All-optical switching using controlled formation of large volume three-dimensional optical matter

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We demonstrated the creation of large volume three-dimensional optical matter by optically trapping polystyrene spheres in a capillary and the resulting switching operation. The formation of optical matter was confirmed by examining the diffraction pattern of the trap region. Optical switching with an extinction ratio as large as ~20 dB was realized. From the dynamics of the optical matter, it was found that the transition from a disordered state to an ordered one appeared to be quite fast while the recovery of the system to the disordered state took a much longer time. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2944233]

Since Yablonovitch and John introduced the concept of photonic crystals (PCs),[1,2] periodic dielectric structures, the physical properties of PCs have been extensively explored for various all-optical device functions.[3] To fabricate PCs of different dimensions, many top-down (etching bulk materials) and bottom-up techniques (assembling identical building blocks) were proposed.[4]

Meanwhile, the pioneering work of Ashkin *et al.* on controlling microparticles using a single laser beam,[5] the so-called optical tweezer has been widely employed in various fields of science and technology. With the advances in understanding the underlying physics, the trapping and manipulation of microparticles have progressed from single particles to a large number of particles using interference and holographic techniques.[6–11] However, optical trapping could also be utilized to generate ordered structures, similar to the bottom-up methods. As a result, the concept of optical matter emerged representing the ordered structures formed in the presence of optical fields.[12–16] Physically, optical matters are similar to PCs except for their dynamic and reversible features. Thus, optical matters will be destroyed with the removal of the optical fields but can be reproduced when the optical fields are reimposed. These features make them quite attractive from the viewpoint of both fundamental research and device application. However, there is no report on functional devices based on optical matter because of the challenges in creating high quality and stable optical matters over large volume.

So far, the most commonly used platform for optical trapping and manipulation is monodisperse microparticles suspended in a fluid, e.g., polystyrene (PS) spheres randomly distributed in water. Most investigations focus on the design, creation, and modification of multiple traps on which the ordered structures are generated.[6–11] In contrast, less attention has been paid to the process of optical matter formation, a transition from disordered to ordered system. In fact, the transition from ordered to disordered system such as Anderson localization, has been extensively studied.[17,18] Recently, we have shown that Anderson localization can be induced in nonlinear PC waveguides, leading to an ideal optical limiting.[19] However, the reverse process, i.e., transition from disordered to ordered system, appears more interesting. On one hand, it becomes possible to observe the continuous evolution of a disordered system into an ordered one, including the intermediate states, by monitoring the diffraction pattern of the trapping region. As shown by Förster *et al.*, the transition to an ordered system should be reflected in the transformation of Debye–Sherrer rings into Bragg peaks.[20] On the other hand, a significant transmission enhancement at the trapping region is anticipated with potential in switching applications. In the absence of the trap, the aqueous solution of PS spheres is a disordered system and an incident light will experience a strong backscattering. Once the transition to an ordered system occurs, however, one would expect a significant enhancement in the transmission of the incident light. Very recently, we have demonstrated such a transition in colloidal liquids by using Z-scan-based optical trapping.[21] Therefore, the transition from disordered to ordered system can be employed to construct all-optical switches if large volume, high quality, and stable optical matters can be created.

The all-optical switch we proposed and fabricated is shown in Fig. 1. The main body of the switch is a glass capillary filled with the aqueous solution of PS spheres. While the inner and outer diameters of the capillary are 100 and 340 μm, the diameter and concentration of PS spheres (Duke Scientific) are 1.9 μm and 10 wt. %, respectively. On an organic glass substrate a groove was made along the x direction to mount the capillary. Along the y direction, two single-mode optical fibers (numerical aperture of 0.13) were accurately aligned head to head into another groove on either side of the capillary. The axes of the capillary and optical fibers were made to be in the sample plane (xy plane). The fibers are used to couple signal light into the trap region and transmitted light out of trap to an optical fiber spectrometer

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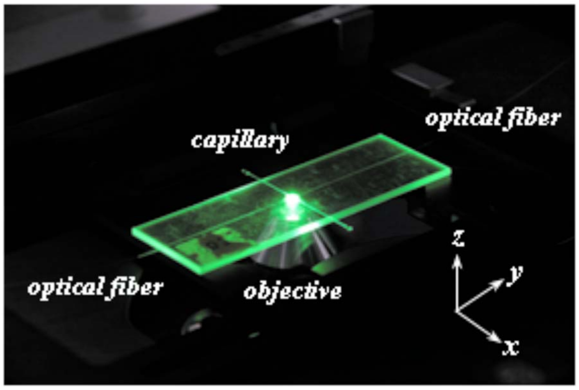

FIG. 1. (Color online) Photograph of the all-optical switching device based on the generation of three-dimensional optical matter.

(Yokogawa AQ6370), respectively. The signal light used was a broadband source ranging from 1.525 to 1.565 μm (Lightcomm). In the switching experiments, we chose to detect the transmitted intensity at a wavelength of 1.547 μm. The device was placed onto the specimen stage of an inverted microscope (Zeiss Axio Observer A1) and the 532 nm light from a solid-state laser was used as the trapping light (or the control light). Through an aperture in the glass substrate, the trapping light was focused onto the capillary along the z direction with a 10× objective lens. The use of a relatively low magnification lens has a twofold advantage. First, due to the longer focal depth compared to a larger magnification lens, it is possible to create relatively large volume optical matter suitable to open a transparent window sufficiently wide and matching the numerical aperture of the single-mode fiber used for detection. Second, it has been found that convection of PS spheres caused by the imbalance between the axial gradient force and the scattering force was less for low magnification objective lens.

In experiments, the trapping dynamics were monitored either through the eyepiece or a charge-coupled device (CCD) connected to the microscope. With the launch of the trapping light we observed redistribution of PS spheres followed by a quasistatic distribution in several seconds. Figure 2(a) shows a dumbbell shaped distribution in the xy plane for a trapping power of 300 mW. A close inspection revealed that the PS spheres in the central rod of the dumbbell were closely packed and did not move. In contrast, the PS spheres in the two bells appeared quite active and showed Brownian motion. It is also noticed that the size of the ordered structure (i.e., the central rod of the dumbbell) is much larger than the focus size of the 10× objective which is only ~10 μm, implying the existence of optical binding among PS spheres.[13,14] To confirm the formation of optical matter, the diffraction pattern was recorded on a screen placed several centimeters away on top of the device. A clear diffraction pattern was observed once the dumbbell was formed, as shown in Fig. 2(b). Diffraction peaks up to the fourth order were clearly identified, indicating that the structure of the optical matter is face-centered cubic. Also, the hexagonal distribution of the Bragg peaks was found to be slightly elongated along the capillary (x) direction.

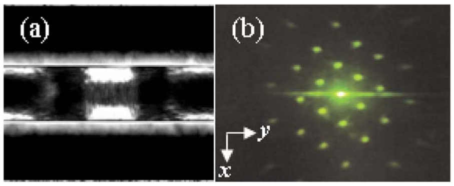

FIG. 2. (Color online) (a) Distribution of PS spheres in the capillary on the xy plane when a trapping light of 300 mW is applied. (b) Diffraction pattern of the trapping region observed on top of the capillary.

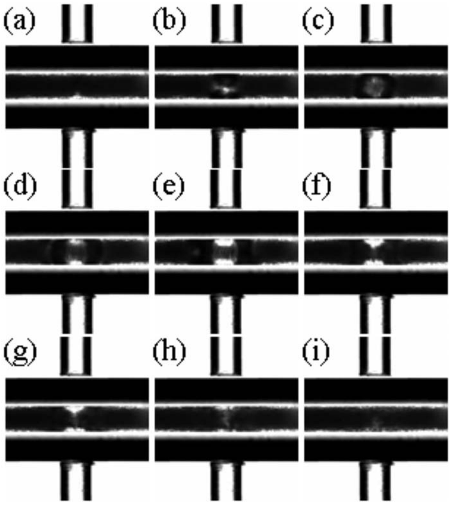

FIG. 3. Evolution of the distribution of PS spheres in the capillary on the xy plane during the optical switching process under a trapping power of 300 mW. (a) is in absence of trapping light, (b)–(e) correspond to different times just after the launch of the trapping light, and (f)–(i) correspond to different times after removal of the trapping light. The times at which the images were recorded are (a) 0 s, (b) 125 s, (c) 128 s, (d) 130 s, (e) 180 s, (f) 300 s, (g) 330 s, (h) 360 s, and (i) 500 s.

The formation of optical matters implied a transition from disordered to ordered state in the trap region corresponding to the central rod of the dumbbell. This opened a transparent window for the signal light. Once the trapping light was shut off, the optical matter gradually returned to a disordered state and signal light got scattered. Thus, we could realize an all-optical switch by utilizing the dynamic and reversible features of optical matter.

Figure 3 shows CCD images of the distribution of PS spheres in the xy plane at different stages of switching process. Figures 3(a) and 3(b) show the state just before and after the trapping light was introduced. After that, we can see the fast movement of PS spheres from the sidewall to the center part of the capillary [Fig. 3(c)], dumbbell formation and opening of transparent window for signal light [Fig. 3(d)] and steady state after completion of dynamic trapping [Fig. 3(e)]. When the trapping light was turned off, the close-packed PS spheres became loose and the dumbbell shape structure collapsed [Figs. 3(f) and 3(g)]. After several minutes, the dumbbell shape disappeared completely and PS spheres were uniformly distributed in water once again [Figs. 3(h) and 3(i)].

The switching operation of the device was detected by the spectrometer that recorded the dynamic change in the transmitted intensity when the trapping light was turned on and off. The switching behaviors under different trapping powers are compared in Fig. 4. In each case, the switching operation was repeated five times to show the well reproduced switching operation. The reference signal obtained in the absence of the capillary is also provided. After examining the switching behavior in all cases, we found four remarkable features that need to be addressed. First, we achieved in

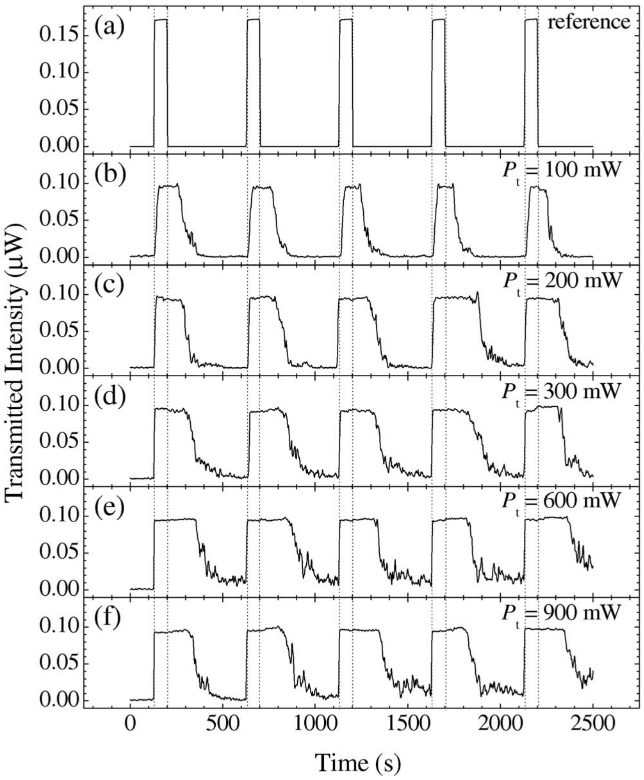

FIG. 4. Five consecutive switching operations under different trapping powers (P_t). (a) reference signal without the capillary: (b) P_t=100 mW, (c) P_t=200 mW, (d) P_t=300 mW, (e) P_t=600 mW, and (f) P_t=900 mW.

all cases an extinction ratio close to 20 dB suitable for practical devices. Second, the time constant for switch on is much shorter than that for switch off. This is because the former was governed by optical force while the latter was dominated by the Brownian motion. In addition, the rise time becomes faster with increasing trapping power. It decreases from 7.5 to 0.55 s when the trapping power is increased from 100 to 900 mW. Third, the optical matter could live for a long time after the trapping light had been removed. The larger the trapping power, the longer the lifetime of the optical matter with saturation seen from 600 mW. This behavior and the diffraction pattern indicated that PS spheres were packed closely in the presence of optical force so that the van der Waals force between them was strong enough to counter the Brownian motion that tends to destroy the optical matter. This phenomenon may find applications in optical memory. Finally, the recovery of the device to the off status (or the system to disordered state) was found to depend on the trapping power with quick recovery observed at low trapping powers.

In summary, by designing and generating optical matter, we have demonstrated an all-optical switch based on optical matter generation. Significant enhancement in transmission accompanied with the disordered to ordered transition was employed to realize the switching operation. Repeatable switching operation with extinction ratio as large as ~20 dB has been achieved. Our experiments suggest that optical trapping can be utilized to realize a transition from a disordered to ordered system and create stable optical matter over large volumes by deliberately designing the configuration of the trapping system.

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