A LINEAR MAGNETIC TWEEZERS FOR PRECISE PARTICLE MANIPULATIONS

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ABSTRACT

Magnetic tweezers provide a method to maneuver magnetic probes for biomolecules and cells studies with least damage to these samples. We are developing an ideal 2D magnetic tweezers for precision static and dynamic magnetic particle manipulation. It requires a constant magnetic gradient that is position-independent within the operation space and linearly proportional to the control current. That is, Gradient of B($\vec{r}$, I) = constant vector*I. We also require a high bandwidth for the ability of fast switching.

Typical magnetic tweezers can't provide a constant magnetic flux gradient and thus the force exerted on magnetic particles is position dependent. The position dependent force makes accurate force measurement and precise manipulation more difficult. The magnetic tweezers described here relies on a special configuration of coils with air cores to provide a linear gradient of magnetic flux density. This study reports the design and experiment of the 2D magnetic tweezers that enable us to manipulate magnetic particles.

INTRODUCTION

Biological techniques are entering a new era. A number of techniques have been utilized to investigate the localization, dynamics, and chemical interactions that occur in the living cells, and a variety of techniques of micro particle manipulations, such as atomic force microscopy [1], optical tweezers [2], magnetic tweezers [3] [4], have big impacts on biological science. These techniques had been widely used to control cells and measure the micromechanics behavior of biopolymers such as DNA and cytoplasm.

Among these techniques, magnetic tweezers exert least damage in the analysis of molecular systems or live cells. Typically, magnetic tweezers are made of several ferromagnetic poles and metal coils. However, these magnetic tweezers are not linear due to the intrinsic non-linearity of ferromagnetic cores; and they also can't provide a constant magnetic flux gradient due to non-linear flux concentration near the pole tips and thus the force exerted on magnetic particles is position dependent. The non-linear and position dependent force makes accurate force measurement and precise manipulation more difficult. In this article, we describe an ideal 2D magnetic tweezers for precision static and dynamic magnetic particle manipulation. It requires a constant magnetic gradient that is position-independent within the operation space and linearly proportional to the control current. That is, Gradient of B($\vec{r}$, I) =

constant vector*I. We also has a high bandwidth for the ability of fast switching.

A LINEAR MAGNETIC TWEEZER DESIGN

The magnetic force F on a magnetic particle is given by

$$\overrightarrow{F} = \overrightarrow{m} \bullet (\nabla \overrightarrow{B})$$

where m denotes the magnetization of the particle and B denotes the magnetic flux density. The force is proportional to the magnetic field gradients. Since magnetic fields generated by a fixed current source scale inversely with the size, the magnetic field gradients scale with the inverse 2^{nd} power of the size. Table 1 summarizes the related scaling laws in manipulating magnetic particles.

Particle dimension	α
Magnetic moment	α^3
Magnetic force w. same magnetic field gradient	α^3
Stoke velocity	α^2
Required magnetic field gradient to maintain velocity	α^{-2}
Required field component miniaturization scaling	α

Table 1. Scaling of magnetic field components.

A magnetic field gradient of 100's T/m is achievable with the microfabricated gradient coils. Thus, miniaturizations can compensate the loss of magnetic flux and field gradients and enable us to substitute the non-linear ferromagnetic cores by linear core material: the air. It also decreases the coil inductance and enables the faster switching speed.

When two identical helical coils are positioned co-axially with a relative axial displacement and driven by currents with same magnitude and opposite (same) direction, the coils generate constant magnetic field gradients (constant magnetic fields). The magnetic flux density is given by

$$B = \int_0^L \int_a^b \left(\frac{\mu N i r}{L(b-a)[r^2 + (b-z+x)^2]} \mp \frac{\mu N i r^2}{L(b-a)[r^2 + (b+z+x)^2]} \right) dr\,dx$$

where μ, N, r, L, b, a, z, x are the vacuum permeability, the number of turns, radius distance from coil axis, coil length, the internal radius and the external radius of the coil, the distance from the center of working area to the edge of the coil, and the length of the coil respectively. The minus and plus signs indicate a "Maxwell-like" or a "Helmholtz-like" excitation respectively. Fig.1 shows the magnetic field along the symmetrical axis.

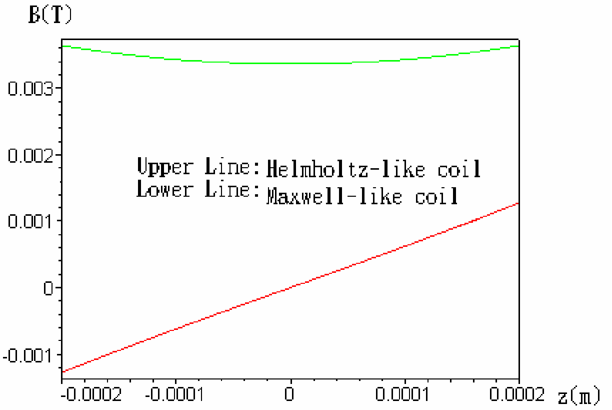


***Figure1**. Magnetic flux density from a coil set with both "Maxwell-like" and "Helmholtz-like" current excitation plotted as a function of z. Where N=32, i=0.5A, a=0.5mm, b=0.9mm, L= 800 m.*

As shown in Fig.1, a constant magnetic field gradient occurs in a 400μm region by the "Maxwell-like" excitation, and a near constant bias field is generated in a lightly narrower region by the "Helmholtz-like" excitation.

When the two coils are driven by the linear combination of a constant bias current i and a control current i_1, i.e. driven by $(i+i_1)$ and $(i-i_1)$ respectively, the magnetic field is given by

$$B=\int_0^L\int_a^b\left(\frac{\mu N(i+i_1)r}{L(b-a)[r^2+(b-z+x)^2]}+\frac{\mu N(i-i_1)r^2}{L(b-a)[r^2+(b+z+x)^2]}\right)drdx$$

EXPERIMENT

According to the design described above, we made a scaled-up, 2-axis linear magnetic tweezers with 1-mm ID coils as shown in Fig. 2.

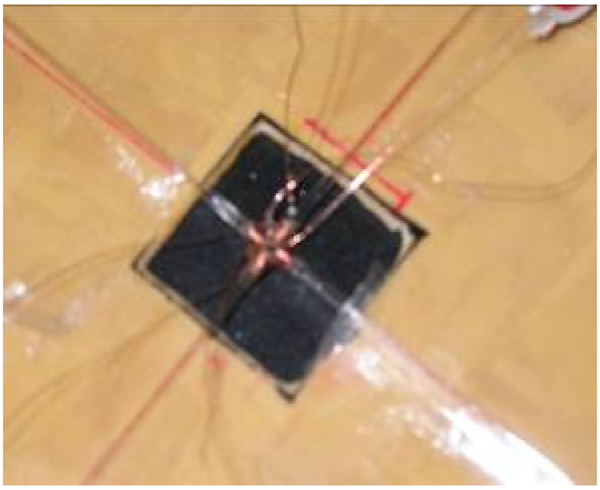
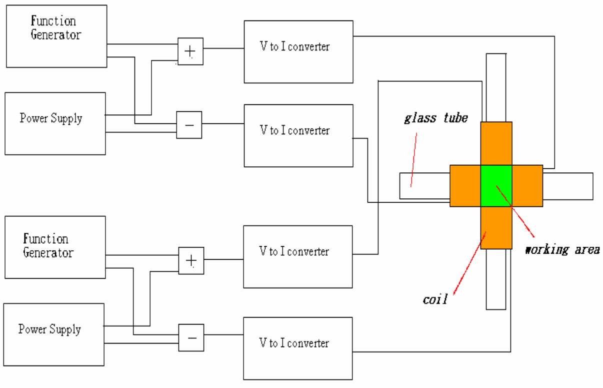
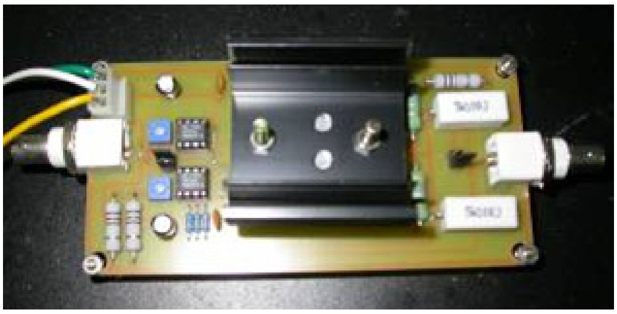


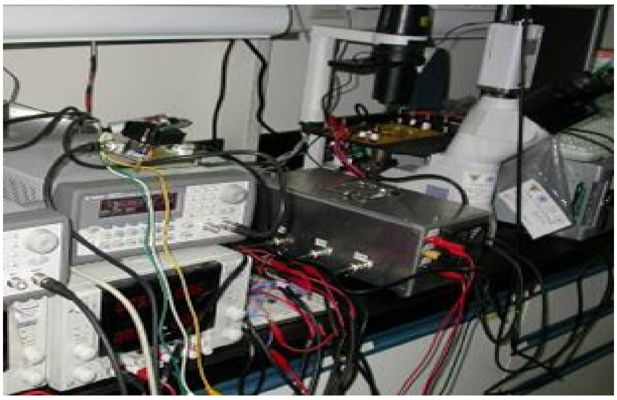
Fig.2 A 2-axis magnetic tweezers.



(a)



(b)



(c)

Figure 3 (a) the block diagram of experimental setup (b) the current driver (c) the physical setup.

The drive currents of the coils are generated by function generators, addition/subtraction circuit and V to I converts (Fig. 3(a), 3(b)). The magnetic tweezers is installed on a microscope with video microscopy as shown in Fig. 3(c). Magnetic beads with OD = 4.5 μ m (Dybabeads M450, volume magnetization of 30 KA-m-1) are used in this study.

RESULTS AND DISCUSSIONS

To evaluate the linearity of the magnetic flux density, we measured the Stoke velocity of magnetic beads. At the Stoke velocity v, the magnetic force on a magnetic bead is equal to Stoke resistance of the liquid given by

$$6\pi\eta rv=m\times(\nabla B)$$

where η is the viscosity of the liquid. The velocity was measured by direct measurement of video recordings frame by frame and the typical velocity is around 100μm/s when driven at the specified conditions. The theoretical values and measurement data are show in Fig.4.

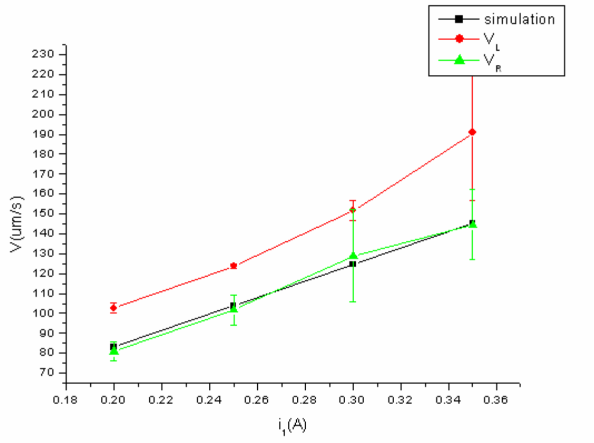


Figure4. Calculated and measured velocities of magnetic beads as a function of 1_i*. Where N=32, i=0.15.A, a=0.5mm, b=0.9mm, L=0.8mm.*V_R and V_L mean *the velocities toward +x direction and –x direction.*

The theoretical and measured Stoke velocities of magnetic beads match well except for some non-ideality from the misalignment of the assembled, scaled-up coils and the non-ideal helical coils used in the Helmholtz configuration. A microfabricated version will greatly reduce this non-ideality.

CONCLUTIONS

In this study, based on the concepts of Maxwell-like and Helmholtz-like current excitation of a miniaturized set of coils with air-cores, we made a scaled-up (mm-sized), 2-aixs magnetic tweezers which can provide constant magnetic gradients and linear to the control current. A miniaturized version of the tweezers which can give two-orders of magnitude higher magnetic gradients is under development and we will report the measurement results of the microfabricated version in other place.

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