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Magnetic nanowire-enhanced optomagnetic tweezers

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We report an optomagnetic tweezers technique that utilizes the highly localized magnetic field gradients induced near the tip of a magnetic nanowire to provide strong trapping forces on magnetic nanoparticles with high spatial resolution. Integral to our approach is a method to trap, translate, and rotate a single magnetic nanowire in three dimensions. Our simulation predicts that forces in the range of 100 pN can be generated on 200 nm magnetic particles within 0.2 μm from a 200 nm diameter nickel nanowire. Such forces are relevant in many biological processes, suggesting that this approach will be of value in biophysical studies. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3050520]

Single beam optical tweezers,[1] as well as a variety of implementations of magnetic tweezers,[2,3] have proven for recent years to be valuable tools for manipulation of microscale objects, notably in biological studies.[4] The exertion of highly localized forces on nanoscale particles, however, presents a further challenge with either technique; optical tweezers are limited by a combination of the minimum focal width governed by diffraction[5] as well as high optical powers required to trap nanoscale objects. Likewise, the generation of magnetic field gradients over small volumes, necessary to enable localized magnetic force exertion, is a challenge for magnetic tweezers approaches. There is considerable interest in techniques for such nanomanipulation. For example, enhanced optical near fields around metallic structures due to surface plasmons have been used to confine subwavelength particles to small trapping volumes.[6] Sharpened tips of magnetic materials have also been used to exert forces over small volumes in electromagnetic tweezers, but such approaches require complicated pole fabrication processes and high electrical currents to generate large magnetic forces, potentially heating samples and necessitating cooling components.[7]

Due to their morphologies, nanowires composed of magnetic materials naturally generate strong magnetic field gradients over small volumes near their tips; they therefore would allow for controllable and localized manipulation of magnetic nanoparticles, given a suitable method for manipulation of the nanowires themselves. A few methods exist for manipulating individual nanowires of certain materials, including single beam[8] and holographic optical tweezers,[9] as well as optoelectronic tweezers.[10] However, none have achieved full three dimensional (3D) manipulation of metallic magnetic nanowires. Here, we demonstrate a method to enable 3D optomagnetic manipulation of a magnetic nanowire and thereby to realize an optically reconfigured, high spatial resolution magnetic trap near the tip of the trapped wire.

The technique we have developed to manipulate individual magnetic nanowires is diagramed in Fig. 1(a). Optical tweezers are used to trap a biotinylated polystyrene bead, which is conjugated to a streptavidin-coated paramagnetic bead. Under an applied magnetic field, the magnetic bead exerts an attractive force on magnetic nanowires in solution. Attaching the magnetic bead to the optically trapped polystyrene bead is necessary since optical trapping of the magnetic bead itself is difficult due to the strong scattering and absorption resulting from metallic elements within the magnetic beads.[11] Therefore, by using the optically trapped polystyrene bead as a liaison between the optical and magnetic components of the system, full 3D manipulation of the nanowire is possible; the optical trap trivially allows for translational motion in all three directions, and rotations can be induced by controlling the orientation of the external magnetic field.

To quantitatively understand how a magnetic nanowire could function as a high-resolution magnetic trap for mag-

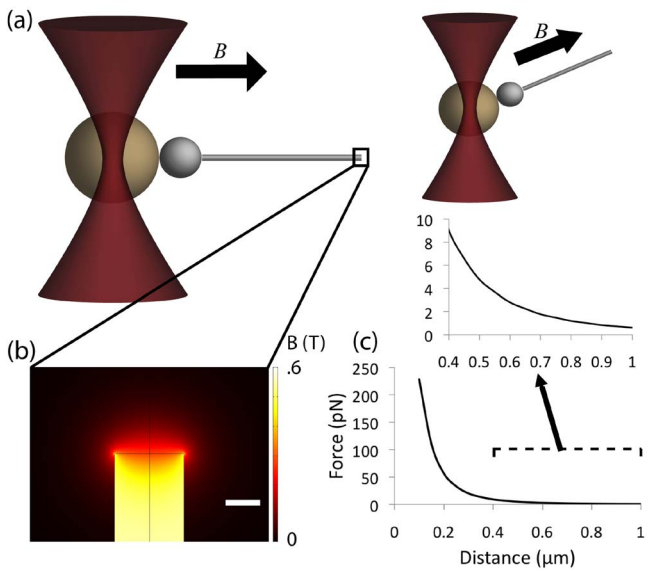

FIG. 1. (Color online) (a) Method for nanowire manipulation. An optical trap maintains the position of a polystyrene bead attached to a magnetic one which exerts an attractive force on a nanowire. Translational motion is achieved by translating the optical trap, and rotational motion is achieved by rotating the constant field. (b) Simulation results illustrating the tightly confined magnetic field, *B*, distribution around a 200 nm diameter nanowire tip (scale bar is 100 nm). (c) Calculated force on a uniformly magnetized 200 nm diameter sphere as a function of its center's distance from the nanowire tip along the nanowire's long axis.

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netic nanoparticles, we simulated the magnetic field strength and distribution near a 200 nm diameter, 10 μm long nickel nanowire field using finite element modeling (COMSOL 3.2A, magnetostatics module). We assumed the wire to be uniformly magnetized to saturation with $M=50.7$ A m^2 kg^{-1} as experimentally determined for nickel nanowires by Prina-Mello *et al.*[12] In our experiment, we use a 200 nm diameter magnetic particle with an estimated $M=10.5$ A m^2/kg, based on the particles' composition (~15% magnetite, according to the manufacturer, Spherotech), and saturation magnetization values of magnetite particles of comparable volumes, ~70 A m^2/kg as measured by Goya *et al.*[13] Since in these simulations we assume that the external field along the nanowire's axis is strong enough to saturate the particles, the magnetization components in the bead along the perpendicular axis induced by the fringing field near the nanowire's tip are small, and therefore we assume uniform magnetization in the bead along the nanowire's axis. The force was calculated by integrating the Maxwell stress tensor over the surface of the uniformly magnetized bead. The results of the calculations, shown in Fig. 1(c), indicate that forces on the order of hundreds of piconewtons are exerted within 0.2 μm of the tip. Incidentally, a point dipole calculation assuming magnetic moment of the bead to be concentrated at its center yielded forces that differed from the precise tensor calculation by less than 10% between 0.1 and 0.5 μm and by less than 2% at distances greater than 0.5 μm. These results indicate a small trapping volume of ~6.3 al (0.2 μm$\times\pi\times$0.01 μm^2); smaller trapping volumes can be achieved by using nanowires of smaller diameters.

Biotin-coated polystyrene microspheres and streptavidin-coated paramagnetic beads (of 6–8 and 3–3.9 μm diameters, respectively) at original concentrations of 1% w/v were purchased from Spherotech. 10 μl of the 6–8 μm bead and 3 μl of the paramagnetic bead solutions were diluted in 0.9 ml of water and treated with sodium dodecyl sulfate, which served to reduce nonspecific agglomeration of the beads. Nickel nanowires were electrochemically fabricated with a simple template synthesis method[14] using nanoporous alumina membranes from Whatman, Inc. and subsequently released in solution. The nanowires we fabricated are approximately 200 nm in diameter, according to the membrane's pore size. Our optical tweezers, which employ a 1064 nm, 50 mW laser, are constructed on a Zeiss inverted microscope.

We placed ~20 μl of the aqueous solution containing the mixture of beads, and ~10 μl of that containing the nanowires, together on a cover slide; we roughly tuned the concentration of the nanowires such that in the final mixture the ratio of nanowires to magnetic beads was about 5:1. This mixture was then examined under a 100× objective with a numerical aperture of 1.4, which also focused the laser beam to enable the optical trapping. The constant magnetic field was applied by placing at a distance of 3–6 cm from the sample a permanent magnet (K&J Magnetics, BX0X0X0) with a surface field of 6835 G, as specified by the manufacturer. One set of two attached beads could be found, trapped, and brought near a nanowire in solution, which then was attracted to the beads. Translational motion of trapped beads and nanowire was achieved by manually translating the microscope's sample stage and rotational motion of the nanowires by rotation of the external magnet, as shown in Fig. 2.

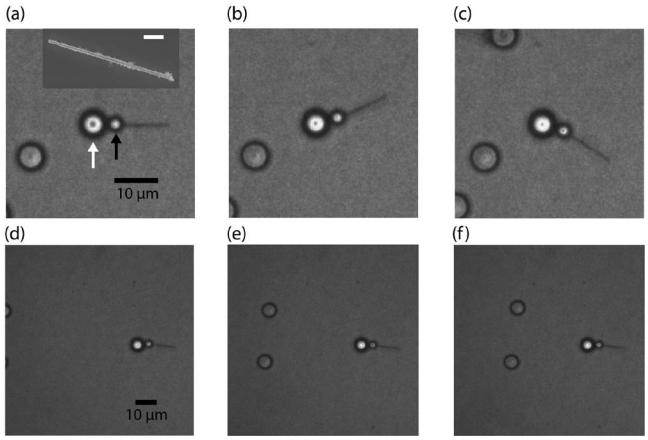

FIG. 2. Demonstrations of rotational [(a)–(c)] and translational [(d)–(f)] nanowire motions, and scanning electron microscopy image of a typical nanowire (scale bar is 2 μm). In all cases, the large polystyrene bead, denoted by the white arrow in (a), is optically trapped and attached to the smaller magnetic bead, denoted by the black arrow. Translation is induced by translating the microscope stage relative to the trap, and rotation is induced by rotating the permanent magnet. Images were cropped to show important features.

We confirmed that our technique is capable of generating a strong and stable magnetic trap by manipulating a fluorescent magnetic nanoparticle (Spherotech, 200–390 nm diameter) trapped at the nanowire's tip, as shown in Fig. 3. To experimentally confirm that our predicted forces in Fig. 1 were on the same order of magnitude as those exerted on our nanoparticles, we used the Stokes drag law, $F=6\pi\eta r v$, to relate particle velocity v, measured as particles approached the tip, to the force acting on them. Measurements were made in a viscous solution of 95% glycerol by volume, with a measured viscosity $\eta=0.6$ Pa s; since the polystyrene beads were difficult to optically manipulate in this dense and viscous solution, to obtain the following results, we simply observed the interactions of free nanowires and particles. We took $r=0.1$ μm in the Stokes law despite the spread in bead sizes to ensure a lower bound for the force. Four separate measurements of velocity using different wires and beads yielded forces of 0.4, 0.5, 0.3, and 0.1 pN, and hence an average force of 0.33 pN over a range of approximately 0.63–0.8 μm.

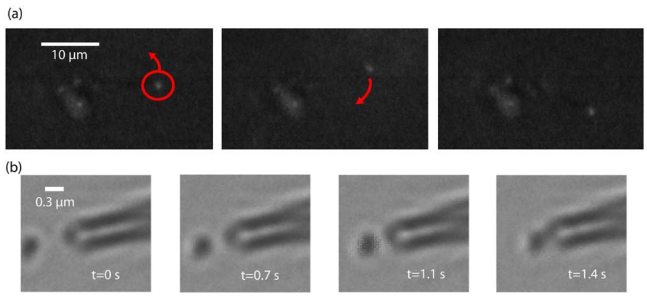

FIG. 3. (Color online) (a) Fluorescence images demonstrating a magnetic nanoparticle trapped at the end of a nanowire and moved in a circular pattern by rotating the nanowire, whose other end is attached to the optically trapped polystyrene bead. The bright spot circled in red is the bead at the end of the nanowire; background light being focused through the optically trapped polystyrene particle is responsible for the larger bright area to the left. (b) Sample bright-field images taken as a particle approached a nanowire tip; velocity and drag forces were estimated from such data.

This measured average is about one-fifth of our predicted value at 0.7 μm; this difference is likely due to a number of factors. Although before our experiments were done the permanent magnet was positioned <1 cm from the sample to fully saturate the nanowires and particles with an ~ 0.5 T field, during the experiments, the magnet was kept approximately 3–4 cm from the sample, resulting in a field strength of about 0.1 T. Therefore during our experiments both the nanowires and particles were most likely not magnetized to saturation, but based on magnetization curves measured in Refs. 12 and 13 we roughly estimate that they would have been within about 60% of saturation. The Stokes law also underestimates the real magnetic force due to the wall effect resulting from the fixed nanowire tip near the particle. Differences between the particles' compositions and that assumed in our simulations, as well as effects of the Brownian motion, could also contribute to the difference between measured and predicted forces.

More sophisticated experiments will be required to definitively ascertain the forces, and especially so at lesser distances from the tip. However, we did observe that once a nanoparticle was trapped at the nanowire tip in our glycerol solution, we were unable to rotate the nanowire at a speed high enough to detach the particle; particles remained at the nanowire tip as it traveled in excess of 12 μm/s, indicating qualitatively the significant trapping forces at the tip.

For more sophisticated or rapid manipulations, a number of improvements to the technique can be made; in our setup, the speed at which the optically anchored nanowire could be translated and rotated was limited by the relatively low power of our trapping beam; use of a higher power laser would allow for more rapid manipulation. Such a system should be capable of reliably and controllably depositing nanowires onto a substrate or between electrodes, which could be of value for characterization purposes.[15] This general technique for magnetic nanowire manipulation is, furthermore, applicable not only to nanowires composed entirely of magnetic materials but to any nanowires that contain even a small amount of magnetic material; it could therefore conceivably be applicable in any situations in which the nanowires of interest can be magnetically functionalized.

A notable feature of this technique is that, in comparison with using optical forces directly to trap nanoscale objects, the optical power required here is relatively low since the size of the polystyrene bead that is optically trapped can be chosen independently of the nanowire and magnetic particle to be manipulated. Furthermore, this technique for manipulation of nanoparticles, compared with optical tweezers, does not require that the laser be focused on the particle of interest, thereby mitigating potential photodamage risks.

The exertion of highly localized magnetic forces on biological cells is one of the particularly interesting potential applications of this technique. A number of recent studies have focused on studying and regulating certain cellular behaviors by exerting forces on magnetic forces within or attached to cells.[16] Forces exerted on magnetic nanoparticles attached to cell membranes have, for example, been utilized to activate mechanosensitive ion channels and therefore to produce a variety of observable cellular responses.[17] However, most techniques used for such purposes result in magnetic field gradients over large volumes, and therefore forces being applied over large regions of the cell; our approach, by allowing the exertion of spatially localized forces without requiring mechanical connections to the macroscopic surroundings, could enable interesting studies, including potentially in closed microfluidic chambers. Among a number of possible applications, therefore, our method could potentially add to the growing body of techniques aimed at understanding a variety of biological processes.

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