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(54) **SYSTEM FOR APPLYING OPTICAL FORCES FROM PHASE GRADIENTS**

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See application file for complete search history.

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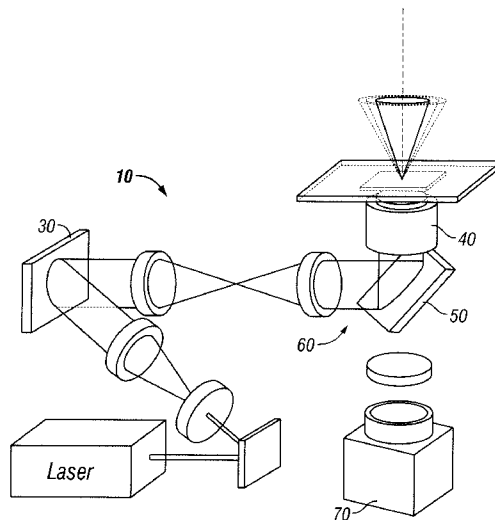
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(57) **ABSTRACT**

A system and method for creating extended optical traps for applying optical forces to a material to be manipulated for a commercial application. The system and method include applying a hologram of appropriate characteristics to a beam of light wherein the hologram characteristics include a transverse optical component to apply optical forces transverse to an optical axis of the system. A shape phase component achieves this transverse optical component and also intensity gradient components can be applied via the hologram to provide programmable extended optical traps for a selectable commercial application.

**8 Claims, 4 Drawing Sheets**



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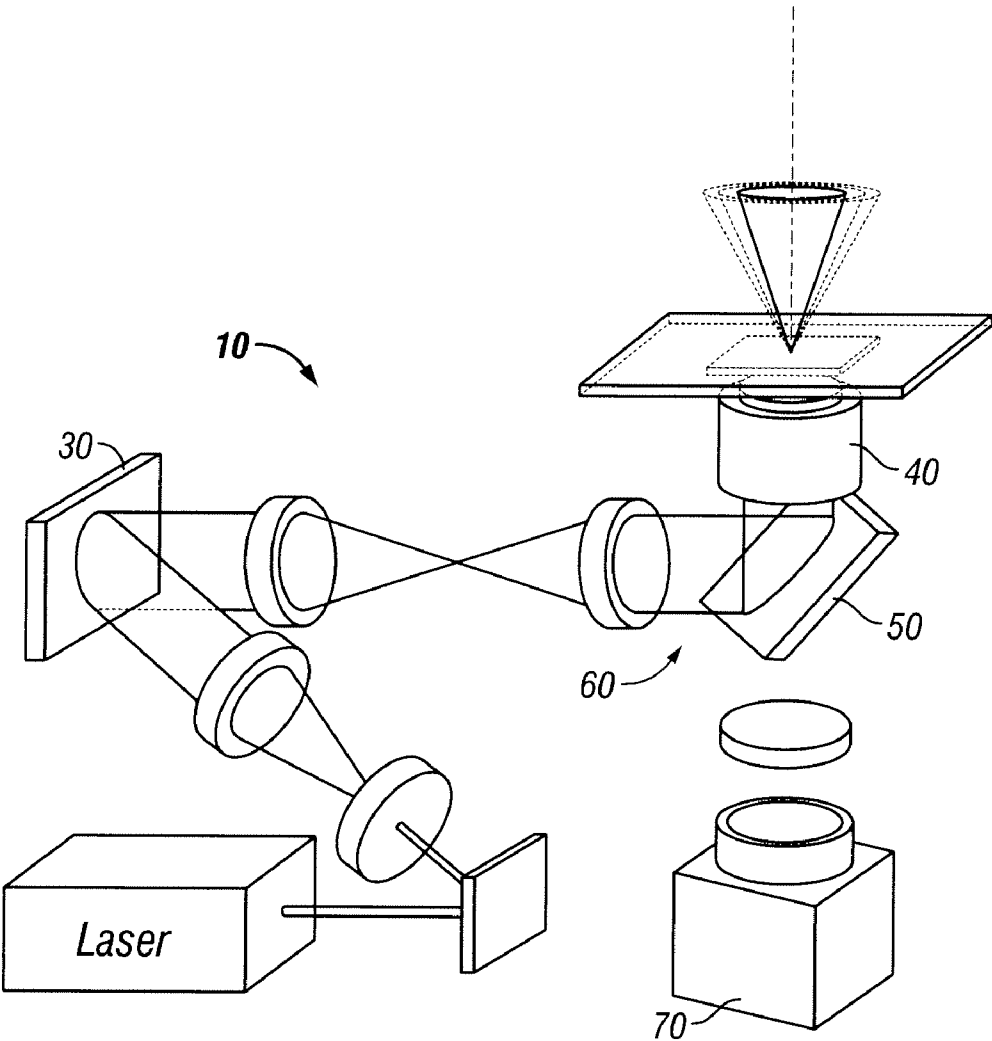


FIG. 1

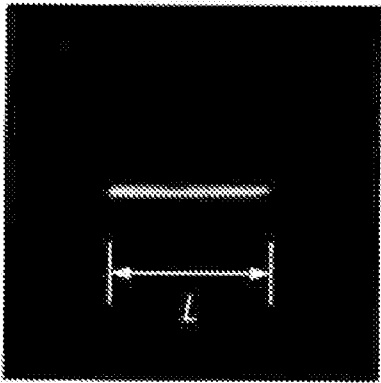


FIG. 2A

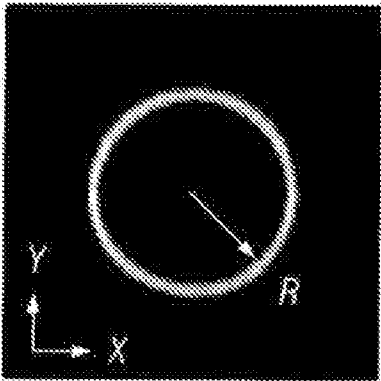


FIG. 2B

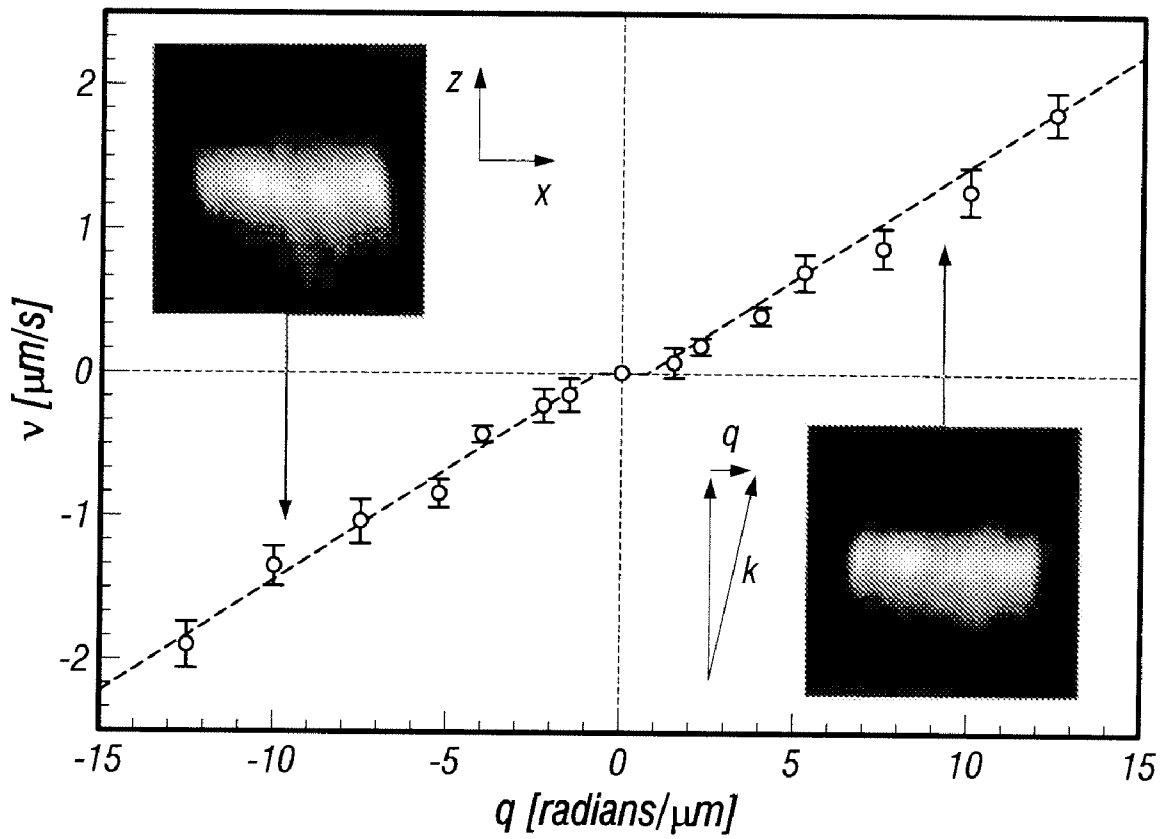


FIG. 3



FIG. 4A(1)

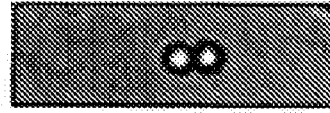


FIG. 4A(2)



FIG. 4B(1)



FIG. 4B(2)

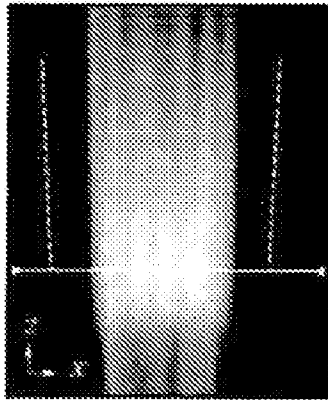


FIG. 4C(1)

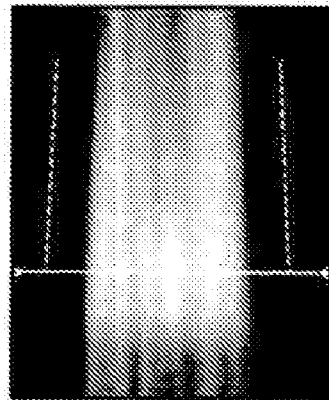


FIG. 4C(2)

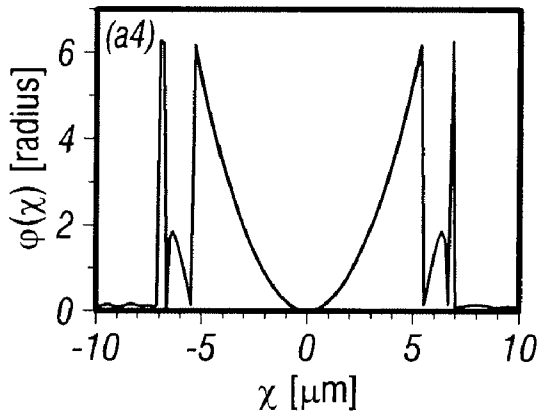


FIG. 4D(1)

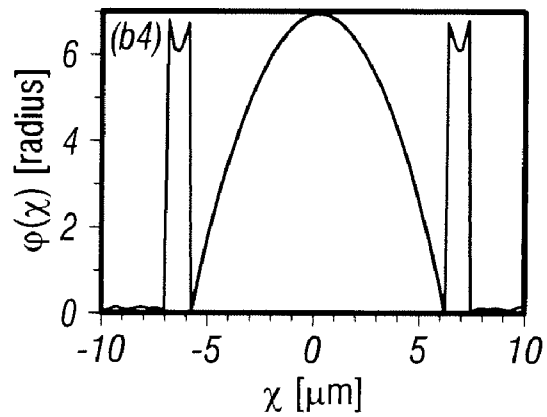


FIG. 4D(2)



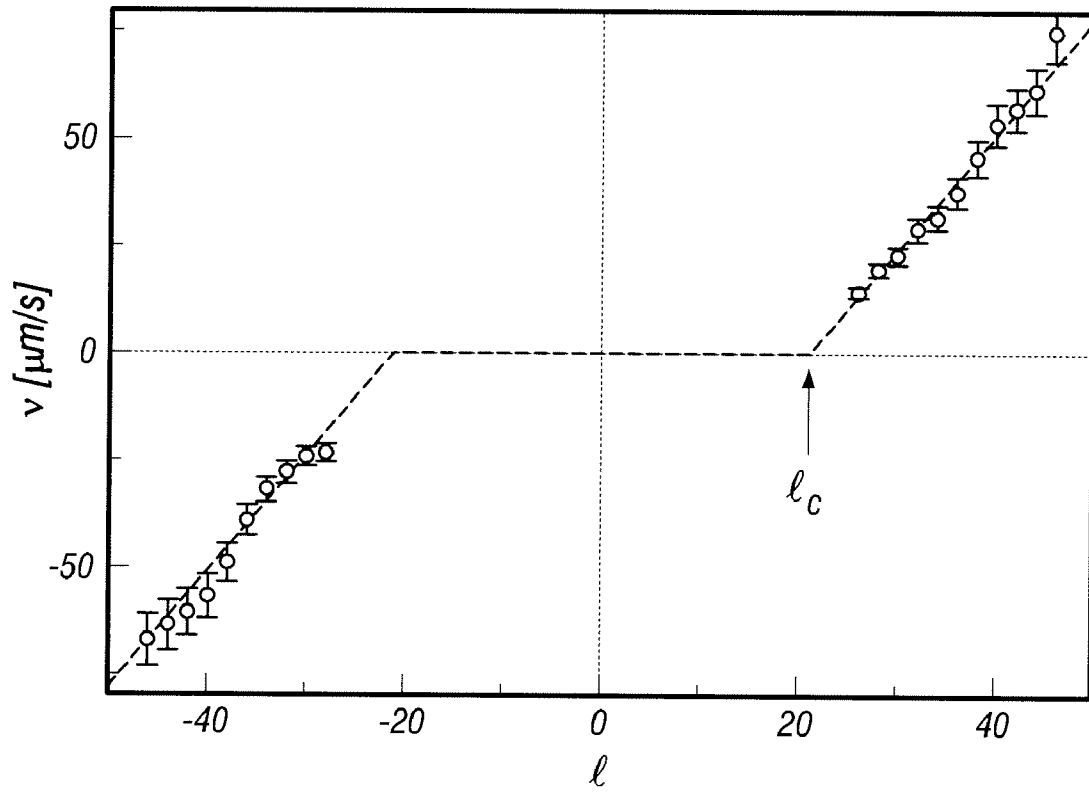


FIG. 5A

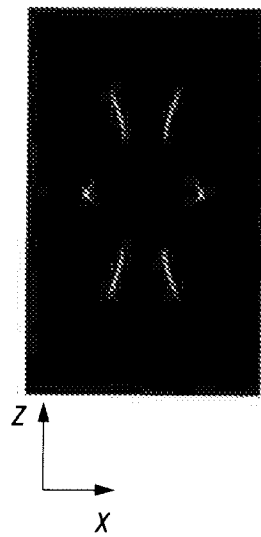


FIG. 5B

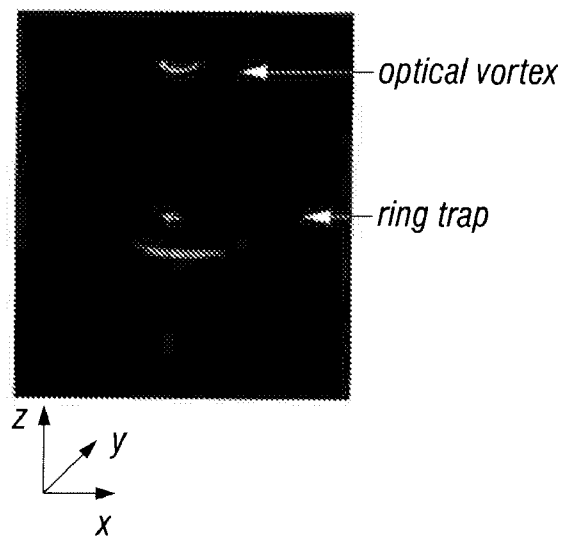


FIG. 5C

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## SYSTEM FOR APPLYING OPTICAL FORCES FROM PHASE GRADIENTS

The United States Government has certain rights in this invention pursuant to a grant from the National Service Foundation through Grant Number DMR-0606415.

This invention is directed toward a system and method for applying optical forces by use of phase gradients. More particularly, the system and method employs phase gradients in a light field to create a new category of optical traps which provide additional features compared to conventional intensity gradient traps (optical tweezers).

### BACKGROUND OF THE INVENTION

Optical tweezers have demonstrated substantial value in various commercial applications, such as for example, separation of particles of different characteristics and dynamic manipulation of small objects for numerous, commercial, manufacturing and processing applications. However, optical tweezers do have substantial limitations on the degrees of freedom that can be created, thereby limiting the types and efficiency of forces and manipulations that can be used for demanding commercial applications.

### SUMMARY OF THE INVENTION

A method and system have been developed for a new category of optical force by using phase gradients in place of, or in concert with, light intensity gradients. This new category of optical force enables redirection of electromagnetic radiation pressure to create optical forces transverse to an optical axis. This new type of optical force can be used alone or in combination with conventional longitudinal forces and other intensity gradient profiles to create a useful and versatile tool. These optical forces can establish a highly flexible means to apply virtually any type of force vector to perform commercially important processes, some of which could not previously be accomplished without the advantages of this new type of optical force phase based gradient.

Various aspects of the invention are described hereinafter; and these and other improvements are described in greater detail below, including the drawings described in the following section.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a schematic of a holographic optical trapping system using shape phase holography to project extended traps;

FIG. 2A illustrates an experimentally generated holographic line trap using the system of FIG. 1, the line trap carrying a phase gradient in the  $\hat{x}$  direction and imaged in the plane of best focus; FIG. 2B illustrates a focal pattern of a holographic ring trap of  $l=30$  and generated by the system of FIG. 1;

FIG. 3 illustrates dependence of mean velocity,  $v$ , on phase gradient,  $q$ ; the inset images are axial slices in the  $xz$  plane through the intensity distribution of the line trap of FIG. 2A at two indicated values of phase gradient,  $q$ ;

FIG. 4A(1) illustrates a phase gradient barrier for two 1.5  $\mu\text{m}$  diameter silica spheres (the scale bar is 5  $\mu\text{m}$ ); FIG. 4A(2) illustrates a phase gradient well in a uniformly bright line trap for the two 1.5  $\mu\text{m}$  diameter silica spheres; FIG. 4B(1) illustrates the phase gradient barrier for uniform in-plane intensity of the focused line; FIG. 4B(2) illustrates the phase gradient well with uniform in-plane intensity of the focused line; FIG.

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4C(1) illustrates the phase gradient barrier in an axial section through the measured intensity sharing the intensity divergence due to the phase profile; FIG. 4C(2) illustrates the phase gradient well in a uniformly bright line trap for convergence due to the phase profile; FIG. 4D(1) illustrates the associated designed phase gradient for the configuration of FIG. 4A(1) featuring the desired parabolic profile and off-line phase variations designed to minimize intensity variations and FIG. 4D(2) shows the associated designed phase gradient for the configuration of FIG. 4A(2); and

FIG. 5A is a plot of particle velocity,  $v$ , versus topological charge,  $l$ , where data points show the peak velocity  $v$  of a single one of the colloidal silica sphere particles circulating around a ring shape (see FIG. 5C); FIG. 5B shows a computed axial section through a holographic ring trap of radius  $R=20 \mu\text{m}$  and helicity  $l=30$ ; FIG. 5C illustrates a volumetric representation of the measured three-dimensional intensity field in a holographic ring trap of radius  $R=20 \mu\text{m}$  and  $l=10$ .

### DETAILED DESCRIPTION OF PREFERRED EMBODIMENT

A holographic optical trapping system for performing shape phase holography is shown at 10 in FIG. 1. This system 10 can create optical traps with phase gradients transverse to the optical axis 20, as well as provide optical tweezers created by intensity gradients.

The phase gradients generated by the method described herein can redirect radiation pressure to create optical force fields transverse to the optical axis 20. Photon orbital angular momentum (OAM) is one experimentally realized example of this phenomenon. Phase-gradient forces can be applied by combining them with intensity gradients in holographically projected light fields to create a new category of extended optical traps with tailored force profiles.

The vector potential describing a beam of light of frequency  $\omega$  and polarization  $\hat{\epsilon}(r)$  can be written as

$$A(r,t)=u(r)e^{i\Phi(r)}e^{-i\omega t}\hat{\epsilon}(r) \quad (1)$$

where  $u(r)$  is the real-valued amplitude and  $\Phi(r)$  is the real-valued phase. We assume for simplicity that the light is linearly polarized so that  $\hat{\epsilon}(r)$  is real. For a plane wave propagating in the  $\hat{z}$  direction,  $\Phi(r)=kz$ , where  $k=n_m\omega/c$  is the light's wavenumber,  $c$  is the speed of light in vacuum, and  $n_m$  is the refractive index of the medium. Imposing a transverse phase profile  $\phi(r)$  on the wavefronts of such a beam yields,

$$\Phi(r)=k_z(r)z+\phi(r), \quad (2)$$

where  $\hat{z}\cdot\nabla\phi=0$ . The direction of the wavevector,  $k(r)=k_z(r)\hat{z}+\nabla\phi$ , now varies with position, subject to the constraint  $k^2=|k|^2=k_z^2+|\nabla\phi|^2$ , which applies in the paraxial limit,  $k\gg|\nabla\phi|$ . The associated electric and magnetic fields are given in the Lorenz gauge by,

$$E(r,t)=-\frac{\partial}{\partial t}A(r,t) \quad \text{and} \quad (3)$$

$$H(r,t)=\frac{1}{\mu}\nabla\times A(r,t),$$

where  $\mu$  is the magnetic permeability of the medium, which we assume to be homogeneous and isotropic. Following the well known Abraham's formulation, the momentum flux carried by the beam is,

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$$g(r) = \frac{1}{c^2} \text{Re}\{E^* \times H\} = \frac{k}{n_m \mu c} I(r) \nabla \Phi \quad (4)$$

where  $I(r) = |u(r)|^2$  is the light's intensity, and where we have employed the gauge condition,  $\nabla \cdot A = 0$ .

The momentum flux separates into an axial component  $g_z(r) = k k_z I(r) (n_m \mu c)^{-1} \hat{z}$  and

$$g_{\perp}(r) = \frac{k}{n_m \mu c} I(r) \nabla \varphi \quad (5)$$

transverse to the optical axis **20**, which is responsible for transverse forces.

It has been recognized that the helical phase profile,  $\phi(r) = l\theta$ , imbues a beam of light with an OAM flux,  $r \times g_{\perp}$ , amounting to 1 per photon. Here,  $\theta$  is the azimuthal angle around the optical axis, and  $l$  is an integer describing the wavefronts' helical pitch. This OAM is distinct from the photons' intrinsic spin angular momentum. Through it, even linearly polarized light can exert a torque around the optical axis. Equation (5) reveals this to be a manifestation of the more general class of transverse forces arising from phase gradients.

Intensity gradients also exert forces on illuminated objects. In this case, the dipole moment induced in the object responds to gradients in the field, yielding a force proportional to the gradient of the intensity, which therefore is manifestly conservative. For a small sphere of radius  $a$ , the intensity-gradient force has the form,

$$F_{\nabla}(r) = n_m \frac{k^2 a^3}{2} \left( \frac{m^2 - 1}{m^2 + 2} \right) \nabla I, \quad (6)$$

where  $m = n_p/n_m$ , is the ratio of the particle's refractive index,  $n_p$ , to the medium's,  $n_m$ . Unlike  $g$ ,  $F_{\nabla}$  can be directed up the optical axis. The resulting axial restoring force is the basis of single-beam optical traps.

Because beams of light have gradients in both the intensity and the phase, the total optical force is not conservative. This is evident because,

$$\nabla \times g = \frac{k}{\mu n_m} (\nabla I) \times (\nabla \Phi) \quad (7)$$

does not vanish in general. Although it is known that optical traps exert non-conservative forces, subsequent reports have treated optical tweezers as (conservative) potential energy wells.

Phase-gradient forces can thus be created using a new class of extended optical traps created through shape-phase holography. The system **10** shown schematically in FIG. **1**, uses a phase-only spatial light modulator **30** (SLM) (Hamamatsu X8267-16) to imprint computer-generated programmable holograms on a laser beam (Coherent Verdi 5W) at a vacuum wavelength of 532 nm. The modified beam is relayed to an objective lens **40** (Nikon Plan Apo, 100 $\times$  oil immersion, NA 1.4) that focuses it into the intended three-dimensional optical trapping pattern. A beam splitter **50** reflects the laser light **60** into the objective's input pupil while allowing images at other wavelengths to pass through to a video camera **70** (NEC TI-324AII).

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The holograms designed for this study bring the laser light **60** to a focus along one-dimensional curves,  $C$ , embedded in the three-dimensional focal volume of the objective lens **40**. Each hologram also encodes a designated intensity profile  $I(s)$  and phase profile  $\phi(s)$  along the arclength  $s$  of  $C$ . This is accomplished by numerically back-projecting the desired field along  $C$  onto the plane of the SLM **30** to obtain the ideal complex-valued hologram,  $\psi(r) = |b(r)| \exp(ip(r))$ . An appropriate shape-phase algorithm assigns the phase shifts  $p(r)$  to the SLM's pixels with a probability proportional to  $|b(r)|$ . An alternate phase pattern imprinted on the unassigned pixels diverts excess light away from  $C$ .

The images in FIGS. **2A** and **2B** show a focused line trap and ring trap, respectively, each designed to have uniform intensity and phase gradients. These images were obtained by placing a mirror in the microscope's focal plane and imaging the reflected light. Because the holograms come to a diffraction-limited focus, their axial intensity gradients are steep enough to trap particles in three dimensions. To study the phase-gradient force predicted by Eq. (5), we track colloidal spheres moving along these traps.

In the case of the line trap, we first subjected the trapped particle to linear phase gradients,  $\nabla \phi = q x$ , over the range  $q = \pm 12$  radians/ $\mu\text{m}$ . The insets to FIG. **3** show axial sections through volumetric reconstructions of the trap's three-dimensional intensity distribution for two different values of  $q$ . The diffraction-limited focal line remains in the  $xy$  plane despite the imposed phase gradient. The beam's direction of propagation, however, deviates from  $\hat{z}$  by the angle  $\sin^{-1}(q/k)$ . This tilt directs a component of the beam's radiation pressure along  $x$ . The images in FIG. **3** confirm the phase gradients' magnitude and uniformity.

The line trap was projected into an aqueous dispersion of colloidal silica spheres  $2a = 1.53 \mu\text{m}$  in diameter sealed into the  $40 \mu\text{m}$  thick gap between a glass microscope slide and a #1 glass coverslip. Focusing the trap near the sample's midplane avoids reflections from the glass-water interface and minimizes hydrodynamic coupling to the walls. Equation (5) and the Stokes mobility law for a colloidal sphere then suggest that a trapped particle's speed,  $v$ , should be proportional to  $q$ .

To test this prediction, we measured the time required for a single sphere to travel the length,  $L = 5 \mu\text{m}$ , of a 100 mW trap as the sign of  $q$  was flipped 20 times for each value of  $|q|$ . The observed root-mean-square off-line excursions of roughly 200 nm suggest axial and lateral trap stiffnesses comparable to those of a point-like optical tweezer powered by 1 mW. Under these conditions, the trapped sphere traveled along the line at speeds up to  $2 \mu\text{m/s}$  when subjected to the largest phase gradients. Results obtained by systematically varying  $q$  are plotted in FIG. **3**. They show the anticipated linear dependence, except very near  $q = 0$ , where phase-gradient forces are too weak to overcome localized pinning centers created by small uncorrected intensity variations.

More complicated phase gradients give rise to more interesting physical effects demonstrating the versatility of the use of phase gradients. The particles shown in FIGS. **4A(1)** and **4A(2)** also are trapped along a uniformly bright line trap of length  $L = 10 \mu\text{m}$ . This line, however, has a parabolic phase profile,  $\phi(x) = \pm(qx)^2$ , that is predicted to force objects either out to the ends of the line or toward its center depending on the sign. The images in FIG. **4A(1)**-**4D(2)** demonstrate both effects for a pair of trapped colloidal spheres. Axial sections in FIGS. **4C(1)** and **4C(2)** through the three-dimensional intensity distribution show that the phase-gradient barrier results from light diverging along the line's length, while the well results from the projection of converging rays. FIGS. **4D(1)** and **4D(2)** show the designed phase gradient conditions

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featuring the designed parabolic profile and off-line phase variations so as to minimize intensity variations (FIG. 4D(1) is correlated to FIG. 4A(1) and FIG. 4D(2) correlated to FIG. 4A(2)). So long as the particles are rigidly confined to the uniformly bright focal line, Eq. (7) suggests that the phase-gradient force approximates a conservative potential energy landscape.

Like holographic line traps, holographic ring traps, such as the example in FIG. 2B, can be endowed with arbitrary phase profiles, including the uniform azimuthal phase gradient,  $\phi(r)=l\theta$ , that defines a helical mode. A helical profile, by itself, causes a beam to focus into a ring of light, forming a torque-exerting optical trap known as an optical vortex. Whereas the radius of an optical vortex,  $R_v$ , is proportional to its helicity, holographic ring traps can be projected with any desired radius,  $R$ , independent of  $l$ . This advantageously facilitates many applications, such as colloidal transport under varying phase gradients and many complex process steps. Also unlike optical vortices, holographic ring traps have strong enough axial intensity gradients to trap objects in three dimensions. This can be seen in the computed axial section in FIG. 5B in which the trap appears as two bright focal spots on the midline. Imposing a helical phase profile on a ring trap suppresses the beam's axial intensity through destructive interference, diverting it instead to a radius,  $R_l$  from the axis. If the ring's radius  $R$  exceeds the vortices',  $R_v$ , the converging helical beam focuses not only to the intended ring trap, but also to two conventional optical vortices above and below the focal plane, which appear as bright features in FIG. 5B. This structure also is evident in the ring trap's measured three-dimensional intensity field in FIG. 5C. The optical vortices' comparatively weak axial intensity gradients are evident in FIG. 5B.

A ring trap with a uniform azimuthal phase gradient exerts a torque about its axis. We demonstrated this by tracking a colloidal silica sphere circulating around a holographic ring trap of radius  $R=2.6\ \mu\text{m}$  projected into the midplane of a  $40\ \mu\text{m}$  thick sample. The trapped particle was subjected to azimuthal phase gradients in the range  $l=\pm 50$ , and its peak speed was measured to within 10% for each value of the helicity. The results are plotted in FIG. 5A.

Like optical vortices, holographic ring traps carrying orbital angular momentum are subject to  $l$ -fold and  $2l$ -fold azimuthal intensity variations due to non-ideal phase scaling that trap the particle for  $||l|<l_c$ . For  $||l|>l_c$ , however, the particle's peak speed increases linearly with  $||l|$ , consistent with the predictions of Eq. (5). Intermittent circulation near  $||l|=l_c$  gives rise to large velocity fluctuations characterized by giant enhancement of the particle's effective diffusion coefficient. Disorder in the effective force landscape also gives rise to interesting collective dynamics for multiple particles trapped on the ring, including transitions among periodic, chaotic and weakly chaotic steady states. Phase-gradient forces in holographic ring traps therefore provide useful model systems for studying fundamental problems in nonequilibrium statistical mechanics. They also can provide numerous practical applications as the basis for microscopic pumps, mixers, and optomechanical micromachines. Azimuthal phase gradients also can be used to endow a holographic ring trap with more complicated force profiles, even if the ring's intensity is uniform.

Phase gradients in a beam of light can thus give rise to forces transverse to the optical axis, and these forces can be harnessed for a new type of optical trap. Tuning optical traps' force profiles with phase gradients will be useful for manipulating microscopic objects, and will greatly facilitate rapid measurements of colloidal interactions, for example.

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Although phase-gradient forces generally are non-conservative, they can act as conservative force fields on appropriately restricted manifolds. More generally, optical forces' non-conservativity can engender useful attributes in illuminated particles' dynamics, including departures from Boltzmann statistics for systems nominally in equilibrium. Phase gradients can also give rise to spatial variations in the polarization. Although optically isotropic materials are not influenced by polarization gradients, anisotropic materials can be. Phase-directed polarization gradients can be tailored and therefore should provide additional independent avenues for controlling microscopic systems.

The foregoing description of embodiments of the present invention have been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the present invention to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the present invention. The embodiments were chosen and described in order to explain the principles of the present invention and its practical application to enable one skilled in the art to utilize the present invention in various embodiments, and with various modifications, as are suited to the particular use contemplated.

What is claimed is:

1. A method for creating extended optical traps for applying optical forces to a material for performing a commercial application, comprising:

applying a hologram to a beam of light wherein the hologram creates a shaped phase optical trap by specifying a vector potential along a particular curve in three dimensions, which provides transverse optical forces relative to an optical axis and for a holographic ring trap made of the shaped phase optical trap, the hologram is independent of any helicity, and

applying the transverse optical force to the material to carry out the commercial application.

2. The method as defined in claim 1 further including providing the hologram with an intensity gradient component to create the shaped phase optical trap with both a phase gradient and an intensity, or amplitude, gradient component for a one dimensional form of the vector potential.

3. The method as defined in claim 1 wherein the shaped phase optical trap includes photo orbital angular momentum.

4. The method as defined in claim 1 wherein the shaped phase optical trap includes tailored force profiles to accomplish the commercial application.

5. The method as defined in claim 4 wherein the hologram further includes an intensity gradient component which for a small sphere of radius "a" comprises a force:

$$F_V(r) = n_m \frac{k^2 a^3}{2} \left( \frac{m^2 - 1}{m^2 + 2} \right) \nabla I$$

where  $m = n_p / n_m$  with  $n_p$  an index of refraction of the material and  $n_m$ , an index of refraction of a surrounding medium.

6. The method as defined in claim 4 wherein the hologram is provided using a phase-only optical light modulator.

7. The method as defined in claim 4 further including the step of using an objective lens downstream from where the hologram is applied to modify the light beam, thereby creating an extended optical trap having both the transverse optical forces and intensity gradient forces.

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8. A method for creating extended optical traps for applying optical forces to a material for performing a commercial application, comprising:

applying a hologram to a beam of light wherein the hologram creates a shaped phase optical trap which includes tailored force profiles and further includes a component which provides to the beam of light a momentum flux component transverse to an optical axis comprising:

$$g_{\perp}(r) = \frac{k}{n_m \mu c} I(r) \nabla \phi$$

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where k= value of wave vector k

$n_m$  =refractive index of a medium

c = speed of light

$\phi$ = phase

$\mu$ = magnetic permeability

I(r) = light intensity

$\nabla \phi$ = phase profile gradient

10 applying the transverse optical force to the material to carry out the commercial application.

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