Optical particle trapping with computer-generated holograms written on a liquid-crystal display

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Computer-generated holograms written on a liquid-crystal display can be used to generate dynamic light fields of arbitrary shape. This method was used to simultaneously trap polystyrene particles laterally and to displace them independently of one another. © 1999 Optical Society of America

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The trapping of micrometer-sized particles with laser beams has engendered growing interest since publication of the works of Ashkin in 1970 and of Ashkin et al. in the 1980’s. It has found many applications, especially in microbiology. The versatility of optical tweezers has been increased by use of different light fields or wavelengths as well as multiple traps. In a single-trap setup the trap is usually moved by the motion of a microscope stage. In contrast, a multiple-trap design requires a complex setup to achieve independent manipulation of two or more traps. So far this independent manipulation has been accomplished by the use of mirror systems or acousto-optic beam deflectors.

We present an approach in which a liquid-crystal display (LCD) is used for the reconstruction of computer-generated holograms. It enables us to generate arbitrary light fields in the Fourier plane of the LCD and to change them dynamically, as we demonstrate by laterally trapping and independently moving polystyrene particles in water.

Figure 1 shows the experimental setup. A 1.2-W Ar laser (Spectra-Physics 165, λ = 488 nm) illuminates an Epson LCD panel of a VGA projector with 640 x 480 pixels and a pixel pitch of 42 μm. The LCD is of the twisted nematic type and has a fill factor of 44%; when it is used as a phase hologram, the panel’s polarizing layer is stripped off. The display is mounted upon a rotary stage.

The phase-shifting capability of the LCD display is essential for diffraction efficiency. To maximize the intensity of the first diffraction order we rotated the LCD panel by 85° with respect to the input polarization.

The display is read out with a collimated beam. A telescope controls the size of the diffraction-limited hologram reconstruction employed here. A dichroic mirror reflects the beam into the aperture of a Spindler & Hoyer 10× microscope objective lens (N.A., 0.3). The sample dish is illuminated from below by white light, which is scattered by 6-μm polystyrene spheres (n = 1.5). The spheres are imaged onto a Sony XC-55 CCD camera. The relative axial position between dish and focus is adjusted by means of a micrometer screw.

This mechanical positioning can be made obsolete by use of Fresnel holograms.

The reconstruction of the computer-generated phase hologram is similar to that of a TEM₀₁ mode, a so-called doughnut mode, if the phase Φ is given by

\[ Φ(x, y) = \frac{2π}{λ_x} x + \frac{2π}{λ_y} y - n \arctan \frac{x}{y}. \]

The fringe periods of the hologram in the x and y directions are denoted λₓ and λᵧ, respectively. The charge n describes the pitch of the phase spiral in multiples of 2π. At the phase singularity on the spiral axis, the intensity is zero. High-index particles, such as polystyrene spheres, are attracted by regions of maximum intensity. They are trapped by the doughnut ring, whereas low-index particles are trapped in the center. Therefore the doughnut mode is more versatile than a Gauss mode, which traps only high-index particles. The transformation of the Gaussian laser beam into a doughnut beam underlines the beam-shaping abilities of the dynamic LCD computer-generated hologram and could be extended to other shapes.

Three holograms of the sort described by Eq. (1) were superimposed to generate three independent

![Fig. 1. Experimental setup.](image-url)
traps (Fig. 2). It is worth mentioning that many phase singularities can be observed in the hologram. This is not surprising, as even in the case of simple three-beam interference of plane waves multiple phase singularities are observed. The numerical simulation proves that the hologram reconstruction results in a multitude of doughnuts.

Only three of these doughnuts are of significant intensity and can be observed experimentally. Their position was controlled by a personal computer, which recalculated the hologram after a keyboard input. This procedure took ~1 s with an unoptimized code running on a Pentium (90 MHz). A limit is set by the LCD refresh rate, which is ~30 Hz for standard devices.

Three doughnuts of charge 1 were used to trap simultaneously the objects labeled A, B, and C in Fig. 3 and to displace them independently of one another (Fig. 4). Objects A and C consist of several particles that stick together. Finally, object C was moved vertically, whereas A and B remained at their initial positions (Fig. 5). Note that the two nonlabeled particles remain static throughout the whole process. We began the process by placing a doughnut about one particle diameter next to the sphere, which was then set in motion. To move particle B ~60 μm, for example, ten successive hologram calculations were needed.

The limited number of pixels reduces the space–bandwidth product compared with those of computer-generated holograms written on photoresists and leads to reduced quality of the reconstruction. Nevertheless, the quality is reasonably good, as the magnified image of a single doughnut (Fig. 6) shows.

The finite size of a pixel limits the maximum displacement of the reconstruction, for it limits the spatial frequency that can be written into the display. In the case of large displacements, a blazed phase hologram becomes a binarized hologram, because the number of pixels per period decrease to two. This leads to a reduced diffraction efficiency. Nevertheless, trapping was possible over the complete image plane in our setup.

Measurements showed that ~15% of the total incident power is found behind the LCD. The power loss is attributable to three factors: First, the major losses are due to shading of the nontransparent parts of the panel's structure (a minor part is due to reflection) and sum up to 65% of the incident power. Second, because the panel's structure is similar to a cross grating, higher orders are produced, which generate a loss of 54%. A minor source of power decrease of ~8% results from shading of the circular beam profile by the rectangular LCD aperture.
Third, each order fans out with the orders of the holographic structure itself. It is possible to concentrate the whole intensity of one LCD order in the first order of the hologram if blazed holograms are used, which requires a phase modulation of $2\pi$. However, the LCD employed has a maximum phase shift of less than $2\pi$. Therefore a ratio of only 2:1 between first and the zeroth orders was achieved, because there is only a single zeroth order.

Three doughnuts of charge 1 were used to trap simultaneously three polystyrene objects laterally and to displace them independently of one another in a simple setup. By using a high-N.A. objective it should be possible to accomplish axial trapping as well. The method presented enables us to generate arbitrary dynamic light fields that can be used for trapping of micrometer-sized particles. The main drawback is the poor overall efficiency that results from the pixelated structure of the LCD.

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