All-optical switching mediated by magnetic nanoparticles

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We demonstrate the switching of light in the near-infrared region (1.55 μm) through the manipulation of magnetic nanoparticles in a magnetic fluid by using another light in the visible region (0.532 μm). The formation of a photonic gap is found in the magnetic fluid when a laser light or a magnetic field is applied. A shift of the photonic gap to longer wavelengths is observed with increasing laser power or magnetic field strength. © 2010 Optical Society of America

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Optical trapping and manipulation of microparticles and nanoparticles have attracted great interest because of their potential applications in various fields of science and technology [1]. From the viewpoint of device application, it is necessary to manipulate a large number of particles, and various physical mechanisms have been proposed to assemble microparticles into ordered structures [2–7]. In these cases, a phase transition of the system from a disordered state to an ordered one is induced by optical forces. However, such a phase transition rarely occurs in the optical trapping of nanoparticles. Instead, it has been demonstrated that clustering of various nanoparticles appears as the result of optical trapping [8–10]. This phenomenon implies that one can dynamically control the size of scattering particles and thus the scattering strength of the system by optically trapping nanoparticles.

It has been known that magnetic nanoparticles uniformly distributed in a carrier liquid will aggregate into magnetic clusters or columns in the presence of a magnetic field, giving rise to many interesting phenomena. One of them is the modulation of light transmission, which has usually been ascribed to the geometrical shadowing effect [11–13]. Recently, it was revealed that the modulation of light transmission cannot be attributed to the geometrical shadowing effect [10]. Instead, Anderson localization of light is suggested to be the possible physical mechanism [14]. Actually, the appearance of a photonic gap in a disordered system due to Anderson localization of light was predicted theoretically by John many years ago [15]. In this Letter, we propose the use of magnetic fluids as disordered media in which the size of scattering particles can be dynamically controlled by either a magnetic field or a laser beam. A highly efficient optical switch for light in the near-infrared region is demonstrated by optically manipulating magnetic nanoparticles with another light in the visible region.

The configuration of the optical switch is schematically shown in Fig. 1(a). A capillary filled with a water-based magnetic fluid fabricated by the chemical coprecipitation technique is aligned in the x direction. The average diameter and volume density of Fe3O4 particles are estimated to be ~12 nm and 4.7 × 1015 cm−3, respectively. The 0.532 μm light from a solid-state laser was used as the trapping light (or the control light). It was focused onto the capillary along the z direction by using the 10× objective lens of an inverted microscope (Zeiss Axio Observer A1). Two optical fibers aligned in the y direction were used to emit and collect the signal light, which is a broadband source ranging from 1.525 to 1.565 μm (Lightcomm). The use of an infrared light source ensures that magnetic nanoparticles are almost transparent to the signal light, and the transmitted intensity is completely dominated by the scattering effect [16]. The transmitted signal light is collected and analyzed by a spectrometer (Yokogawa AQ 6370). The switching mechanism is schematically illustrated in Figs. 1(b) and 1(c). In the absence of the control light [Fig. 1(b)], the signal light can be transmitted through the magnetic fluid, because its wavelength is much larger than the diameter of the magnetic nano-

Fig. 1. (Color online) Schematics showing (a) the structure of the proposed optical switch, (b) random distribution of magnetic nanoparticles inside the capillary, and (c) formation of magnetic clusters and enhanced backscattering of the signal light induced by the control light.
particles and the scattering is quite weak. Once the control light is imposed, however, the signal light is strongly reflected because of multiple scattering off laser-induced magnetic clusters, as shown in Fig. 1(c).

The CCD images during the switching operation are presented in Fig. 2. In the absence of the control light the magnetic fluid is almost transparent to visible and infrared light [see Figs. 2(a) and 2(c)]. When the control light is switched on, we can judge the formation of magnetic clusters by the morphology change of the magnetic fluid, as shown in Fig. 2(b). According to the numerical simulations based on the finite-difference time-domain technique [17], a photonic gap is formed in this disordered medium, and the central wavelength of the photonic gap is shifted to \(1.55 \mu\text{m}\) when the radius of the magnetic clusters is enlarged to about 200 nm.

The trapping power dependence of the switching behavior at 1.55 \(\mu\text{m}\) is presented in Fig. 3(a), where several remarkable features can be identified. First, with increasing trapping power, after an initial drop, the steady-state transmission increases when the trapping power exceeds a critical level (\(\sim 350\) mW). Second, the transmission dynamics exhibits different behaviors for trapping powers below and above the critical level. In the former case, an exponential decay of the transmission is observed after the control light is switched on. Then, the transmission approaches a constant in the steady state. When the control light is switched off, the transmission recovers exponentially to its original level. In the latter case, the exponential decay in the transmission after the control light is turned on is immediately followed by an exponential rise, leading to an increased transmission in the steady state. When the control light is turned off, a sharp decrease of the transmission occurs prior to the exponential recovery of the transmission. Finally, the shortest switching-on and -off times, which are achieved at 650 and 350 mW, respectively, are derived to be 44 and 293 ms. These are much smaller than those observed in the optical switch based on the formation of optical matter [18]. Since no ordered structure is required and only the clustering of nanoparticles is sufficient, the switching-on time in this switch is significantly reduced. On the other hand, the switching-off time is also dramatically shortened, because magnetic clusters are much more easily destroyed by Brownian motion as compared with optical matter, which is held mainly by Van der Waals force.

Apart from the switching dynamics at 1.55 \(\mu\text{m}\), we have also recorded the evolution of the transmission spectrum with increasing trapping power, as shown in Fig. 3(b). Below the critical trapping power, the gap center appears in the short-wavelength side of the signal light. However, with increasing trapping power, a shift of the gap center to a longer-wavelength region as well as a deepening of the gap is observed. At the critical trapping power, the gap center moved to the wavelength of the signal light, leading to a significant drop in the transmission. The gap center shifts to the long-wavelength side of the signal light and becomes shallower with a further increase in trapping power. Since the gap center in a disordered system is determined by the average size of particles [15], it shifts to longer wavelengths when the size of magnetic clusters becomes larger. With these observations, the abnormal switching behavior observed at high trapping powers can be understood. The scattering of the signal light becomes stronger when the magnetic clusters become larger. As a result, an exponential decrease in the transmission is observed when the control light is turned on. As the average size of the magnetic clusters exceed a critical value (\(\sim 200\) nm in our case), the scattering of the signal light becomes weaker with increasingly growing magnetic clusters, leading to an increase in the transmission. When the control light is removed, the magnetic clusters begin to disperse back into magnetic nanoparticles. When their size is reduced back
to the critical value, the signal light encounters a strong scattering that is responsible for the second sharp decrease in the transmission. Therefore, the most efficient switching is achieved at the critical trapping power, and an extinction ratio close to 40 dB is obtained.

To further confirm that the switching of the signal light is caused by the clustering of magnetic particles, we have fabricated a magnetic fluid film with a thickness of ~50 μm and examined the evolution of the transmission spectrum of the magnetic fluid film with increasing magnetic field, which is shown in Fig. 4. The transmission spectra have been normalized with respect to that obtained without the magnetic field. With an increasing magnetic field, presumably the size of the formed clusters becomes larger, resulting in a strong scattering for visible light and a photonic gap centered at ~550 nm. A deepening and broadening of the gap is observed as the magnetic field is further increased. At the highest magnetic field we used (~380 Oe), the gap ranges from 500 to 1000 nm, and the transmission at the bottom of the gap reaches ~0.10.

So far, we can explain all experimental observations based on the formation of magnetic clusters, although it has not been directly identified. The increase of the volume density of magnetic nanoparticles in the trapping region may also lead to a morphology change of the magnetic fluid and reduction in the transmission of the signal light. However, the large extinction ratio of the switch, the shift of the gap center, and the fast time constant for the second decrease of the transmission at high trapping powers (~25 ms) cannot be interpreted as the increase in the volume density of magnetic nanoparticles. Therefore, we think that the formation of magnetic clusters is the dominant mechanism, but further experiments are needed to verify this point.

In summary, we have experimentally shown the formation of a photonic gap in a magnetic fluid by applying either a laser light or a magnetic field. It is suggested that the clustering of magnetic nanoparticles is the dominant mechanism for the appearance and shift of the photonic gap. This phenomenon has been successfully employed to construct a highly efficient optical switch, and it may find more applications in other functional devices.

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References

17. Software developed by Rsoft Design Group (http://www.rsoftdesign.com) is used for finite-difference time-domain simulation.