Design and fabrication of a three-dimensional microcoil for the development of an integrated LTCC-PDMS microvalve for analytical chemistry microsystem

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1. Abstract

A miniaturized magnetic valve fullfilling the operational requirements for chemical analysis microsystems was designed and a LTCC three-dimensional microcoil was manufactured. The concept of electromagnetic actuation relies on the use of a coil next to a permanent magnet attached to PDMS membrane, causing the deflection of the membrane, opening/closing the fluid flow. The fabricated prototype was evaluated over a range of voltage applied between the terminals from 3 V to 12 V. It was observed that one layer of 36 spirals square windings of a microcoil could produce a force of about 0.001 N at 12 V, necessary for its actuation in real environments.

Keywords: microvalve, electromagnetic actuation, LTCC, multilayer microcoil

2. Introduction

Many research concerning the development of laboratory-on-a-chip (LOAC) has been encouraged by applications of electronics, analytical chemistry [1-3], and bioanalytical chemistry [4,5] in the environmental, medical and industrial fields. It was the unprecedented paper of Manz *et al.* [6] that aroused the manufacturing of microelectromechanical systems (MEMS)-type microfluidic devices for chemical applications, establishing the field of miniaturized total analysis systems (μTAS). This concept suggested the full annexation of analytical procedures into carrier streams of liquids, where those flowing systems take over the duty of sample/reagents transport between unlike fluids manipulation steps. The implementation of miniaturized systems into analytical chemistry have advantages with respect to conventional systems bring forward fast analysis times, fewer consumption of expensive chemical reagents, improvement on the sensibility and reliability of the measurements, increased automation, reduced manufacturing costs and enhanced portability allowing to perform real time analysis in *situ*.

Albeit, from a skilled solution aspect, the triumphant attainment of fully integrated microfluidic system rely on the manufacturing of reliable miniaturized fluidic components. Therefore, much attention has been paid on the fabrication of microfluidic components, such as micropumps [7,8], micromixers [9], world-to-chip microfluidic interfaces [10] and microvalves [11,12]. Particularly, most of MEMS-based microvalves generally fall into one of the two major categories: *active* and *passive* microvalves. Normally, active microvalves are accomplished by means of surface micromachining or MEMS-based bulk technologies. Passive valves only open to forward pressure, exhibiting diode-like characteristics. Active microvalves can use *mechanical* or *non-mechanical* moving parts, as well as *external systems* to perform the actuation. The aim of this work is about active mechanical microvalves since they allow automated controlling with relative fast response time and enable miniaturization. An active mechanical microvalve is normally built using magnetic [13,14], electric [15], piezoelectric [16] or thermal [17] principles as a way to attain mechanical actuation.

According to the study of many microvalves of different types, magnectic actuation is considered to be the most suitable method for the development of a microswitcher working with water monitoring regarding phosphorus analysis. In the case of electrostatic actuation, polar liquids cannot be used due to electrolysis observed at relative high voltages (200 Volts), what can make the device unusable. The piezoelectric actuation needs high voltages or high volume of material to work properly, because piezoelectric actuators usually provide low stroke (force/displacement). Thermal actuation methods are slow owing to the associated phenomenology. Then, magnetic actuation can yield fast response and high stroke, over relative low power consumption.

3. Methods

A. Design and simulation

LTCC technology enables high-performance structuration of complex three-dimensional modules suitable for total analytical devices. Developing systems using the same technology can make integration more approachable. A design model for implementation of a microvalve electromagnetically actuated that fullfill the requirements proposed in this work is shown in Fig. 1.

The whole system is composed by the fluidic system (a LTCC structure with three bottom layers used to bolster the channel that connects inlet and outlet of fluids were made in the above two layers), the active element (a flexible micromembrane in PDMS attached to a permanent magnet made of NdFeB) and the electronic controlled system (a 3-D LTCC microcoil).

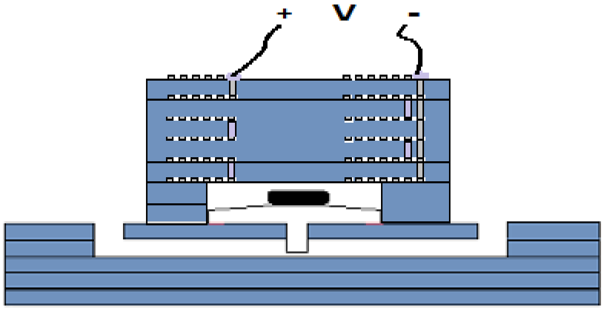

Fig.1. *Concept of the electromagnetic LTCC-PDMS microvalve.*

During actuation, the central part of the membrane is moved upwards, thus opening the valve, or downwards closing the valve. As the intensity of the magnetic flux can be well controlled by the current passing through the conducting wire, the modeling can be very useful for design the appropriate microcoil for the microvalve. Fig. 2 represents the model used for calculating the magnetic field gradient produced by a planar coil. One segment represents a straight segment of wire in the coil. The size of the gap *g* is defined as the distance between the centers of two parallel and neighbor segments. Four consecutive segments form a turn. The flat coil is modeled as a set of conducting wires of finite length, and the magnetic field produced by each segment is counted in the Cartesian domain. Superposition of the magnetic fields generated by all segments will result in the total magnetic field produced by the coil.

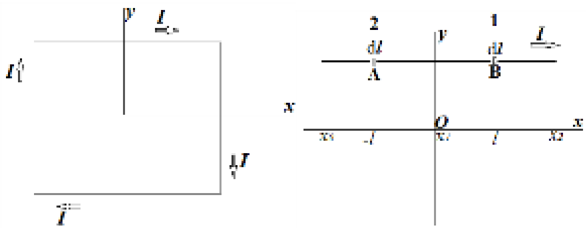

Fig.2. *Model of four segment of conducting wires using the same coordinate system.*

Considering the geometric parameters portrayed in the Fig. 2, the magnetic force is given by

$$\boldsymbol{F} = \frac{V\chi}{\mu_0}(\boldsymbol{B}\cdot\nabla)\boldsymbol{B}. \qquad (1)$$

Where V is the volume of the magnet material, χ the susceptibility, μ_0 the permeability of the free space and the magnetic field $\boldsymbol{B}$ is obtained by Biot-Savart law:

$$\boldsymbol{B} = -\frac{zI}{2\pi\mu_0[(a-y)^2+z^2]}\left[\frac{b-x}{\sqrt{(b-x)^2+(a-y)^2+z^2}}+\frac{x}{\sqrt{(x)^2+(a-y)^2+z^2}}\right]\boldsymbol{j} - \frac{(a-y)I}{2\pi\mu_0[(a-y)^2+z^2]}\left[\frac{b-x}{\sqrt{(b-x)^2+(a-y)^2+z^2}}+\frac{x}{\sqrt{(x)^2+(a-y)^2+z^2}}\right]\boldsymbol{k} \qquad (2)$$

Using Eq. 1 and Eq. 2 it is possible to find the expression for the force generated by the microcoil at a generic point in the space. A program code was written in MatLAB to perform the sum of the force produced by every single segment of wire composing the microcoil. The thickness of the LTCC layer was considered 200 μm. The other parameters are described in Fig. 3.

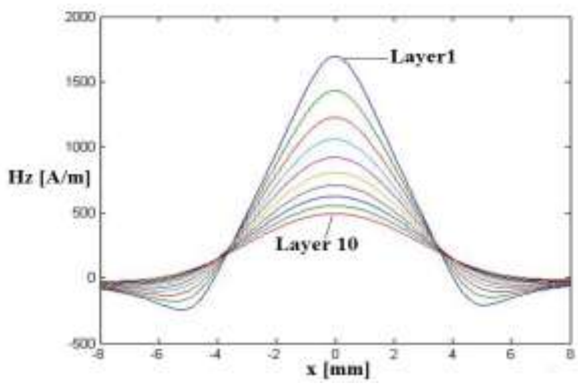

Fig.3. *Magnetic field z component simulation produced by each layer of a three-dimensional coil with 10 flat layers (n = 94, g = 200 µm, I = 0.55A, y = 0 mm, z = 1 mm).*

B. Manufacturing

The fabrication process of the fluidic system was performed using standart LTCC processing (laser machining, screen printing, lamination and sintering). Fig.4 show the design of the layers of the coil used in this work. Staking the layers in the appropriated order gives the microcoil structure. The connections between the layers is made using electrical connections via that is accomplished by screen printing method, with the via holes already machined.

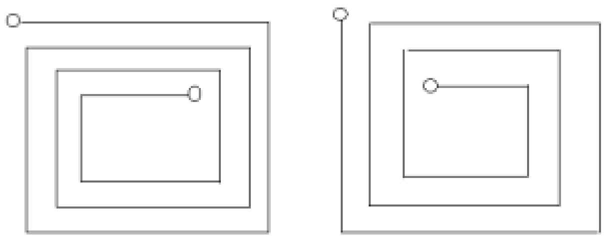

Fig.4. *Schematic representation of the layers used to fabricate the windings on the surface of LTCC sheets.*

C. Experimental setup

The experiments were carried out using a precise balance with a non-magnetic material attached to the permanent magnet initially over the plate. Then the microcoil is placed in a fixed distance from the magnet, with the help of a small nipper (figure 5)

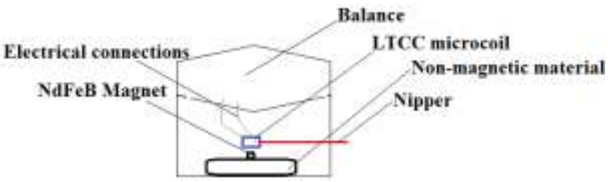

Fig5. *Schematic representation of the experimental setup used to measure the force produced by the coil over the magnet.*

4. Results

When a voltage is applied between the electric terminals of the coil a difference on the reading weight was observed. The initial weight is 31.920 g. Table I show the force measured using the experimental setup pictured in Fig. 5. The calculation of the force was performed multiplying the difference weight, in kg, by 10 m/s².

Table I. *Results observed using the experimental setup of Fig.5 using one layer of microcoil with n = 144, g = 80 µm, y = 0 mm, z = 1 mm.*

Voltages (V)	Measurement		
	Read weight (g)	Difference (g)	Estimated force (N)
3	31.925	0.005	0.00005
5	31.948	0.028	0.00028
8	31.967	0.047	0.00047
10	31.997	0.077	0.00077
12	32.043	0.123	0.00123

5. Conclusions

A membrane type microfluidic valve mechanically actuated was designed and manufactured using PDMS-LTCC technology, where a three-dimensional microcoil was fabricated to achieve the actuation, being able to give a force of about 0.001 N at 12 V, allowing the construction of an electronic controllable microvalve.

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