The experimentally measured most probable size of trapped particles, $\langle d\rangle = 2.0$ m, corresponds to the average transverse speckle size, $\langle\varepsilon_\perp\rangle = 1.7$ m, with good accuracy. In agreement with experiments on trapping with vortex beams [16] the size of the trapped particles is limited from above by the characteristic size of the micro-trap. An additional selective feature of speckled light is that the voids in the intensity pattern have complex topological arrangement [31] through which smaller particles can escape. As a result, the distribution in Fig. 3(d) sharply declines for smaller particles, $d < 2$ m, and proves that each speckle acts as a selective micro-trap. The selection can be performed by tuning the laser wavelength or by varying the numerical aperture of the focusing optics.

## 4. Conclusion and perspectives

We have suggested and demonstrated experimentally a new approach for stable three-dimensional multiple trapping of absorbing particles in air using a single laser beam. The multiple traps are induced by a speckle pattern with a multitude of micrometer-size bottle-beams created by optical singularities in each individual speckle. This work demonstrates a new way of multiple trapping, precise sorting, and guiding of massive numbers of light-absorbing particles in air and other gases, which so far remained beyond the abilities of conventional laser-trapping systems. While the presented here experimental demonstrations have been conducted with only one type of absorbing particles, the theoretical analysis suggests a possibility of trapping other absorbing substances in any gas environment. Finally, the ability of selective trapping, guiding and separation of suspended particles in air by non-contact optical means opens up a variety of applications for laser trapping of matter in gaseous environment.

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