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Journal of Magnetism and Magnetic Materials 293 (2005) 597–604
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

# Magnetic separation in microfluidic systems using microfabricated electromagnets—experiments and simulations

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Available online 7 March 2005

**Abstract**

We present experiments and simulations of magnetic separation of magnetic beads in a microfluidic channel. The separation is obtained by microfabricated electromagnets. The results of our simulations using FEMLAB and Mathematica are compared with experimental results obtained using our own microfabricated systems.


*Keywords:* Microsystems; Magnetic separation; Computational fluid dynamics; Magnetophoresis; FEMLAB software; Microfluidics; Simulation; Electromagnet; Microelectromagnet; Nanotechnology; Channel flow

## 1. Introduction

Manipulation of superparamagnetic nanoparticles encapsulated in polymer beads (magnetic beads) is a well-known technique in biochemical analysis and processing [1,2]. In magnetic separation biochemically functionalized magnetic beads are separated from a solution using magnetic forces. Recently, microsystems offering the same functionality have been reported [3–5]. Microsystems capable of magnetic separation are ideal for inclusion in Lab-on-a-chip systems. The vision of Lab-on-a-chip systems is to have entire biochemical laboratories on a single chip. The advantages of such Lab-on-a-chip systems are that they can handle minute sample volumes (e.g. micro or nanolitres), they are highly portable, and they are potentially inexpensive and thus disposable [6,7].

We present numerical simulations of the movements of such magnetic beads in microfluidic systems and compare with experiments.

## 2. Design and fabrication

The design of our microsystem is shown in Fig. 1. Each microsystem contains three microelectromagnets, each consisting of a copper coil semi-encapsulated in a dielectric layer and a nickel soft magnetic yoke on top of that.

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doi:10.1016/j.jmmm.2005.01.079

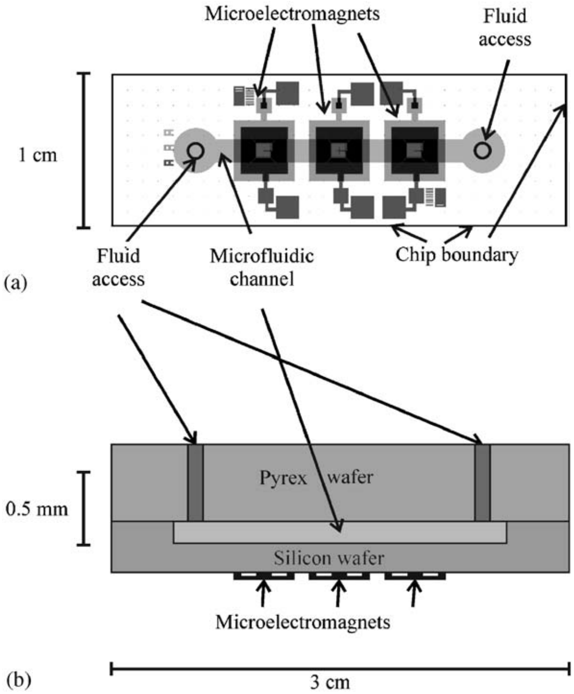


Fig. 1. Overview of the microsystem design. (a) Top-view of the fabricated chip. The microelectromagnets are planar spiral copper coils with 12 turns. The coils are semi-encapsulated in a soft magnetic yoke made from nickel. (b) The microsystem seen from the side. The horizontal scale bar at the bottom applies to both (a) and (b).

We have fabricated electromagnets by use of standard cleanroom technology. Fig. 2 summarizes the fabrication process. For more details see Ref. [8]. The electromagnets that we have used for the experimental part of this paper have the following design parameters: number of turns 12; coil wire height 25 μm, width 60 μm, and spacing 20 μm; electromagnet width 4 mm, and yoke thickness 25 μm; fluid channel depth 150 μm, length 14 mm, and width 1.5 mm.

## 3. Magnetostatic theory

The magnetic induction **B** is calculated using magnetostatics formulae,

$$\mathbf{B} = \nabla \times \mathbf{A} = \mu_0 \mu_r \mathbf{H}, \tag{1}$$

$$\nabla \times \mathbf{H} = \mathbf{J}^f, \tag{2}$$

where **H** is the magnetic field, **A** is the magnetic vector potential, $\mu_0$ is the permeability of vacuum, $\mu_r$ is the relative permeability of the material, and $\mathbf{J}^f$ is the free current density. These equations can be combined to yield

$$\nabla \times ((\mu_0 \mu_r)^{-1} (\nabla \times \mathbf{A})) = \mathbf{J}^f. \tag{3}$$

To simplify the simulations we study circular electromagnets, and thus the magnetostatic problem is reduced from 3D to 2D. This still allows for qualitative comparison with the square magnets of the experiments as discussed by Shafique et al. [9].

We apply cylindrical coordinates $(r, \theta, z)$ with $r = 0$ at the centre of the electromagnet. All free currents are thus in the azimuthal direction $\mathbf{J}^f = J^f(r,z)\hat{\mathbf{e}}_\theta$ which is consistent with a magnetic vector potential $\mathbf{A} = A_\theta(r,z)\hat{\mathbf{e}}_\theta$.

To bring Eq. (3) into a form suitable for the software, FEMLAB®, we introduce the function $u(r,z)$ given by

$$u(r,z) = \frac{A_\theta(r,z)}{r}. \tag{4}$$

Using this, the only non-zero component of Eq. (3) is

$$-\frac{\partial}{\partial r}\left( r(\mu_0\mu_r)^{-1}\frac{\partial u}{\partial r} + 2(\mu_0\mu)^{-1}u \right) - \frac{\partial}{\partial z}\left( r(\mu_0\mu_r)^{-1}\frac{\partial u}{\partial z} \right) = J^f_\theta, \tag{5}$$

which is the canonical form that FEMLAB® solves in its "Magnetostatics–Azimuthal currents" mode of its Electromagnetics Module [10]. In terms of $u(r,z)$ the components of the magnetic induction become:

$$\mathbf{B} = (B_r, B_\theta, B_z) = \left( -r\frac{\partial u}{\partial z}, 0, r\frac{\partial u}{\partial r} + 2u \right). \tag{6}$$

Nickel is a ferromagnetic material, and thus $\mu_r$ is not a constant. However, since nickel is a soft magnetic material and thus almost hysteresis-free, we use the approximate empirical Fröhlich–Kennelly relation $\mathbf{M} = M_s\mathbf{H}/(C + |\mathbf{H}|)$ for hysteresis-free magnetization to describe the material [11].