Optical switching based on the manipulation of microparticles in a colloidal liquid using strong scattering force*

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(Received 5 May 2010; revised manuscript received 16 May 2010)

This paper demonstrates the realization of an optical switch by optically manipulating a large number of polystyrene spheres contained in a capillary. The strong scattering force exerted on polystyrene spheres with a large diameter of 4.3 μm is employed to realize the switching operation. A transparent window is opened for the signal light when the polystyrene spheres originally located at the beam centre are driven out of the beam region by the strong scattering force induced by the control light. The switching dynamics under different incident powers is investigated and compared with that observed in the optical switch based on the formation of optical matter. It is found that a large extinction ratio of $\sim$ 30 dB and fast switching-on and switching-off times can be achieved in this type of switch.

Keywords: optical switching, scattering force, optical matter

PACC: 4250V, 4265C, 7280P

1. Introduction

Optical trapping and manipulation of small objects such as micro- and nanoparticles have attracted great interest in the last two decades due to their potential applications in various fields of science and technology. Basically, the trapping and manipulation of particles rely on the momentum transfer from photons to particles. This mechanic effect is generally referred as an optical force which can be further categorized into scattering and gradient forces for particles without absorption.[1] While the scattering force pushes particles along the direction of light propagation, the gradient force tends to attract them to the high intensity region of a laser beam. In the first experiment on optical trapping performed in 1970 by Ashkin, microparticles were stably trapped by utilizing two laser beams propagating in opposite directions to balance the scattering force induced by the laser beams.[2] A remarkable breakthrough in optical trapping was achieved in 1986 when Ashkin *et al.* demonstrated the trapping of microparticles by using a single laser beam.[3] In that case, the scattering force in the forward direction was balanced by the longitudinal gradient force in the backward direction induced by a highly focused laser beam.

From the viewpoint of practical application,[4,5] it seems more attractive and important to manipulate a large number of particles rather than a single particle. Therefore, the research work in this field has been focusing on the design and manipulation of multitraps where ordered structures can be created.[6,7] Various physical mechanisms, such as optical binding,[8–10] surface plasmons,[11,12] and evanescent waves,[13] etc. have been proposed to manipulate a large number of particles and the most popular technique is based on holographic optics.[14–16] However, the ordered structures generated by holographic technique have not been employed in the fabrication of functional devices.

Recently, we proposed a simple and effective way to trap a large number of particles and create ordered structures based on the combination of single beam optical trapping and conventional Z-scan technique.[17] By optimizing the trapping power and scanning speed, a transition of the trap region from a disorder state to an ordered one was realized at the focal point, leading to a self-induced transparent

*Project supported by the National Natural Science Foundation of China (Grant Nos. 10974060 and 10774050) and the Program for Innovative Research Team of the Higher Education of Guangdong Province of China (Grant No. 06CXTD005).

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phenomenon which can be employed to realize optical switches. Based on this mechanism, we successfully demonstrated an "all-optical" switch with an extinction ratio as large as $\sim$ 20 dB by optically trapping microparticles contained in a capillary to form an optical matter.[18] In the Z-scan-based optical trapping experiments, it was found that two mechanisms were responsible for the enhancement of the transmitted intensity observed at the focal point.[19] One is the formation of an ordered structure which is observed at low trapping powers above the threshold. The other is the reduction of the volume density of particles in the beam region induced by the strong scattering force at high trapping powers. In the latter case, microparticles are pushed out of the beam region by strong scattering force, resulting in an enhancement in the transmitted intensity. This phenomenon implies a new mechanism for the construction of optical switches based on the manipulation of a large number of particles. In this article, we report on the first demonstration of optical switches based on the redistribution of microparticles by utilizing strong scattering force. Well-reproduced switching operation with a large extinction ratio is realized. In addition, the switching dynamics is investigated in detail and compared with that observed in the optical switch based on the formation of optical matter.[20]

2. Switching mechanism

The configuration of the device used to realize the switching operation is schematically shown in Fig. 1. A capillary containing the aqueous solution of uniformly distributed polystyrene (PS) spheres was placed into a groove made on an organic glass slide in the x direction. The diameter and concentration of the PS spheres are 4.3 μm and 10% (Duck Scientific) respectively. Along the y direction, two optical fibers used to emit and detect the signal light were accurately aligned head to head into another groove on either side of the capillary. The 1546-nm light from a broadband light source (Lightcomm) was selected as the signal light. The transmitted intensity of the signal light was detected by a spectrometer (Yokogawa AQ6370). The 532-nm light from a solid state laser was employed as the trapping light (control light) and it was focused into the capillary with the 10× objective lens of an inverted microscope (Zeiss Axio Observer A1). A coupled charge device (CCD) connected to the microscope was used to monitor the dynamic distribution of PS spheres during the switching operation.

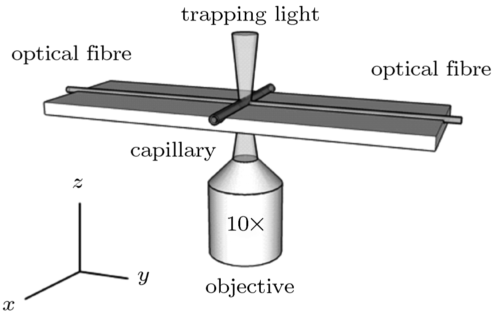

Fig. 1. Schematic diagram of the proposed optical switch based on strong scattering force.

In the absence of the control light, the signal light suffers from strong scattering by randomly distributed spheres and the transmitted intensity is quite small. Since the mean free path of photons in the suspension of spheres is inversely proportional to the volume density of spheres,[21,22] it is expected that the transmission of the signal light would increase significantly if the density of spheres is dramatically reduced. This suspect is confirmed by the numerical simulations based on the finite-difference time-domain (FDTD) technique,[23] as shown in Fig. 2.

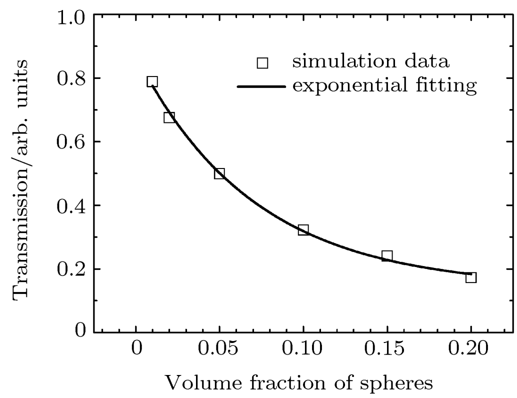

Fig. 2. Dependence of the transmission of a signal light through a parallelepiped containing randomly distributed spheres on the volume fraction of spheres. The open squares are data obtained by FDTD simulation while the solid curve is an exponential fitting to the simulation result.

We simulate the transmission of a 1550-nm light through a parallelepiped ($18 \times 18 \times 100$ μm^3) containing randomly distributed spheres of 4.3 μm diameter and derive the dependence of the transmission on the volume density of spheres. In the numerical simulations, the mesh sizes in all directions are set to be 0.15 μm and the diameter of the incident light beam is chosen to be 15 μm. In addition, a perfectly matched layer boundary condition is employed. It is noticed that the transmission increases almost exponentially with decreasing density of spheres. It implies that a significant enhancement in the transmission can be achieved if the density of spheres can be reduced by utilizing the scattering force of the control light. This is the underlying physical mechanism for the proposed optical switch.

Now let us examine the optical forces exerted on the spheres within the beam region. In general, the optical forces exerted on a microparticle without absorption can be classified into the scattering force in the forward direction and the gradient forces in the transverse and longitudinal directions.[1] Since an objective lens with a small magnification (10×) was used in our experiments, the gradient force in the longitudinal direction can be neglected. At the initial stage after the control light is switched on, the control light suffers from strong scattering and the scattering force dominates the movement of spheres. In contrast, the gradient force in the transverse direction is not significant because the light intensity at the beam centre is strongly attenuated, leading to a small gradient in light intensity across the beam diameter. Once the spheres located at the beam centre are pushed away, however, a significant enhancement in the gradient force is expected because of the dramatic increase of the light intensity at the beam centre. The gradient force tends to attract spheres back to the beam centre, counteracting with the scattering force which drives spheres out of the beam region. Eventually, a balance is achieved between the scattering and gradient forces and the system reaches a steady state.

As discussed above, microparticles will be pushed out of the beam region when they suffer from strong scattering force, leading to a reduction in the volume density of particles and an enhancement in the transmitted intensity. Basically, the scattering force exerted on a microparticle whose diameter is larger than the wavelength of light can be expressed as follows:[2]

$$F_{\text{scat}} = 2qP/c, \tag{1}$$

where P is the power of the incident light, $q \sim 0.1$ is the fraction of light effectively reflected back, and c is the speed of light in vacuum. In fact, it was found by Ashkin that large (2.68 μm) spheres were accelerated by incident light while small (0.585 μm) spheres were left behind in the mixture of these two spheres.[2] In addition, it was revealed that the velocity of a sphere achieved in a liquid was proportional to the radius of the sphere. Therefore, a significant increase in scattering force is expected when using 4.3 μm spheres instead of 1.9-μm ones which have been used in the same device for realizing an optical switch.[18]

In the above discussion, we deal with only the case of a single particle. When the trapping of a large number of particles is concerned, the situation becomes quite complicated and we need to consider other effects such as multi-particle interaction. However, the dominant role of strong scattering force remains unchanged and other effects play less important roles. Therefore, an optical switch based on strong scattering force can be constructed by employing exactly the same device described in Ref. [18].

3. Switching operation

Figure 3 compares the static distribution of PS spheres in the xy plane of the capillary at the on state for the two optical switches mentioned above. The power of the control light is chosen to be 300 mW. The left image shows the formation of a dumbbell-shaped optical matter due to optical binding.[8−10] In this case, a highly ordered distribution of 1.9 μm spheres is achieved which is confirmed by the diffraction pattern of the trap region.[18] The significant enhancement in the transmitted intensity results from the formation of optical matter. In comparison, the right image presents the distribution of 4.3-μm spheres in the capillary when the scattering force is strong. It can be seen that most of the spheres originally located around the focus point are pushed out of the beam region, forming a depletion region which is also much larger than the focus size.

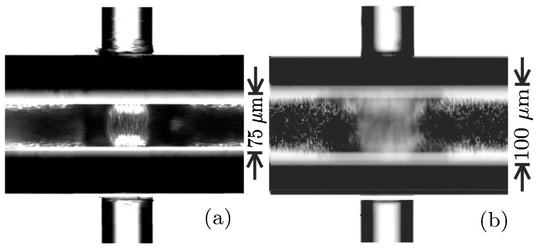

Fig. 3. Static distributions of PS spheres in the xy plane of the capillary recorded by the CCD for two types of optical switch, (a) optical switch based on optical matter; (b) optical based on scattering force.

For the optical switch based on strong scattering force, the evolution of the distribution of PS spheres in the capillary during a switching operation is presented in Fig. 4. The states introduced just before and after the control light are shown in Figs. 4(a) and 4(b), respectively. After that, we can see the quick movement of spheres out of the beam centre [Fig. 4(c)], the appearance of a depletion region at the beam centre [Fig. 4(d)], and the creation of a transparent window for the signal light after some time [Fig. 4(e)].

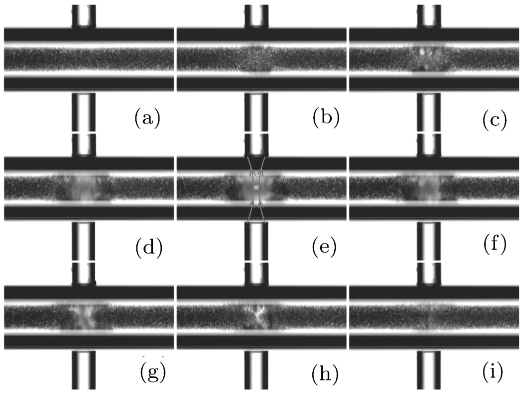

Fig. 4. Evolution of the distribution of PS spheres in the xy plane of the capillary at different stages of a switching process under an incident power of 400 mW: (a) the distribution of PS spheres in the absence of the control light, (b)–(e) the distributions of PS spheres at different times after the launch of the control light, (f)–(i) corresponding to the distributions of PS spheres at different times after the removal of the control light. The spot size of the control light, the path of the signal light and length scale are shown in image (e).

After the control light is shut off, the spheres outside the transparent window move back by normal diffusion (Brownian motion) [Figs. 4(f)–4(h)]. Finally, the depletion region is filled by spheres and the transmission window is closed. The system returns to its original state [Fig. 4(i)].

Apart from the dynamic distribution of PS spheres inspected by using the CCD, the switching operation of the device was also examined by the spectrometer which recorded the dynamic change of the transmitted intensity when the control light was turned on and shut off. The switching behaviours under different incident powers ($P_{\rm in}$) are compared in Fig. 5. At a low $P_{\rm in}$ of 200 mW, a regular switching operation with a stable transmitted intensity at the on state is not observed although an overall increase in the transmitted intensity is seen. In this case, it is thought that the scattering force is strong enough to move spheres but not sufficient to create a depletion region. As $P_{\rm in}$ exceeds 300 mW, regular and well-reproduced switching operations emerge. An extinction as large as $\sim$ 30 dB was achieved in all switching processes. This value is higher than that achieved in the optical switch based on optical matter which is only $\sim$ 20 dB.[18] In that case, the enhancement in the transmitted intensity is caused by the formation of optical matter which is actually a dynamic photonic crystal (PC).[24,25]

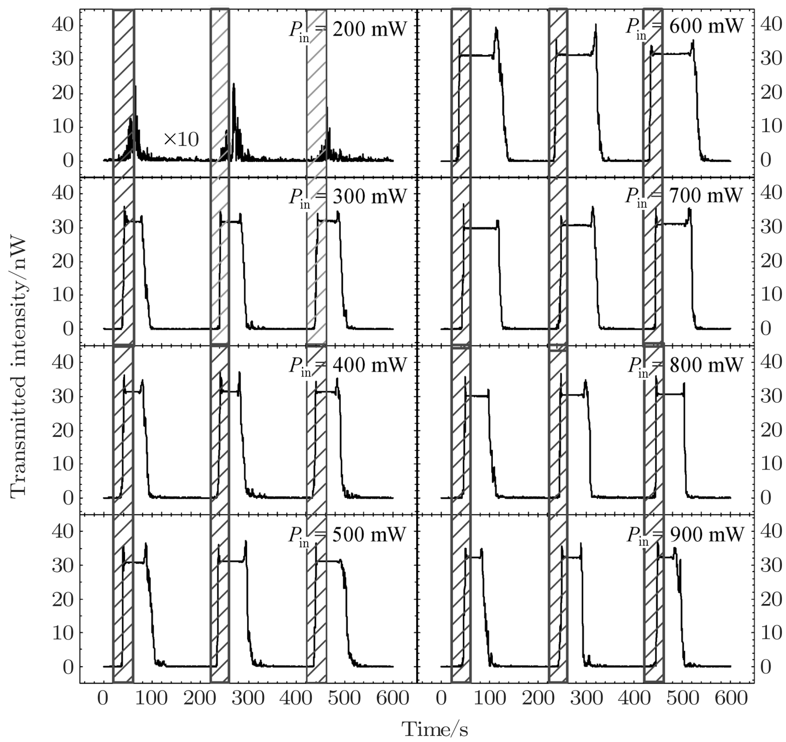

Fig. 5. Three consecutive switching operations under different incident powers ($P_{\rm in}$). The shadowing areas indicate the time intervals in which the control light is imposed.

A comparison of the full widths of the diffraction peaks between the optical matter and the colloidal PC fabricated by a self-assembled technique indicates that the density of disorders in the optical matter is higher than that in the colloidal PC.[26] The existence of these disorders leads to a reduction in the transmitted intensity and extinction ratio. In comparison, most of the spheres originally located at the beam centre are removed in the optical switch based on scattering force. As a result, a larger extinction ratio is obtained in such a kind of switch.

In Fig. 5, some common features are observed at different incident powers. For instance, a constant transmitted intensity is observed at the on state and it does not depend on incident power. In addition, a small spike is observed in both the rise and decay processes of the transmitted intensity. Apart from these common features, the switching dynamics exhibits a strong dependence on incident power. It will be addressed in detail in the next section.

4. Switching dynamics

The switching-on processes of the optical switch under different incident powers are compared in Fig. 6. Physically, the switching-on process can be considered as the phase transition of the trap region from a state occupied by randomly distributed spheres to a state with very few spheres. This transition is accompanied by an exponential rise of the transmitted intensity from a low level to a high one. Therefore, we can also use the Fermi–Dirac function to fit the switching-on process, similar to what we did in Ref. [20]. Hence, the evolution of the transmitted intensity for the signal light with time $I(t)$ can be described by

$$I(t) = \frac{I_{\mathrm{ON}}}{1+\exp[-(t-t_{\mathrm{r0}})/t_{\mathrm{r1}}]}, \tag{2}$$

where $I_{\mathrm{ON}} \sim 0.032$ μW is the transmitted intensity of the signal light at the on state, t_{r0} and t_{r1} are two parameters used to characterize the transition process. The fitting results are also shown in Fig. 6. Since the signal light suffers from strong scattering by the spheres in the beam region, the transmitted intensity is quite low at the off state. However, a significant enhancement in the transmitted intensity is expected when the volume density of spheres is reduced to a critical value by the scattering force. The time period necessary to achieve this critical volume density is given by t_{r0}. In comparison, t_{r1} describes the time period in which the rest spheres are removed from the beam region and the system reaches a steady state. In Fig. 7(a), we present the dependence of t_{r0} on P_{in}.

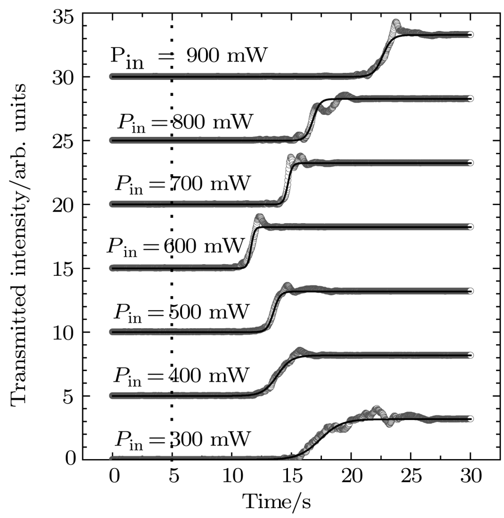

Fig. 6. Switching-on processes under different incident powers (P_{in}) (open circles) and the fits to the experimental data (solid curves) by using the Fermi–Dirac function. The dotted line indicates the time ($t = 5$ s) when the control light is switched on.

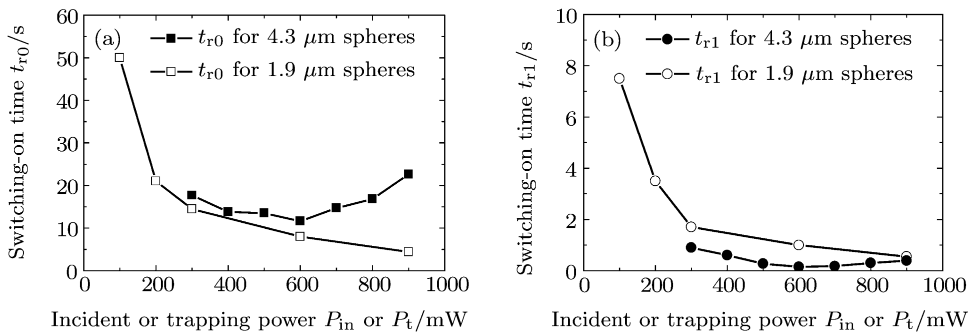

Fig. 7. Dependence of the switching-on times t_{r0} (a) and t_{r1} (b) on incident power (P_{in}) or trapping power (P_{t}) for the optical switch based on scattering force using 4.3-μm spheres and that based on optical matter using 1.9-μm spheres.

For comparison, the dependence of t_{r0} on trapping power (P_t) for 1.9-μm spheres (i.e., the optical switch based on optical matter) is also provided. It can be seen that for 4.3-μm spheres the variation of t_{r0} with P_{in} is not significant. It ranges from 11.61 s to 22.65 s for the incident powers used in the experiments. In addition, it is noticed that t_{r0} does not change monotonously with increasing P_{in}. It decreases first and then increases with increasing P_{in}. Consequently, a minimum value of 11.61 s is observed at 600 mW. In comparison, a dramatic reduction of t_{r0} from 50 s to 4.4 s is found for 1.9-μm spheres which are trapped by gradient force.

The dependence of t_{r1} on P_{in} for 4.3-μm spheres is shown in Fig. 7(b). Also, the evolution of t_{r1} with increasing P_t for 1.9-μm spheres is provided for comparison. For 4.3-μm spheres, it is noticed that t_{r1} decreases first and increases again with increasing P_{in}. As a result, a minimum value of 0.15 s is observed at 600 mW. In comparison, a marked reduction of t_{r1} from 7.5 s to 0.55 s is observed for 1.9-μm spheres whose movement is dominated by gradient force. It has been suggested that t_{r1} in the optical switch based on optical matter characterizes the oscillation of spheres around regularly defined sites with attenuated amplitude.[20] In the optical switch based on scattering force, however, it describes the escape time of 4.3-μm spheres out of the beam region driven by scattering force. Therefore, it appears to be faster for 4.3-μm spheres at low incident powers. At high trapping (or incident) powers, a rapid damping of oscillation is expected for 1.9-μm spheres and t_{r1} becomes similar for both switches. In addition, the moving speed for 4.3-μm spheres becomes faster at high incident powers. Consequently, it takes a longer time to reach the steady state, resulting in a larger t_{r1}.

In the switching-on processes shown in Fig. 6, it is remarkable that a spike is observed in the rise process for all incident powers. We think that the appearance of the spike is a symptom for the competition between the scattering and gradient forces. As mentioned above, the scattering force dominates the motion of spheres at the initial stage and the gradient force becomes significant only when the spheres at the beam centre are driven out. This spike represents the process in which spheres are firstly driven out of the beam centre and then some of them are attracted back. Eventually, a balance is achieved between these two optical forces and a constant transmitted intensity is obtained.

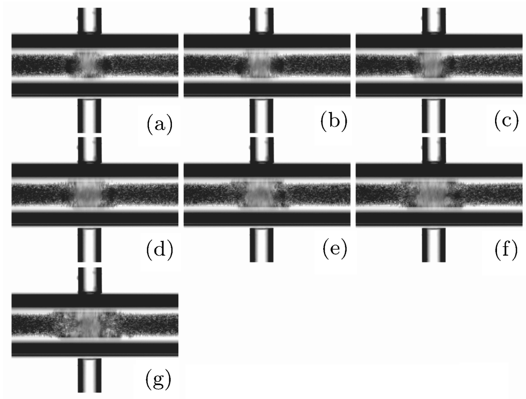

Fig. 8. Distributions of PS spheres in the steady state under different incident powers (P_{in}) showing transparent windows with different widths: (a) P_{in} = 300 mW, (b) P_{in} = 400 mW, (c) P_{in} = 500 mW, (d) P_{in} = 600 mW, (e) P_{in} = 700 mW, (f) P_{in} = 800 mW, (g) P_{in} = 900 mW.

The transparent windows opened at different incident powers are compared in Fig. 8. It is apparent that the transparent window becomes wider with increasing incident power. This situation is similar to that observed in the optical switch based on optical matter.[20] In that case, an increase in the volume of the formed optical matter is observed with increasing trapping power. Here, it is found that the width of the transparent window saturates for incident powers higher than 600 mW. However, a close inspection reveals that the distribution of spheres at the two edges of the transparent window appears to be different. While the spheres at the two edges of the transparent window appear to be static at 600 mW, they behave active at 900 mW. We think that this phenomenon explains why the minima of t_{r0} and t_{r1} are achieved at 600 mW.

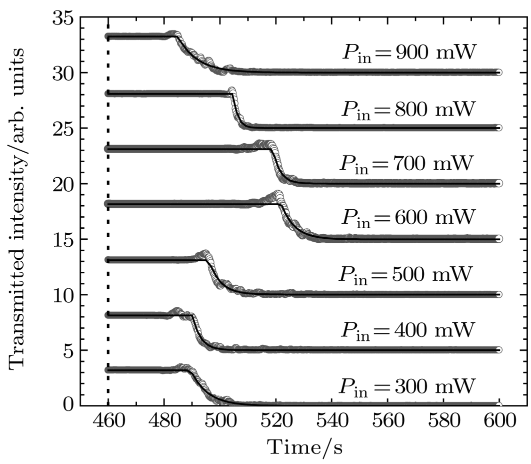

Fig. 9. Switching-off processes under different incident powers (P_{in}) (open circles) and the fits to the experimental data (solid curves) by using a steady state followed by an exponential decay. The dotted line indicates the time (t = 460 s) when the control light is switched off.

The switching-off processes of the device recorded at different incident powers are shown in Fig. 9. In each case, we can see a steady state with a constant transmitted intensity followed by a single exponential decay after the control light is shut off. After the removal of the control light, PS spheres being driven out begin to move back to the beam centre by normal diffusion. At the early stage, the diffusion does not affect the transmitted intensity of the signal light because spheres have not reached the beam centre. Once they approach the beam centre, however, a dramatic reduction of the transmitted intensity occurs because of the strong scattering of the signal light.

Similar to the switching-on processes, the switching-off processes can also be characterized by two time constants t_{d0} and t_{d1}. While t_{d0} characterizes the time period in which the transmitted intensity remains unchanged, t_{d1} gives the time constant for the exponential decay of the transmitted intensity. The fitting results for the switching-off processes at different incident powers are also presented in Fig. 9. The dependences of t_{d0} and t_{d1} on P_{in} are presented in Figs. 10(a) and 10(b), respectively. Also, the experimental data for the optical switch based on optical matter are also plotted for comparison. In Fig. 10(a), it can be seen that the value of t_{d0} for 4.3-μm spheres is much shorter than that for 1.9-μm spheres. In the optical switch based on optical matter, the formed optical matter can survive for a long time because of van der Waals force. The lifetime of the optical matter increases significantly with increasing trapping power.[18] It implies that the increased interaction among spheres at high trapping powers can postpone the annihilation of the optical matter which is caused by Brownian motion. For the optical switch based on scattering force, the time period in which the transmitted intensity remains unchanged is determined by the movement of spheres back to the beam centre. The driving force for this movement is the large gradient in volume density. Thus, this process is expected to be much faster than the annihilation process of the optical matter, resulting in a much shorter t_{d0}. Apart from the small value, t_{d0} does not increase monotonously with increasing P_{in} for 4.3-μm spheres. Instead, a maximum value of $\sim$ 60 s is observed at 600 mW. In Figs. 7(a) and 7(b), it has been shown that the shortest switching-on times (t_{r0} and t_{r1}) are obtained at 600 mW. This behaviour has been explained as the rapid achievement of the steady state because of the suitable moving speed of spheres induced by the control light. In this case, the spheres located at the two edges of the transparent window appear to be static. Therefore, the diffusion of these spheres after the control light is shut off is slower in comparison with the case of high incident powers when the spheres in the two edges of the transparent window remain active. At low incident powers, it takes a shorter time to close the transparent window because it is narrower.

In Fig. 10(b), it is observed that there is no obvious dependence of t_{d1} on P_{in} or P_t for both 4.3-μm and 1.9-μm spheres. However, it can be seen that the value of t_{d1} for 4.3-μm spheres is shorter by one order of magnitude than that for 1.9-μm spheres. For the optical switch based on scattering force, most of the spheres at the beam centre are driven out, resulting in a large gradient in the density of spheres. Therefore, the diffusion of spheres back to the beam centre after the removal of the control light appears to be faster. In comparison, t_{d1} in the optical switch based on optical matter is mainly determined by the diffusion of spheres after the collapse of the ordered structure (or the annihilation of the optical matter). In this case, the diffusion is slower because of the smaller gradient in the density of spheres.

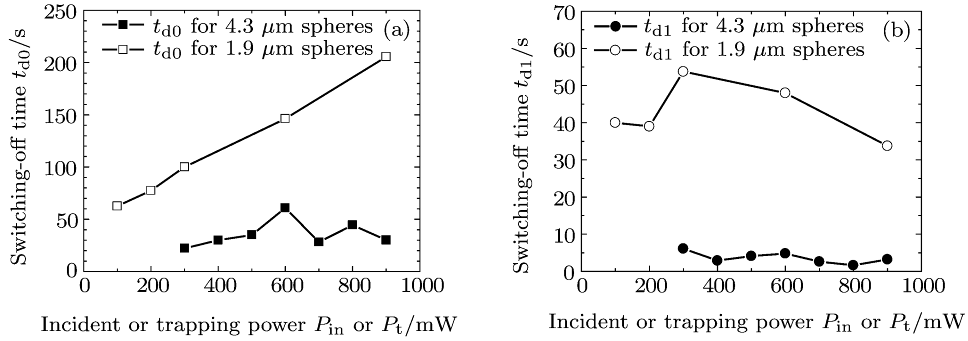

Fig. 10. Dependence of the switching-off times t_{d0} (a) and t_{d1} (b) on incident power (P_{in}) or trapping power (P_t) for the optical switch based on scattering force using 4.3-μm spheres and that based on optical matter using 1.9-μm spheres.

As compared to the spike appearing in the switching-on process, the spike observed in the switching-off process is more difficult to be understood. It probably originates from the focus of the signal light by the few spheres which firstly arrive at the beam centre. These spheres may act as lenses focus the signal light into the collection fiber, resulting in a higher transmission. Once the number of spheres returning to the beam centre becomes large, the scattering of the signal light becomes strong and the transmitted intensity decreases dramatically. However, more experiments are needed to clarify this issue.

5. Dependence of switching dynamics on radiation time

In the switching operations described above, the time period in which the control light is presented (i.e., radiation time $t_{\rm rad}$) is chosen to be 40 s. It has been clarified that the switching-on dynamics exhibits a dependence on incident power, although not as significant as that observed in the optical switch based on optical matter. On the other hand, it is interesting to find out whether the switching-off dynamics exhibits any dependence on radiation time. To do so, we have fixed the incident power at 400 mW and examined the switching-off dynamics of the device under different radiation times ranging from 20 s to 100 s. The extracted switching-off times ($t_{\rm d0}$ and $t_{\rm d1}$) as functions of radiation time are presented in Fig. 11.

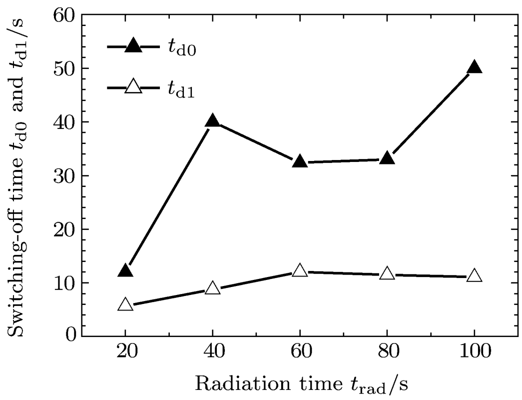

Fig. 11. Dependence of the switching-off times $t_{\rm d0}$ and $t_{\rm d1}$ on radiation time $t_{\rm rad}$.

As shown in Fig. 11, no obvious dependence of the switching-off times on radiation time is found except at a very short $t_{\rm rad}$ of 20 s. Figure 12 shows the distribution of PS spheres in the capillary at different radiation times. It can be seen that the transparent window is quite narrow when $t_{\rm rad} = 20$ s. As $t_{\rm rad}$ exceeds 40 s, the width of the transparent window remains nearly unchanged. Obviously, the switching-on time ($t_{\rm d0} + t_{\rm d1}$) for the device to reach the steady state with a constant transmitted intensity is longer than 20 s, especially at low and high incident powers. It implies that a steady state (or a steady distribution of spheres) has not been achieved within this time period, as shown in Fig. 12(a). If the control light is shut off in this period, the recovery of the system to the original state will be faster. The saturated transparent windows observed in Figs. 12(b)–12(f) indicate that it takes about 40 s to establish a steady distribution of PS spheres in the capillary. During this time period, only the spheres out of the beam region remain active and they have nearly no influence on the transmitted intensity of the signal light. Once the steady distribution of spheres is reached, a further increase of radiation time will not affect the switch-off dynamics.

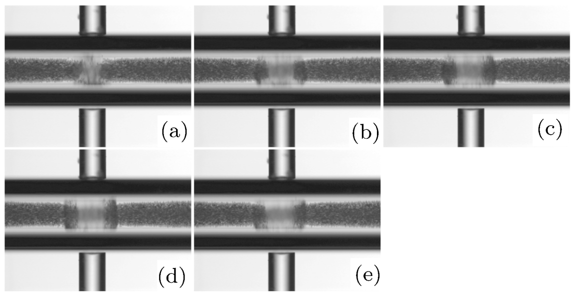

Fig. 12. Distributions of PS spheres under different radiation times ($t_{\rm rad}$): (a) $t_{\rm rad} = 20$ s, (b) $t_{\rm rad} = 40$ s, (c) $t_{\rm rad} = 60$ s, (d) $t_{\rm rad} = 80$ s, (e) $t_{\rm rad} = 100$ s.

6. Conclusion

In summary, we have constructed an optical switch by utilizing the strong scattering force exerted on PS spheres with a large diameter. As compared with the optical switch based on the formation of optical matter, this switching device exhibits different switching dynamics because of a different switching mechanism. Extinction ratio as large as ~ 30 dB and faster switching-on and switching-off times have been achieved in this kind of switch. It indicates a significant progress in the switching devices based on the trapping and manipulation of a large number of particles.

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