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Optical manipulation and rotation of liquid crystal drops using high-index fiber-optic tweezers

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We report an optical fiber tweezer based on high-index material for trapping and optical manipulation of microscale particles in water. The use of a high-index material increases the trapping force with respect to the more common silica, through tighter focusing of light. We demonstrate the potential of this simple and versatile device by trapping and rotating nematic liquid crystal drops. We monitor the rotation of the drop by detecting light modulation observed with the same fiber using backscattered light, which exhibits modulation in intensity due to the rotation of the drop; this further extends the capabilities of the fiber tweezers. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2775321]

Optical tweezers are extensively used for manipulating dielectric particles,[1] biological cells,[2] and other organelles.[3] Applications include cell sorting, motion tracking, and force studies in cell membranes. Optical tweezers employing circularly polarized optical field can be used to rotate objects, which are anisotropic, such as liquid crystal (LC) drops.[4] In this case, they can also be used to study the properties of the objects in the optical trap, by monitoring the backscattered light intensity or its polarization state. Optical tweezers are typically created by tightly focusing laser beams with objective lenses,[1] but can also be realized using optical fibers.[5,6] The latter offers a number of advantages, which include low cost, flexibility in incorporating fiber-optic components used in optical communication wavelengths or other wavelengths, and ease in object manipulation. While conventional silica fibers can be conveniently shaped into tapered lenses, their performance when immersed in a medium such as water depends critically on the radius of curvature of the fiber tip. Since many important systems are dispersed in water, it would be desirable to have fiber tweezers that could work robustly in such a liquid.

In this letter, we report the engineering of a fiber-optic tweezer for trapping and manipulation in water; it is based on bismuth, a high-index material. We demonstrate the potential of this device by trapping and rotating liquid crystal drops. We further exploit the optical anisotropy of the drops to show that we can simultaneously monitor the motion of the trapped object. The versatility of our optical tweezers coupled with the light response of these drops offers new possibilities for all-optical switching capabilities in photonic devices based on microfluidics[7] and photonic crystal fibers.[8]

In practice, optical tweezers are expensive; they typically employ an optical microscope, which requires coupling the laser light into the microscope and precisely steering the optical trap through the use of lenses, mirrors, and acousto/electro-optical devices. By contrast, fiber based optical tweezers are cheap. However, since the refractive index of water ($n_{\text{water}}=1.33$) is close to that of silica ($n_{\text{silica}}=1.45$) the focusing of light is not effective, typically resulting in large spot sizes and small working (focal) lengths; this renders the optical trap ineffective in applications that require trapping of micron-scale particles. Decreasing the radius of curvature of the fiber tip enhances the focusing of light, but also causes light leakage through the fiber cladding, resulting in a decrease in efficiency of the optical trap. In our experiments, we use lens fibers created by tapering and heating a single mode bismuth ($n_{\text{Bi}}=2.22$) fiber having core and cladding diameters of 4.4 and 125 μm, respectively, a numerical aperture of 0.2, and a mode field radius $\omega_0=3.1$ μm. Figure 1(a) shows an optical image of a bismuth lens fiber with a radius of curvature of 24 μm.

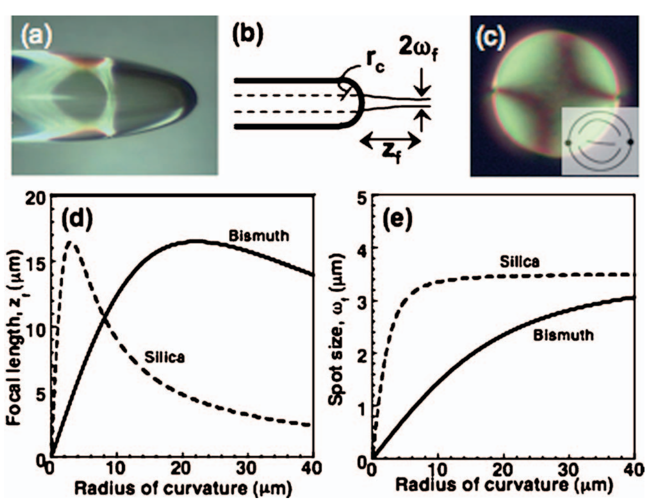

FIG. 1. (Color) (a) Optical image of the high-index fiber used for optical trapping and manipulation. (b) Schematic of a focused beam from a tapered bismuth lens fiber. r_c is the fiber tip radius of curvature, ω_f is the spot size, and z_f is the focal length. (c) Cross-polarizer image of a bipolar liquid crystal drop. Inset: sketch of the director field as inferred from the image. (d) Calculated focal length and (e) spot size for a lens fiber with a mode field radius of 3.5 μm vs the fiber tip radius of curvature.

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To emphasize the benefits of using fibers made of high-index materials, such as bismuth, as compared to the more conventional silica fibers, we calculate[5] the beam waist position or focal length z_f of the lens fiber, and the beam spot size ω_f for both silica and bismuth [see Fig. 1(b)], assuming the only propagating mode inside the fiber is Gaussian. Results for silica and bismuth made fibers with a mode field radius of 3.5 μm are presented in Figs. 1(d) and 1(e) as a function of the lens radius of curvature r_c for a beam wavelength of 1.550 μm. For the silica fiber, the focal length is sharply peaked at $r_c \approx 3$ μm [Fig. 1(d)]; values above and below this radius of curvature greatly reduce the maximum size that an object can have in order to be trapped. Furthermore, above this particular value of r_c, the spot size becomes comparable to the diameter of the fiber core [Fig. 1(e)] greatly reducing the gradient force from the optical trap. These constraints on the fiber lens design can be alleviated when a higher-refractive-index bismuth fiber is used. As can be seen in Figs. 1(d) and 1(e), the bismuth fiber lens produces smaller spot sizes, irrespective of the radius of curvature, and larger focal lengths for $r_c > 7$ μm than the silica lens fiber; these imply more effective particle trapping and larger working distance, respectively, extending the use of optical fibers as tweezers for applications in water. To confirm the focusing power of our tweezers, we arranged a pair of tapered bismuth fiber lenses, with a radius of curvature of 24 μm, so that they faced each other. We verified they could be optimally coupled inside water at a separation of $\sim$30 μm, which is approximately twice the fiber focal length with a loss of $\sim$0.2 dB.

We explore the optical manipulation capabilities of our fiber tweezers with nematic LC drops; these are made by extruding the liquid crystal penthylcyanobiphenyl (5CB) (Merck), through a glass capillary tip (inner diameter of $\sim$3–10 μm) in the presence of coflowing water containing 1 wt % of polyvinyl alcohol.[9] Use of this polymer ensures the stability of the drops against coalescence and fixes the boundary conditions for the director field $\mathbf{n}$ to be tangential at the drop surface. The resultant drops are thus bipolar and have $\mathbf{n}$ aligned on average along the axis joining the topologically required surface point disclinations. An image of a typical drop, viewed through crossed polarizers, is shown in Fig. 1(c); it is flattened between two glass slides to force the defect axis to lie in the plane of observation. The schematic in the inset of Fig. 1(c) is a sketch of $\mathbf{n}$ as inferred from the image; it clearly shows the bipolar character of the drop. The experiments are performed by placing the emulsion drops on a cover glass slide that is located on the stage of a Nikon inverted microscope (TE2000-U), with the lens fiber forming an angle of $\sim$34° with respect to the vertical axis, as shown in Fig. 2. The rotation of the drops is studied by observing vertically through crossed polarizers and recording with a charged-coupled device (CCD) camera at a frame rate of 30 Hz. Continuous wave light of vacuum wavelength $\lambda = 1.550$ μm from a semiconductor laser is launched into the tweezer fiber though a fiber-optic path consisting of a polarization beam splitter and polarization controllers (see Fig. 2).

Liquid crystal drops with diameter sizes between $\sim$3 and $\sim$20 μm could be optically trapped using a measured laser output power of less than 10 mW. When the laser is linearly polarized, the axis joining the two surface disclinations of the bipolar drops, which is the average optic axis of the drops, is aligned with the direction of the light polarization. This is achieved through solid body rotation of the drop, as the optical fields needed to induce reorientation of the LC molecules themselves would typically be an order of magnitude higher.[10,11] Optical micrographs of a liquid crystal drop observed under crossed polarizers are shown in Figs. 3(a)–3(c); the images correspond to three different polarization directions of the incident trapping light. We observe that the texture is reproduced after a drop rotation of exactly 180°.

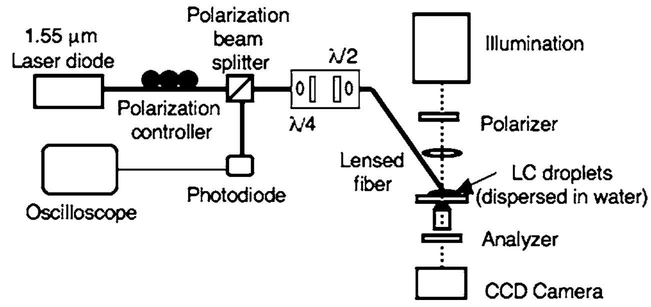

FIG. 2. Experimental setup for manipulation and observation of liquid crystal drops. The lens fiber acts as both an optical trap by focusing laser radiation and as a probe by capturing the backscattered radiation.

Continuous rotation of the drop can be achieved with circularly polarized light, which we obtain from linearly polarized light using of a bulk polarization controller (see Fig. 2). One way to induce rotation of the drop is by absorption of a circularly polarized light with a Gaussian mode distribution.[12] This momentum transfer mechanism was used to rotate optically trapped bipolar drops made from E-44 (Merck) liquid crystal at a wavelength of 1.064 μm.[4] For transparent particles, the torque due to light absorption vanishes and rotation can be achieved only if the particles are birefringent.[13] The change in the polarization state of the incident light after passing through such particles imparts momentum to the particle. The torque experienced by the

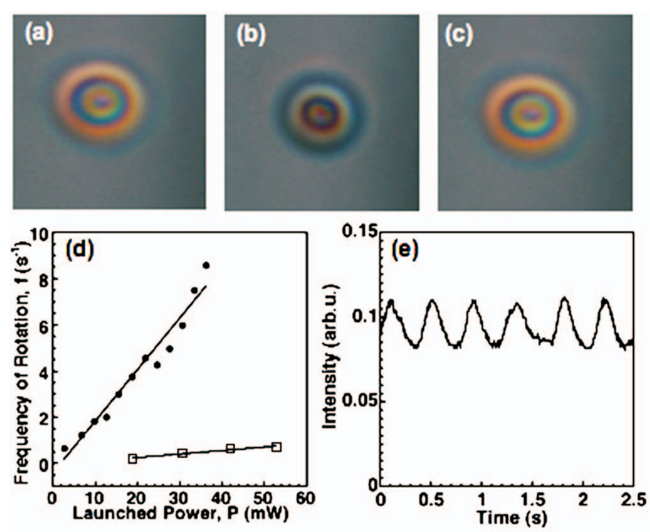

FIG. 3. (Color) [(a)–(c)] Cross-polarizer images of a bipolar liquid crystal drop trapped with the fiber-optic tweezers for different orientations of its average optic axis; we achieved this by rotating the $\lambda/2$ wave plate by (a) 0°, (b) 90°, and (c) 180°. The texture is recovered after 180° rotation. (d) Measured frequency of rotation for drops of $2a = 4.4$ μm (●) and $2a = 17.2$ μm (□) as a function of the power of a circularly polarized incident light. (b) Intensity modulation observed in the backscattered radiation due to the rotation of the trapped liquid crystal drop.

particle is $\Gamma_{circular}=P[1-\cos(2ka\Delta n)]/\omega$, where P is the power of the incident circularly polarized light, a is the drop radius, $k=2\pi/\lambda$ is the free-space wave number, and Δn is the birefringence. This equation is strictly valid for a birefringent slab of material. Since most or the LC drops we employ have a size which is larger than the spot size of the fiber tweezers, we assume this equation gives a reasonable approximation to the optical torque. By choosing a particle such that $2a\Delta n = p\lambda/2$, with p an integer, this optical torque is maximized and is equal to $2P/\omega$; interestingly, this is twice that experienced by a particle which rotates due to complete absorption of light.

For a liquid crystal drop with $a=2.2$ μm, $2a\Delta n \sim 0.45\lambda$ and the optical torque is almost maximum. The rotation of such drop can be induced with continuous wave light for incident powers as small as ~3 mW, which we measure at the exit of the fiber tweezer. The frequency of rotation, as measured with the CCD camera, increases linearly with the pump power, as shown in Fig. 3(d). We obtain a frequency of rotation per incident pump power of (0.22 ± 0.02) s^{-1} mW. To account for this result, we balance the optical torque imparted by the light and the opposing torque due to drag of the surrounding viscous liquid given by Stokes law: $\Gamma_{drag}=16\pi^2\eta a^3 f$, with f the rotation frequency of the particle and η the viscosity of the surrounding fluid. For $a=2.2$ μm, $\eta=10^{-3}$ N m s^{-1} and $\Delta n=0.16$, we find $f/P=0.94$ s^{-1} mW, which is of the same order of the experimental result.

The large focal length of the lens fiber allows trapping of objects as large as ~20 μm. We illustrate results for a trapped drop of $a=8.6$ μm in Fig. 3(d). We again find a linear f-P relation, characterized by a slope of (0.015 ± 0.002) s^{-1} mW, which is smaller than that obtained for the smaller liquid crystal drop and is again close to the theoretical expectation, $f/P=0.007$ s^{-1} mW.

Although the 5CB liquid crystal used in our experiments has good transmission at $\lambda=1.550$ μm,[14] there may still be some light absorption that could contribute to the optical torque. This contribution would reduce the theoretical estimate for the drop with $a=2.2$ μm and would increase this estimate for the drop with $a=8.6$ μm; in each case it would improve the agreement with the experimental values. To confirm this effect, we trapped a particle with $a=5.0$ μm; in this case, $2a\Delta n \sim \lambda$ and the optical torque due to birefringence should vanish. However, we observe that this drop still rotates, confirming that there is some light absorption that contributes to the rotation.

In addition to trapping, manipulating and rotating liquid crystal drops, the fiber-optic tweezers can be used to monitor the backscattered light from the trapped object. As the liquid crystal drop rotates in our experiment, we detect the polarization component of the reflected light that is perpendicular to that of the incident light, using a fiber-pigtailed polarization beam splitter connected to an ac coupled photodiode (see Fig. 2). Rotation of the drop causes modulation of the light polarization, resulting in a periodic variation of the backscattered intensity [Fig. 3(e)]. This allows the use of the trapping device to monitor the light backscattered from the trapped particle. We verified that the modulation frequency observed in the reflected light correspond to the frequency measured with a CCD camera under the microscope.

In conclusion, we have demonstrated optical manipulation and rotation of nematic liquid crystal drops using high-index bismuth optical fiber tweezers. By controlling the polarization state of the incident light, we could rotate the average director field of the drops by using linearly polarized light, and cause its periodic rotation by using circularly polarized light; this results in a modulation of the backscattered light intensity that can be monitored with the optical fiber used for trapping the drops. We have achieved a maximum speed of rotation of 8.6 Hz for a 4.4 μm size drop with a continuous wave radiation of 36 mW at $\lambda=1.550$ μm. Finally, we emphasize the versatility and capabilities of our fiber-optic tweezers that could be an advantage for certain applications.

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