MEMS HELMHOLTZ COILS FOR MAGNETIC RESONANCE SPECTROSCOPY

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Abstract — Miniature coils for use in magnetic resonance spectroscopy have been constructed in a rectangular Helmholtz arrangement based on a pair of substrates separated by spherical alignment spacers. An optimal geometry has been developed using simple theory and verified by numerical analysis. Prototype devices have been fabricated using silicon substrates shaped by anisotropic etching to form a sample trough and alignment features and carrying Cu/Au conductors fabricated by electroplating. Prototypes have good electrical performance.

Key Words: Magnetic resonance, MEMS

I INTRODUCTION

Microcoils find application in magnetic resonance spectroscopy of nanolitre volumes\(^1-3\), and planar and solenoidal coils have both been constructed\(^4,5\). Micro-electro-mechanical systems (MEMS) technology is increasingly used for fabrication\(^6-9\), since this approach also allows 3D coil arrangements. Here we demonstrate the construction of rectangular MEMS Helmholtz-type coils, which potentially allow a uniform field to be created over a large sample volume.

II COIL GEOMETRY

Figure 1 shows the assumed geometry, which consists of two long thin rectangular single-turn coils with in-plane conductor separation \(2S_y\) separated by a distance \(2S_z\) and carrying a current \(I\).

Figure 1. Rectangular Helmholtz coil arrangement.

The magnetic field created by the conductors in the 2-D model shown in Figure 2 can be found using Ampere’s law and summing contributions \(H_i\) from the four conductors. The total vertical field is

\[
H_z = \frac{I S_y}{\pi} \left\{ \frac{1}{[S_y^2 + (S_z+z)^2]} + \frac{1}{[S_y^2 + (S_z-z)^2]} \right\}
\]

(1)

\[
\begin{align*}
\text{Out of figure} & \quad \text{Into figure} \\
\#4 & \quad \#3 \\
\#2 & \quad \#1 \\
S_z & \quad S_z \\
S_y & \quad S_y \\
H_z1 & \quad H_z1
\end{align*}
\]

Figure 2. Two-D model of the magnetic field.

The first design task is to choose the ratio \(S_z/S_y\) so that the field \(H_z\) is uniform for the greatest distance in the z-direction. Differentiating, we obtain:

\[
d^2H_z/dz^2 \bigg|_{z=0} = \frac{I S_y}{\pi} \left\{ -4/[S_y^2 + (S_z)^2] + 16S_z^2/[S_y^2 + (S_z^2)^3] \right\}
\]

(2)

The second derivative is zero when \(S_z = S_y/\sqrt{3}\). This ratio differs from the classical result for circular coils, namely that the coil spacing should equal the radius. The field at the centre of the structure is

\[
H_z \big|_{z=0} = \frac{I S_y}{\pi} \left\{ 2/[S_y^2 + (S_y^2/3)] \right\} = 1.5 \frac{I}{\pi S_y}
\]

This value represents an increase of 1.5 on the field at the centre of a single coil.
Figure 3 shows the variation of the field $H_z$ with distance $z/S_y$ from the coil centre. The fields of the separate coils are shown, together with their sum. The total field is uniform near $z = 0$. Slightly different values of $S_z/S_y$ yield similar results (dotted), implying dimensional tolerance.

III MEMS HELMHOLTZ COIL

We have developed a novel self-aligning assembly for Helmholtz coils using two anisotropically etched silicon substrates carrying plated conductors, as shown in Figure 4. The substrates are held at the correct separation using spherical metal beads, which are soldered in place and link the conductors to form a continuous winding.

The vertical separation of the conductors is $2S_z = 2r/\sqrt{3}$, so the Helmholtz arrangement is achieved when $2r = 2S_y$, i.e. when the spacer bead diameter equals the in-plane conductor separation. Figure 5 shows the layout of a single die from a MEMS Helmholtz coil with $S_y = 500 \, \mu m$. The coil surrounds a 5 mm x 1 mm etched trough to contain the MR sample, and passes through metallized pits that allow solder attachment of the linking beads. The complete assembly is built from two similar substrates, the upper substrate being shortened to allow wire-bonding to bond pads on the lower one.

IV NUMERICAL MODEL

Full numerical models of both single and Helmholtz coil arrangements have been constructed, using the commercial package CST Microwave Studio 5.0.0TM, a 3D transient electromagnetic solver using the Perfect Boundary Approximation method, as shown in Figure 6. The model includes the silicon components, linking metallic beads and connections to a PCB carrier in FR-4.
The dimensions used in the simulation are as Figure 5, while the material parameters are as in Table 1. Magnetic fields were calculated throughout the volume of interest. Figure 7 shows variations with x, y and z of the important H_z component in a Helmholtz coil, along lines through the device centre. The variation H_z(z) is very similar to that in Figure 3. However, H_z(x) deviates from uniformity as the coil end conductors are crossed. The resistance and inductance of a single coil were calculated as 2.0 Ω and 16.0 nH at 63.6 MHz, the frequency for an MR system in a 1.5 T static field.

Table 1. Properties of MEMS coil materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>σ (s/m)</th>
<th>μ_r</th>
<th>ε_r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>4.1 x 10^7</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>5.8 x 10^7</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>In</td>
<td>1.2 x 10^7</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>0.02</td>
<td>1.0</td>
<td>11.9</td>
</tr>
<tr>
<td>SiO2</td>
<td>3.3 x 10^{-14}</td>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td>FR-4</td>
<td>1.7 x 10^{-11}</td>
<td>1.0</td>
<td>4.7</td>
</tr>
</tbody>
</table>

V FABRICATION AND TESTING

V.1 FABRICATION
To fabricate prototype devices, a 4" diameter (100) oriented intrinsic (5000 Ωcm) Si substrate was first thermally oxidised, and the oxide patterned to form an etch mask. The wafer was then anisotropically etched in KOH down (111) crystal planes to form alignment features and sample troughs. The oxide was stripped, and the wafer re-oxidised to form a 4 µm thick isolation layer. Non-magnetic seed layers of Ti and Cu were then deposited by RF sputtering. The terraced substrate was coated in a thick layer of Shipley Eagle 2100 ED photoresist by electrodeposition. Thick conductors (2 µm Au on 10 µm Cu) were then formed by electroplating. The resist was stripped, and exposed areas of seed metal removed by wet and dry etching. The wafer was then diced.
To assemble a Helmholtz coil, the lower die was first mounted on a small PCB based on an FR-4 substrate with Cu tracks, and gold wirebond connections were made to the die. Au or Cu metal spheres of 1 mm diameter were then soldered into the etched alignment pits by reflow of In metal in an N₂ atmosphere. The smaller upper die was then soldered in place using a similar process. Figure 8a shows an etched silicon die carrying electroplated conductors and solder-attached spheres. Figure 8b shows a variety of completed devices, including single-coil devices formed on Si and on reference Pyrex substrates, and Helmholtz coils on Si.

V.2 Electrical Testing

Electrical performance was measured with an HP8753ES network analyser. Figure 9 shows the frequency dependence of the real and imaginary parts of the impedance of three different single turn coils. Resistances lay in the range 0.63 – 1.75 Ω and inductances in the range 11.1 – 16.5 nH. These results correspond to an estimated Q-factor of up to 10 at 63.6 MHz. In fact, planar coils configured as resonators at the same frequency had a Q-factor of 3, in reasonable agreement with the above.

VI Conclusions

A novel rectangular Helmholtz coil has been developed for use in magnetic resonance spectroscopy. The Helmholtz arrangement is achieved by using a pair of etched substrates separated by spherical conducting spacers. The assembly is entirely self-aligning. An optimal geometry has been developed using simple theory and verified by numerical analysis. Prototype devices have been fabricated using silicon substrates shaped by anisotropic etching to form a sample trough and alignment features and conductors fabricated by electroplating. Prototypes have shown good electrical performance, and MR spectroscopy experiments are now planned.

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REFERENCES