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Self-induced transparency in colloidal liquids by *Z*-scan-based optical trapping

Qiao-Feng Dai,[1] Hai-Ying Liu,[1] Jin Liu,[1] Li-Jun Wu,[1] Qi Guo,[1] Wei Hu,[1] Xiang-Bo Yang,[1] Song-Hao Liu,[1] Sheng Lan,[1,a)] Achanta Venu Gopal,[2] and V. A. Trofimov[3]
[1]*Laboratory of Photonic Information Technology, School for Information and Optoelectronic Science and Engineering, South China Normal University, Guangzhou, Guangdong 510006, People's Republic of China*
[2]*DCMP and MS, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India*
[3]*Department of Computational Mathematics and Cybenetics, M. V. Lomonosov Moscow State University, Moscow 119992, Russia*

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We demonstrated a transition from a disordered to an ordered state in a colloidal liquid by utilizing *Z*-scan-based optical trapping. The *Z*-scan process plays a role of gradually and continuously narrowing and deepening the optical potential well. When the trapping power was increased above a certain level, a self-induced transparency occurs, leading to a significant enhancement in transmission. The dynamic transition was confirmed by monitoring the diffraction pattern of the trapping region. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2903712]

Optical trapping and manipulation of microparticles have received intensive and extensive studies in various fields of science and technology since the pioneering work of Ashkin and co-workers in 1970 and 1986.[1,2] In the past two decades, the research works in this field have proceeded from the trapping of single particles to the manipulation of a large number of particles. So far, the most popular technique used to trap and arrange an ensemble of particles is based on holographic optics.[3] However, the disadvantage of the holographic technique is the complexity of the experimental arrangements. Optical manipulation utilizing different mechanisms, such as optical binding,[4–6] surface plasmon polariton,[7,8] and evanescent wave,[9] have been employed to assemble a large number of microparticles into ordered structures of various dimensions. Furthermore, the physical properties of these artificial nonlinear materials, such as third-order nonlinearity, modulation instability, and optical spatial soliton arrays, have also been investigated.[10–12]

To date, 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.[3] In comparison, less attention has been paid to the trapping process that represents a transition of the trapping region from a disordered system to an ordered one. In fact, the propagation of light in disordered systems has been extensively studied, with an emphasis on the localization of light, e.g., Anderson localization.[13,14] Recently, we have shown that Anderson localization can be induced in nonlinear photonic crystal waveguides, leading to a transition from an ordered to a disordered system and an ideal optical limiting.[15] In the absence of the trapping effect, PS spheres are randomly distributed in water, forming a disordered system. A light incident on a sample cell containing suspended PS spheres will suffer from a strong backscattering. Once the transition of the disordered to an ordered structure occurs, however, one would expect a significant enhancement in the transmission of the incident light, i.e., the sample cell would become transparent. Apparently, such a transition is quite interesting from the viewpoint of fundamental research and very useful for constructing functional devices. In this letter, we propose and demonstrate a simple method to realize such a transition in a colloidal liquid based on the combination of the single beam optical trapping and the conventional *Z*-scan technique.[2,16]

The physical picture of our idea is schematically illustrated in Fig. 1. It is well known that a light beam acts as an optical potential well where microparticles are trapped due to the existence of the gradient force. For a focused Gaussian beam, the width and depth of the potential well are determined by the field intensity distribution of the Gaussian beam. When the beam size is slowly and continuously reduced, the width of the potential well will be accordingly narrowed while its depth will be significantly increased. As a result, the particles initially trapped by the potential well have nearly no chance to escape and their separation will become smaller and smaller. This process is equivalent to

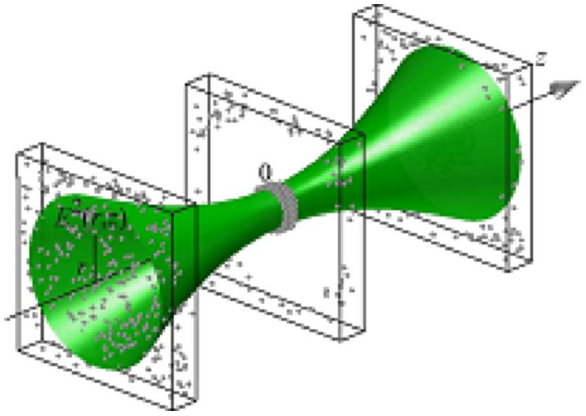

FIG. 1. (Color online) Schematic description of the principle for the creation of a close-packed array by utilizing a *Z*-scan-based optical trapping. The change in the particle concentration within the beam waist at three places (before, after, and at the focus point) is shown.

a)Author to whom correspondence should be addressed. Electronic mail: slan@scnu.edu.cn.

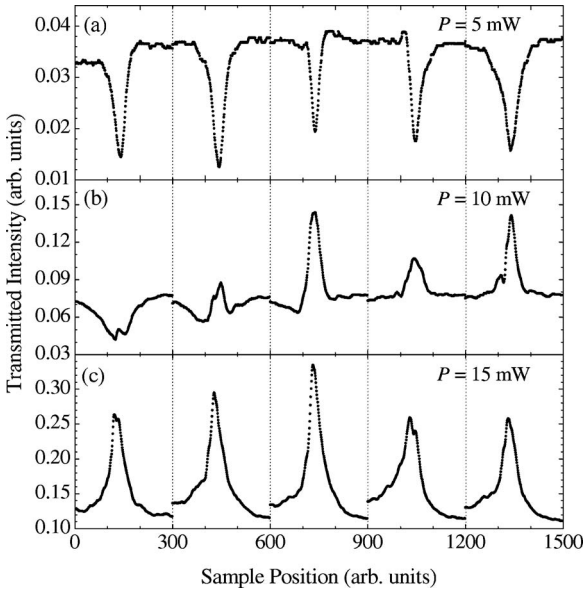

FIG. 2. Evolution of the transmission behavior of the sample cell with increasing trapping power P in the Z-scan trapping experiments. (a) $P=5$ mW, (b) $P=10$ mW, and (c) $P=15$ mW. For each trapping power, the first five consecutive scans (separated by dotted lines) are presented. For each curve, the central position where a valley (or a peak) appears corresponds to the focus point of the scanning process.

squeezing the water in between the particles out of the optical potential well, making them closer and closer. Finally, a close-packed array of the microparticles that fully occupies the beam volume will be obtained provided that the number of the particles being trapped is adequate. Therefore, a transition of the trapping region from a disordered to an ordered structure can be realized by utilizing this method.

In the experiments, we employed the conventional Z-scan technique to vary the beam size.[16] The arrangement is very similar to that for an open-aperture Z-scan experiment except that the detector was mounted on the same moving stage with the sample cell. The 532 nm light from a solid-state laser was used not only for trapping but also for detection. It was focused by using a 5× objective onto the sample cell. In most experiments, the scanning processes were performed in a region of $z \in (-d, +d)$ with $d=5.7625$ mm. The scanning speed was set to be 191 μm/s. The beam diameter was varied from ~2 mm at the two ends of the scanning to ~10 μm at the focus point. In order to obtain a close-packed structure at the focus point, we chose 1.9 μm PS spheres with the highest concentration (~10%) available from the provider (Duke Scientific Corporation).

The results of the Z-scan trapping experiments are shown in Fig. 2 where the transmitted intensity is plotted as a function of the sample cell position. The evolution of the transmission behavior of the sample cell with increasing trapping power P is also shown. For each trapping power, the first five measurements are presented.

As $P \leqslant 5$ mW, we observed a deep attenuation of the transmitted intensity at the focus point, as shown in Fig. 2(a). A relative change in the transmitted intensity $[(I_{\text{focus}} - I_{\text{far}})/I_{\text{far}}]$ as large as −66.7% was obtained, where I_{focus} and I_{far} represent the transmitted intensities at and far from the focus point, respectively. The reduction is ascribed to the increased number of trapped PS spheres at the focus point. In this case, an effective trapping only occurred when the sample cell approached the focus point. Thus, the number of the PS spheres collected by the trapping light with a small beam spot was not sufficient to fill the beam volume in a close-packed form. Consequently, the PS spheres were still randomly distributed in water but with higher concentration, resulting in a stronger backscattering and a lower transmission. After passing through the focus point, the beam size was enlarged. However, the PS spheres being trapped were still concentrated at the beam center, leaving a depletion region that is transparent to the incident light, as shown in Fig. 1. As a result, the transmitted intensity rapidly increased. In this case, the transmitted light intensity was weak at the center and strong in the surrounding depletion region. Consequently, the PS spheres were driven toward the depletion region by both the gradient force and the normal diffusion. Finally, they were randomly distributed in water again and the transmitted intensity returned to the original level.

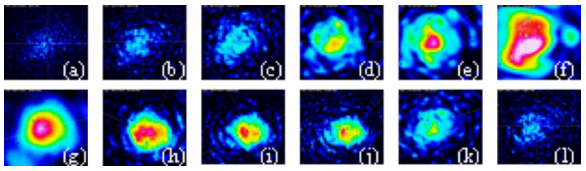

FIG. 3. (Color online) Evolution of the transmitted light recorded by a CCD in the Z-scan trapping process performed at a trapping power of 100 mW. The images were taken at different sample positions where the sample cell was [(a)–(c)] before and far from the focus point, [(d) and (e)] before and close to the focus point, (f) at the focus point, (g) just after the focus point, and [(h)–(l)] after and far from the focus point.

The situation was completely changed when P was increased to ~10 mW. In the first scan, as shown in Fig. 2(b), a tiny peak appeared at the focus point although the tendency of the transmitted intensity reduction close to the focus point remained unchanged. It was also noticed that the transmission valley became broad. The transmission peak at the focus point became obvious in the second scan. A significant change was found in the third scan in which the valley at the focus point was completely converted to a peak. In the following scanning processes, we observed in most cases a transmission peak at the focus point. Occasionally, a transmission valley was seen, indicating that the trapping was not stable.

As P was further raised to ~15 mW, a sharp transmission peak was always observed in all scanning processes, as shown in Fig. 2(c). We believe that the trapping power in this case was strong enough so that the PS spheres held by the optical potential well was sufficient for the formation of a close-packed structure around the focus point. It is remarkable that the maximum change in the transmitted intensity measured at this power level is close to 200%, suggesting the formation of well-defined structures. For $P > 15$ mW, transmission peaks were observed in all scanning processes. A transmission enhancement of more than 800% has been achieved under the optimized conditions.

In order to more clearly and directly show the self-induced transparency of the incident light, we have recorded the evolution of the transmitted light by utilizing a charge-coupled detector (CCD). A typical example for a trapping power of 100 mW is presented in Fig. 3. Figures 3(a)–3(c) represent the situations in which the sample cell was far from the focus point and the trapping was not effective. In Figs. 3(d) and 3(e), the sample cell approached the focus and an

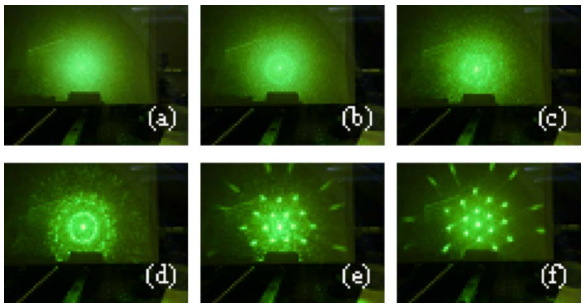

FIG. 4. (Color online) Evolution of the diffraction pattern of the trapping region in the first half-scan $(-d,0)$ at a trapping power of 100 mW. The photographs were taken at different sample positions corresponding to those shown in Figs. 3(a)–3(f).

apparent increase in the transmitted intensity was observed. In Fig. 3(f), a significant enhancement in the transmitted intensity occurred and the sample cell became almost transparent. After that, the transmitted intensity began to gradually decrease, as shown in Figs. 3(g)–3(k). Finally, the sample cell was recovered to the original status at the end of the scan [see Fig. 3(l)]. It is noticed that the increase of the transmitted intensity is faster than the decrease process because the former is governed by optical trapping while the latter is mainly dominated by diffusion.

So far, we have observed the self-induced transparency and attributed it to the transition from a disordered to an ordered system. However, more direct evidence for the formation of ordered structures was manifested in the diffraction pattern of the trapping region which was projected onto a screen located far from the focus point. The evolution of the diffraction pattern for a trapping power of 100 mW is shown in Fig. 4. Only the diffraction patterns taken in the first half-scan $(-d,0)$ are presented and they correspond to the situations shown in Figs. 3(a)–3(f). In Fig. 4(a), the transmitted light appeared as a large beam spot with a Gaussian-like intensity distribution. No enhancement was observed in any direction because the sample cell was a disordered system. A bright light ring (Debye–Scherrer ring) with a small centered spot appeared in Fig. 4(b) and it became more obvious in Fig. 4(c). In Fig. 4(d), many bright spots were found to surround the first light ring, forming a second ring with a wider width and a larger diameter. Clear hexagonal diffraction pattern was seen in Fig. 4(e), indicating the formation of a well-defined structure. In Fig. 4(f), the diffraction spots became quite bright and one could easily discriminate the zero-, first-, second-, and third-order diffraction spots. The evolution of the diffraction pattern from Debye–Scherrer rings into Bragg peaks with increasing order is in good agreement with that theoretically predicted and experimentally observed by Förster *et al.*[17] The important thing is that we observed the continuous evolution of a disordered system into an ordered one. The bright light spot observed by the CCD in the transparent status shown in Fig. 3 corresponds to the zero-order diffraction spot because the CCD with small detection area could not collect the higher-order diffraction spots.

It is noticed from Fig. 2 that the transmitted intensity of the trapping light is increased more than 30 times when the trapping power is increased only 3 times from 5 to 15 mW. It implies an enhancement in the transmission of more than one order of magnitude. The enhancement was underestimated because only the zero-order diffraction of the transmitted light entered into the detector. In addition, we have found that it can be significantly improved by optimizing the experimental conditions. In practice, the modification of the beam size of the trapping light can be achieved by other ways, including optical methods. Therefore, the self-induced transparency phenomenon implies potential applications in the fabrication of functional devices such as optical switches. The switching time of the optical switches may range from several milliseconds to several seconds, depending on the methods of varying the beam size and also on the trapping power used.

In summary, we have proposed and demonstrated a simple method to realize the transition from disordered to ordered systems in colloidal liquids. It was accomplished by combining the single beam optical trapping with the conventional *Z*-scan technique. The formation of ordered structures was evidenced by a significant enhancement of the transmission at the focus point and confirmed by the diffraction pattern of the trapping region. This simple technique can be applied to the construction of functional devices.

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[1] A. Ashkin, Phys. Rev. Lett. **24**, 156 (1970).
[2] A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, Opt. Lett. **11**, 288 (1986).
[3] See, for example, E. R. Dufresne and D. G. Grier, Rev. Sci. Instrum. **69**, 1974 (1998); D. G. Grier, Nature (London) **424**, 810 (2003); H. Melville, G. F. Milne, G. C. Spalding, W. Sibbett, K. Dholakia, and D. McGloin, Opt. Express **11**, 3562 (2003); J. Leach, G. Sinclair, P. Jordan, J. Courtial, M. J. Padhett, J. Cooper, and Z. J. Laczik, *ibid.* **12**, 220 (2004); D. G. Grier and Y. Roichaman, Appl. Opt. **45**, 880 (2006).
[4] M. M. Burn, J.-M. Fournier, and J. A. Golovchenko, Phys. Rev. Lett. **63**, 1233 (1989).
[5] M. M. Burn, J.-M. Fournier, and J. A. Golovchenko, Science **249**, 749 (1990).
[6] S. A. Tatarkova, A. E. Carruthers, and K. Dholakia, Phys. Rev. Lett. **89**, 283901 (2002).
[7] V. Garcés-Chávez, R. Quidant, P. J. Reece, G. Badenes, L. Torner, and K. Dholakia, Phys. Rev. B **73**, 085417 (2006).
[8] M. Righini, A. S. Zelenina, C. Girard, and R. Quidant, Nat. Phys. **3**, 477 (2007).
[9] C. D. Mellor, T. A. Fennerty, and C. D. Bain, Opt. Express **14**, 10079 (2006).
[10] P. W. Smith, P. J. Maloney, and A. Ashkin, Opt. Lett. **7**, 347 (1982).
[11] C. López-Mariscal, J. C. Gutiérrez-Vega, D. McGloin, and K. Dholakia, Opt. Express **15**, 6330 (2007).
[12] P. J. Reece, E. M. Wright, and K. Dholakia, Phys. Rev. Lett. **98**, 203902 (2007).
[13] D. S. Wiersma, P. Bartolini, A. Lagendijk, and R. Righini, Nature (London) **390**, 671 (1997).
[14] T. Schwartz, G. Bartal, S. Fishman, and M. Segev, Nature (London) **446**, 52 (2007).
[15] H. Y. Liu, S. Lan, L.-J. Wu, Q. Guo, W. Hu, S. H. Liu, X. S. Lin, and A. V. Gopal, Appl. Phys. Lett. **90**, 213507 (2007).
[16] See, for example, M. Sheik-Bahae, A. A. Said, and E. W. Van Stryland, Opt. Lett. **14**, 955 (1989); M. Sheik-Bahae, A. A. Said, T.-H. Wei, D. J. Hagan, and E. W. Van Stryland, IEEE J. Quantum Electron. **26**, 760 (1990).
[17] S. Förster, A. Timmann, C. Schellbach, A. Frömsdorf, A. Kornowski, H. Weller, S. V. Roth, and P. Lindner, Nat. Mater. **6**, 888 (2007).