Scanning probe electromagnetic tweezers

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(Received 26 March 2001; accepted for publication 16 July 2001)

We present a micromanipulation technique that utilizes integrated microcoils and magnetic microtips for localized positioning of micron-sized magnetic objects. Forces of 10 pN, and submicron positioning control are demonstrated on the 2.8 μm diameter superparamagnetic beads. The technique also implements an optical illumination scheme that provides a clear viewing of the magnetically trapped objects without including the scattering background from the magnetic manipulator tip. This simple instrument provides a noninvasive, low cost alternative to the optical trapping techniques normally used in micromanipulation. Among the possible advantages are the negligible heating of the manipulated sample, effective decoupling of the manipulation component of the experiment from the optical studies of the systems of interest, and the ability to perform studies in a variety of fluids. © 2001 American Institute of Physics. [DOI: 10.1063/1.1402963]

Progress in nanotechnology critically depends on the advances in instrumentation for characterization and manipulation of objects ranging in size from atomic to micrometer dimensions. Scanning tunneling microscopy and atomic force microscopy have allowed imaging with atomic resolution, as well as atomic manipulation at a low temperature and ultrahigh vacuum. The optical trapping methods have become routine for manipulating latex micron-sized balls attached to objects of biological interest at room temperature. In addition, various microelectromechanical systems are being utilized for the physical tweezing of the micro-objects. There is also a significant interest in the manipulation of magnetic objects. Magnetic tweezers have found wide uses in biological applications, such as investigations of the physical properties of the cytoplasm, mechanical properties of cell surfaces, and elasticity and transport of single DNA molecules. For the cell studies, most of these techniques rely on the micromanipulation of a magnetic particle positioned inside a cell wall or bound on the surface of a cell, while the single molecule investigations involve linking the magnetic particle to one end of the molecule strand. In all of these studies, micromanipulation is performed by a magnetic manipulator consisting of permanent or soft coil-wound magnets with macroscopic dimensions. Typical forces available through these techniques are in the range of 0.1–10 pN.

In this letter, we describe a technique that implements a scanning probe version of a magnetic manipulator allowing forces of similar magnitude to be applied to magnetic particles. Manipulation of micron-sized magnetic objects is performed by an electromagnetic device that integrates a microcoil and a soft ferromagnetic microtip. This simple device can remotely manipulate magnetic objects with submicron resolution, while operating at a distance of more than 40 μm, and showing negligible heating of the manipulated object. In addition, the manipulation technique is performed in parallel with the viewing technique that decouples the optical illumination of the manipulated objects from the illumination of the manipulator. This has the advantage of allowing optical investigation of the samples to not be obscured by the light scattering from the manipulation component of the experiment.

The scanning probe electromagnetic tweezers device is shown in Fig. 1. The device is fabricated by winding a 25 μm diameter copper magnet wire around a 50 μm diameter soft-ferromagnetic wire. The usual winding design consists of two coil layers with six to eight turns each. Similar microcoils have previously been used in the studies of the Aharonov–Bohm effect, propagation of magnetic domain walls, high-sensitivity detection of electron and nuclear spin resonance, and in the application of high gradient magnetic fields in the high-sensitivity force magnetometry. In order to create high field gradients, soft-ferromagnetic wire is electrochemically etched into a sharp probe in aqueous 40% sulfuric acid solution at 3 V. The tip is then positioned in the vicinity of the coil, as seen in Fig. 1, in order to be maximally magnetized by the coil fields. Uses for ferromagnetic tips of this form have been found in magnetic force microscopy and laser Raman spectroscopy.

FIG. 1. Photograph of the micromagnetic manipulator. Magnet wire, 25 μm in diameter, is wound over a 50 μm diameter soft-ferromagnetic wire. The wire is electrochemically etched into a sharp tip and positioned inside the microcoil. Small tip and microcoil dimensions maximize the magnetic fields and field gradients, thus maximizing the forces applied to the magnetic particles.

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microscopy, magnetic resonance imaging microscopy, and microfluidic pumping. The microcoils and ferromagnetic microtips are both preferred for the application of sufficient magnetic forces in the tweezers applications, since the forces on the magnetic bead depend on the field dependent magnetization of the bead and the magnetic field gradient at the bead:

\[ F_{\text{bead}} = (m_{\text{bead}})(H) \cdot \nabla)H. \]  

(1)

Since the magnetic field from a coil is inversely proportional to the coil diameter, and the field gradient from a ferromagnetic tip is inversely proportional to the tip dimensions, minimization of both of these parameters in the design of our magnetic micromanipulators is advantageous.

The described device is part of a complete micromanipulation instrument, as described in the block diagram of Fig. 2. The system is placed on a Nikon Diaphot inverted optical microscope mounted on a vibration isolation stage. The micromanipulators tip is placed on a mechanical stage for positioning the tip above the viewing lens of the microscope. We normally implement a 40× Plan objective lens, but other lenses can also be used. The coil component of the manipulator is connected to a programmable constant current source for the tunable operation of the device. Since the coil resistance is on the order of 1 ohm, we do not observe any sample heating during operation up to 250 mA of operating current through the coil, although currents of <100 mA are sufficient for the work reported in this letter. The nonheating feature of the instrument might be an advantage compared to the optical trapping methods used for manipulation of beads in biological applications.

The samples to be manipulated are placed inside a rectangular cross section quartz capillary tube. The tube is 500 \( \mu \text{m} \) in width, with a 50 \( \mu \text{m} \) inner diameter, and 40 \( \mu \text{m} \) capillary wall thickness. The capillary tube is fastened to a sample positioning stage of the microscope, and white light illumination is coupled to the quartz capillary tube from a 1 mm diameter optical fiber connected to a Xenon white light source (Oriel). The manipulator tip is positioned mechanically at the center of the optical axis of the viewing lens prior to instrument operation. The capillary tube containing the magnetic particles is placed between the tip and the lens, and the microtip is positioned within several microns of the outside capillary tube surface. In this design, the manipulated object is always in the center of the viewing location, and during the operation the capillary tube is moved with respect to the manipulator tip.

This relative sample–tip placement method creates several important advantages in the operation of the instrument and in the observation of the manipulated samples. Because of the differences in the index of refraction of the capillary tube and the air, light is confined to the capillary tube and does not illuminate the manipulator tip. This presents a significant advantage during the instrument operation since there is no spurious light scattering from the tip that would obscure the light scattered from the sample of interest. The capillary tube wall separating the tip and the sample also prevents the particles from coming into contact with the manipulator tip. Since the samples of interest are normally inside a liquid solution, the capillary tube also provides a convenient container for a variety of host solutions for biological applications. We note that we have also manipulated objects...
on top of the microscope glass slides. However, such a manipulation method limited us to solutions (such as glycerol) that sustained a thin film form on the slides, and did not bead up or evaporate during the experiment. Additionally, this method presented us with problems due to light scattering from the manipulator tip. It is worth mentioning that the surface tension of the sample host liquid prevented the magnetic particle from coming into contact with the manipulator tip positioned outside of the liquid layer in those experiments.

In order to demonstrate the manipulation of samples using the scanning probe electromagnetic tweezers, we placed 2.8 μm superparamagnetic beads into the capillary tube, and added 1 μm polystyrene beads into the same solution. We found an area where there were two closely spaced nonmagnetic beads and, using the manipulator with 100 mA microcoil current, we cleared the area by removing all of the magnetic beads and, using the manipulator with 100 mA microcoil, winding additional coil turns, or using thinner beads by using the methods of pulsed currents through the microcoil, winding additional coil turns, or using thinner capillary tube walls.

In summary, we have described and demonstrated a magnetic micromanipulation tool for positioning magnetic objects of micron dimensions with submicron resolution. The instrument provides an alternative to the optical tweezers methods often used to manipulate objects in biological studies. The technique offers several advantageous features such as negligible heating, decoupling of the optical investigation from the manipulation component of the experiment, and the ability to completely remove the light scattered by a manipulator that is positioned within tens of microns from the sample of interest. The device may also find uses in medical applications of magnetic manipulation since the complete device (without leads) is less than 1 mm in size.

The authors thank Miriam Katz for careful reading of the manuscript. This work was supported by grants from NSF DMR 9724535, NIH PHS H601959-02, and ONR (DARPA N00014-00-1-0632).

14. Magnet wire and nickel alloy 120 soft-ferromagnetic wire are available from the California Fine Wire Company, Grover Beach, California.