Dynamics of optical matter creation and annihilation in colloidal liquids controlled by laser trapping power

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We investigate the dynamics of optical matter creation and annihilation in a colloidal liquid that was employed to construct an all-optical switch. It is revealed that the switching-on process can be characterized by the Fermi–Dirac distribution function, while the switching-off process can be described by a steady state followed by a single exponential decay. The phase transition times exhibit a strong dependence on trapping power. With an increasing trapping power, while the switching-on time decreases rapidly, the switch-off time increases significantly, indicating the effects of optical binding and van der Waals force on the lifetime of the optical matter. © 2008 Optical Society of America

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Optical trapping and manipulation of microparticles and nanoparticles have attracted great interest since the pioneering work of Ashkin *et al.* [1]. Apart from the use of a single laser beam, techniques based on multiple laser beams, such as holography, have been employed to realize the trapping and manipulation of a large number of particles [2]. Optical manipulation of many particles into ordered structures was based on different mechanisms, such as optical binding [3–5], surface plasmon polariton [6], and evanescent waves [7]. The ordered structures generated and held by photons, referred to as optical matters, have dynamic and reversible features as compared with photonic crystals (PCs) [8]. These features make them quite attractive for both fundamental research and device applications.

So far, most studies have focused on the design, modification, and optimization of multitraps [9]. In comparison, less attention has been paid to the dynamics of optical matter creation and annihilation that represents the phase transition between a disordered state and an ordered one. The phase transition from an ordered state to a disordered one with increasing disorder, e.g., Anderson localization, is a subject that has received intensive studies [10]. Studies on localization of electronic waves in disordered solids have been extended to the localization of electromagnetic waves in disordered dielectric materials and nonlinear PC waveguides [11–13]. Very recently, the reverse process of transition from a disordered state to an ordered one was demonstrated by us using Z-scan-based optical trapping [14]. In addition, we have also constructed an all-optical switch based on optical trapping of polystyrene (PS) spheres [15]. In this Letter, we study the phase transition between a disordered state and an ordered one by analyzing the switching-on and -off processes of the optical switch. The effects of trapping power on the dynamics of the phase transition are also clarified.

The optical switch used in this Letter is schematically shown in Fig. 1 [15]. The diameter and concentration of the PS spheres contained in the capillary are 1.9 μm and 10% (Duke Scientific Corp.). The 532 nm light from a solid-state laser was employed as the trapping light and was focused into the capillary with the 10× objective lens of an inverted microscope (Zeiss A1 observer). In addition, the 1546 nm light from a broadband light source (Lightcomm) was selected as the signal light.

The creation and annihilation dynamics of optical matter were first examined using either an eyepiece or a charge coupled device connected to the microscope. In the absence of the trapping light, the PS spheres were uniformly distributed in the capillary as shown in Fig. 2(a). After the launch of the trapping light, a quasi-static distribution of PS spheres was achieved rapidly, and it looked like a dumbbell in the *xy* plane. Optical matter formation in the central rod

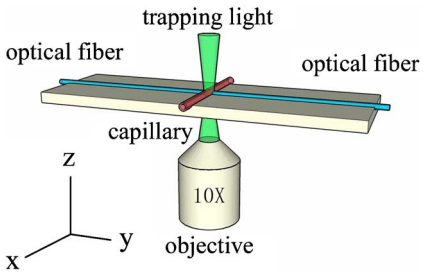

Fig. 1. (Color online) Schematic of the all-optical switch used to study the dynamics of the phase transition between a disordered state and an ordered one induced by optical trapping.

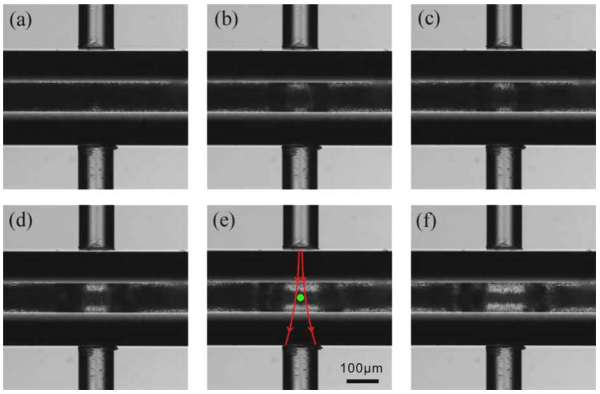

Fig. 2. (Color online) Static distributions of PS spheres in capillaries induced by laser beams at different powers. (a) $P_t=0$, (b) $P_t=100$, (c) $P_t=200$, (d) $P_t=300$, (e) $P_t=600$, and (f) $P_t=900$ mW. The spot size of the trapping light, the path of the signal light, and the length scale are shown in image (e).

of the dumbbell was confirmed by the hexagonal diffraction pattern [15]. It is also noticed that the size of the optical matter 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 [3,4]. We have compared the distribution of PS spheres under different trapping powers as shown in Figs. 2(b)–2(f). It is found that the length of the central rod (or the volume of the optical matter) increases with an increasing trapping power. After removing the trapping light, the dumbbell collapsed after a while and eventually PS spheres were uniformly distributed in water once again.

The switching-on process under different trapping powers is presented in Fig. 3(a). In all cases, the trapping light was introduced at $t_0=10$ s. The transmitted intensity of the signal light in the on state is almost the same for all trapping powers, implying that the optical matters formed at different trapping powers have nearly the same quality. After the launch of the trapping light, there is a threshold time t_{r0} below in which PS spheres are gathered together by the trapping light, resulting in a stronger interaction among them. However, the distribution of PS spheres still deviates very much from an ordered structure, and the transmitted intensity remains to be low. Once the average separation of PS spheres becomes short enough, a regular distribution of PS spheres is achieved through optical binding [3,4]. During this stage, possibly all PS spheres being trapped oscillate around regularly defined sites with attenuated amplitudes, resulting in a significant enhancement in the transmitted intensity. When the PS spheres are completely trapped at the lattice sites, a steady state is reached and the transmitted intensity remains constant. Therefore, the time constant of the second stage t_{r1} represents the real phase transition time from a disordered state to an ordered one. Evidently, the evolution of the transmitted intensity can be described by two steady states connected by an exponential rise. In addition, the phase transition can be considered as the transportation of PS spheres from the disordered state to the ordered one, similar to the

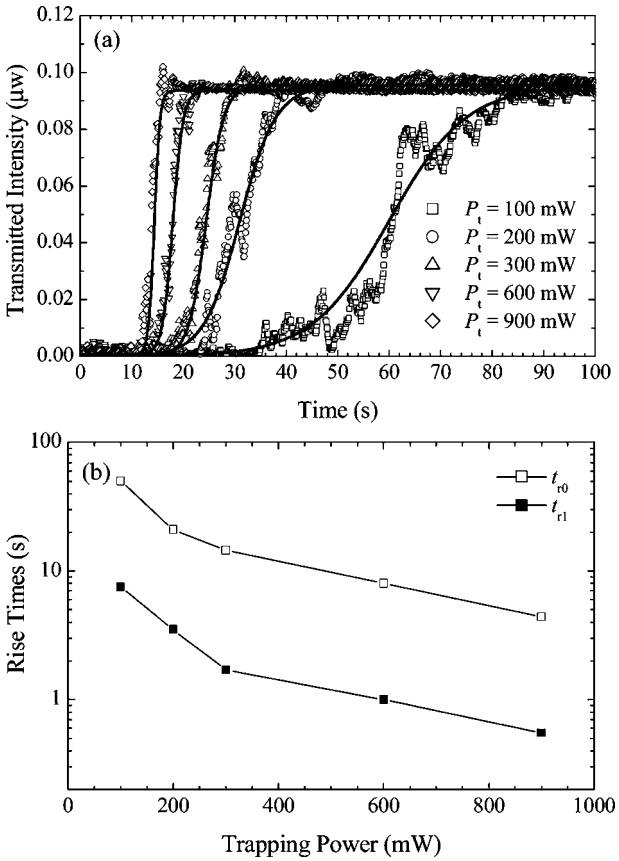

Fig. 3. (a) Switching-on process is shown under different trapping powers. The symbols are experimental data, while the solid curves are fits to the data. (b) Trapping power dependence of the two time constants (t_{r0} and t_{r1}) that characterize the phase transition from a disordered state to an ordered one.

population of the electronic states in a semiconductor. Therefore, the switching-on process can be characterized by the Fermi–Dirac distribution function as follows:

$$I(t) = \frac{I_{\mathrm{ON}}}{1 + \exp[-(t - t_0 - t_{r0})/t_{r1}]}, \qquad (1)$$

where $I_{\mathrm{ON}} \sim 0.095$ μW is the transmitted intensity of the signal light in the on status. The two time constants extracted by fitting the experimental data with Eq. (1) are compared in Fig. 3(b) for different trapping powers. When the trapping power is increased from 100 to 900 mW, t_{r0} decreases from 50 to 4.4 s and t_{r1} decreases from 7.5 to 0.55 s. While the reduction in t_{r0} is due to the increase of gradient force, the reduction of t_{r1} is attributed to the enhancement in the interaction among PS spheres.

The annihilation dynamics of optical matters under different trapping powers is shown in Fig. 4(a), where the trapping light was shut off at $t_0=0$ s. It is observed that the formed optical matter can live a long time of several minutes depending strongly on the trapping power. Similar to the switching-on process, two different stages are clearly seen. While the transmitted intensity remains nearly unchanged in the first stage, a rapid decay in the transmitted in-

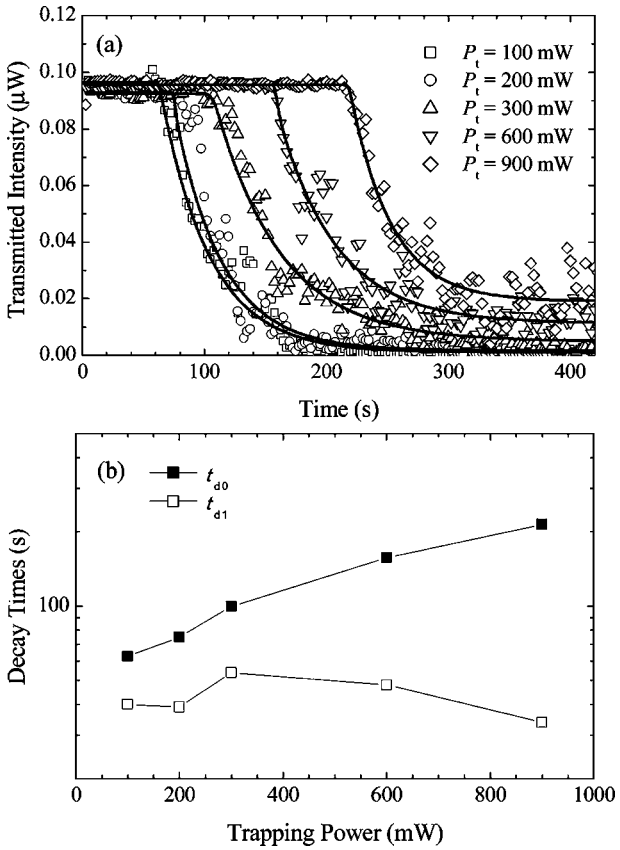

Fig. 4. (a) Switching-off process is shown under different trapping powers. The symbols are experimental data, while the solid curves are fits to the data. (b) Trapping power dependence of the two time constants (t_{d0} and t_{d1}) that characterize the phase transition from an ordered state to a disordered one.

tensity is observed in the second one. The decay process cannot be explained by the Fermi–Dirac function, because the dynamic is governed initially by van der Waals force followed by Brownian motion. Thus, after the trapping light is shut off, the PS spheres begin to oscillate around the regular sites with increasing amplitude due to the thermal kinetic energy. During this time the PS spheres may still be in an ordered state for a time t_{d0}. Once the deviation of the PS spheres from the regular sites becomes large enough, the optical matter collapses very fast, leading to a dramatic decrease in the transmitted intensity. This process is characterized by a single exponential decay with a time constant (t_{d1}) that defines the phase transition from an ordered to a disordered state as shown in Fig. 4(a). The decay process thus depends on a critical density of PS spheres that are in the disordered state. Thus, for higher trapping powers it takes a longer time for the decay process to initiate. In Fig. 4(b), we summarize the lifetimes (t_{d0}) for the optical matter and the phase transition times (t_{d1}) under different trapping powers. When the trapping power is raised from 100 to 900 mW, the lifetime of the optical matter is greatly prolonged from 62.5 to 215 s. Unlike when five consecutive switching operations were carried out for each trapping power [15], here we did not observe the saturation in the lifetime of the optical matter when only one switching operation was conducted for each trapping power. While the increase of optical binding and van der Waals force are responsible for the long lifetimes under high trapping powers, the decay process does not show any dependence on trapping power as is expected for a system with the particle density within the trap in the ordered state below the critical density.

In summary, we have investigated the creation and annihilation dynamics of optical matter. It is found that the transition from a disordered to an ordered state can be well described by the Fermi–Dirac function, and the extracted rise time decreases rapidly with an increasing trapping power. On the contrary, the transition from an ordered to a disordered state is characterized by a flat region followed by a single exponential decay. While the lifetime of the optical matter is found to increase with an increasing trapping power, the decay time does not exhibit any power dependence. It is anticipated that the power dependence of the lifetime of the optical matter may find applications in the construction of temporary optical storage and memory devices.

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