Application of a novel rf coil design to the magnetic resonance force microscope

Z. Zhang and P. C. Hammel
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

G. J. Moore
Wayne State University School of Medicine, Detroit, Michigan 48201

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We report a rf coil design based on the Alderman–Grant coil called the modified Alderman–Grant coil (MAGC), and demonstrate its efficacy in the magnetic resonance force microscope (MRFM). The rf field of the MAGC has a magnitude comparable to that of a solenoidal coil of similar size (for the same input power) but the coil has a much smaller inductance. This is advantageous in electron spin resonance MRFM experiments which would benefit from rf frequencies in excess of 1000 MHz. The open design of the MAGC is also advantageous because it provides superior access to the sample mounted on a mechanical cantilever by the optical fiber and permanent magnet and so allows the sample to be placed at the center of the coil. *© 1996 American Institute of Physics.* [S0034-6748(96)02509-9]

I. INTRODUCTION

The magnetic resonance force microscope (MRFM), based on mechanical detection of magnetic resonance signals, promises substantial improvement in magnetic resonance imaging (MRI).[1,2] Following the initial success of an electron spin resonance (ESR) MRFM experiment,[3] much effort has focused on improving the sensitivity of the instrument[4–6] and on applying the unique capabilities of the MRFM to problems of scientific and technical interest.[7–9] The amplitude of the rf field H_1, through its influence on the intrinsic linewidth of the ESR signal, determines the width of the ''sensitive slice'' within which the resonance condition is satisfied.[10] This effect, in conjunction with the improvement of the saturation of the electron spin magnetization with increasing H_1, means that rf field strength is one of the leading factors that determine the MRFM sensitivity at a given temperature. Another key factor which determines sensitivity is the strength of the applied field H at the site of the sample: a larger field produces a larger electron spin polarization and thus a larger signal. The rf frequency f_{rf} defines H through the resonance condition $2\pi f_{rf}=\gamma H$, where γ is the electronic gyromagnetic ratio. Higher frequency is thus desirable to improve sensitivity. In all previous experimental arrangements reported in the literature,[3,10] the rf field is produced by a conventional millimeter-size coil (about 2 turns) which is impedance matched to the 50 Ω signal source using conventional resonant circuit techniques. This coil design limits the maximum resonant frequency of the circuit to 800–1000 MHz due to the relatively large inductance of the coil. The simultaneous constraints of the geometrical arrangement of the various magnetic fields necessary for magnetic resonance and the requirement that the optical fiber and magnetic tip must have access to the top and bottom of the micromechanical resonator mean that the resonator with attached sample must be displaced somewhat away from the center of the coil where the amplitude of the rf field is maximum.

In this article, we report a new rf coil design which is a modification of the Alderman–Grant coil design,[11] called the modified Alderman–Grant coil (MAGC) (see Refs. 12–14 for other modifications of this coil design) which allows the sample to be placed at the center of the coil. More importantly, the lower inductance of the MAGC relative to a conventional coil allows the upper limit of the rf frequency to be extended to a few GHz.

II. EXPERIMENT

A diagram of the MRFM apparatus is shown in Fig. 1. A small particle of diphenylpicrylhydrazyl (DPPH) is mounted on a pure Si cantilever. The resonant frequency of the cantilever with a mounted sample is 10.68 kHz and the Q value ~12 000. A small NbFeB bar magnet (6.35 mm long and 0.58 mm in diameter) creates a large field gradient $\partial B/\partial z \simeq 1.3$ G/μm at the sample located about 700 μm away. This generates the coupling between the spin magnetization M in the sample under study and the mechanical resonator: $F=M_z(\partial B/\partial z)$ ($\mathbf{B}\|\mathbf{z}$). This field gradient also defines a thin shell (sensitive slice) of constant field within which the ESR condition is satisfied.

Anharmonic modulation[5] in which the amplitudes of both the rf field H_1 and the bias field H_0 are modulated at two anharmonic frequencies while keeping the difference of the two frequencies equal to f_c was used to create a time varying component of M_z at the resonator frequency f_c. The bias field is modulated by a modulation coil attached to the electromagnet with a modulation frequency of 36.00 kHz and a modulation amplitude H_B^m up to 20 G. The rf field is 100% amplitude modulated at 46.68 kHz.

To compare the two coil designs two different rf circuits were used. In the first, we used a conventional 2 turn rf coil about 2 mm in diameter (made of gauge 22 copper wire). The circuit also includes a 1 pF parallel porcelain and ceramic multilayer chip capacitor (American Technical Ceramics, Huntington Station, NY) and a 0.3–1.2 pF series variable capacitor (Johanson Manufacturing) as shown in Fig. 2. Radio frequency power was carried into the circuit by a co-axial cable. This circuit is tuned by adjusting the variable capaci-

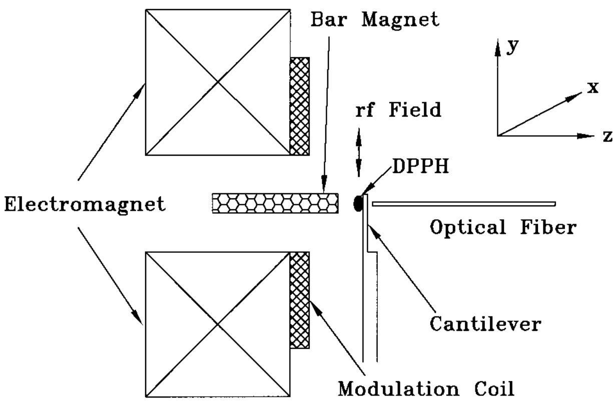

FIG. 1. A schematic diagram of the MRFM experiment. The rf field is produced either by a MAGC such as is shown in Fig. 3 or a conventional, solenoidal coil.

tor and matched to 50 Ω impedance by varying the operating frequency; 50 Ω matching was achieved at 816 MHz. The Q value of this circuit is about 40 measured using a network analyzer (HP 8754A). To allow the bar magnet and the optic fiber to achieve the necessary physical proximity to the cantilever, the sample was placed on the coil axis about 1 mm from its center.

In the second rf circuit, we used a MAGC, whose design is shown in Fig. 3. This MAGC is machined from a solid copper rod with both the outer diameter and the length at ~3 mm and the wall thickness at ~0.4 mm. The rf circuit (see Fig. 2) is essentially the same as in the conventional 2 turn coil design except that the coil is now replaced by the MAGC, which is directly soldered to the leads on the circuit

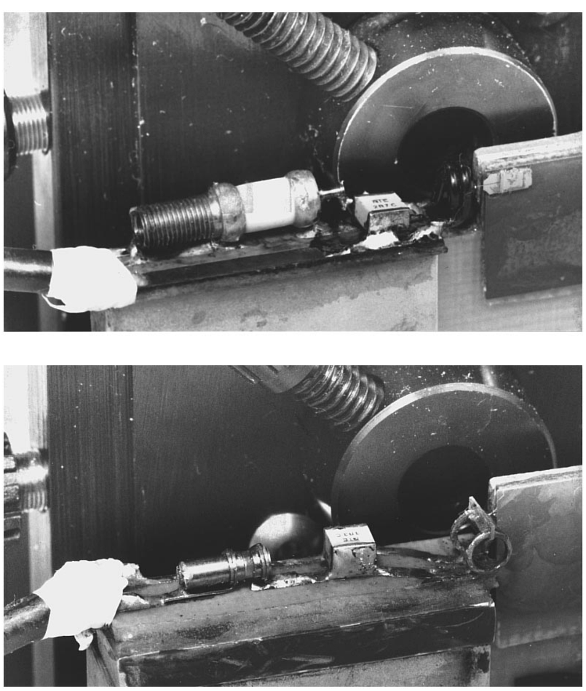

FIG. 2. The 50 Ω matched rf circuits for the conventional 2 turn coil design (top) and the MAGC design (bottom). The structure behind the coil holds the optical fiber chuck. The optical fiber and the bar magnet, which are not shown here, access the cantilever horizontally from the rear and front, respectively.

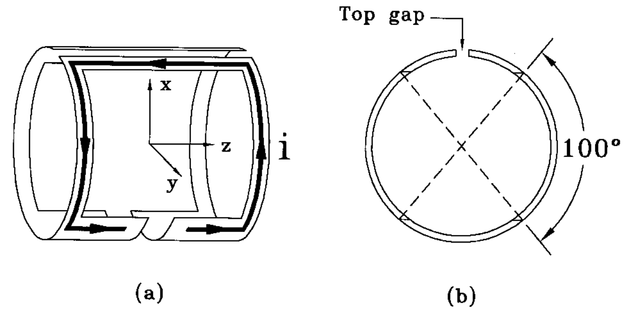

FIG. 3. (a) A perspective view of the MAGC with the rf current shown by the thick line. (b) A sideview of this coil.

board shown in Fig. 2. The rf current i [shown in Fig. 3(a)] generates an rf field along the y axis. With this coil design, it is possible to place the cantilever at the center of the coil such that the plane of the cantilever is in the $x-y$ plane (its motion will be in the z direction) without blocking the bar magnet and the optic fiber from accessing along the $\pm z$ axis. We modified the traditional Alderman–Grant coil[11] by adding a top gap as shown in Fig. 3(b). This eliminates eddy currents induced by the 36 kHz modulation field along the z axis. Tuning the circuit to match 50 Ω impedance is again achieved by adjusting the series variable capacitor and the operating frequency. With a 1 pF parallel capacitor, the resonant frequency of this circuit is well over 1 GHz (the maximum frequency of our current system). This indicates that the inductance of the MAGC is much smaller than that of the conventional coil. To compare results with the conventional coil, a 3.3 pF parallel chip capacitor was used to produce a 50 Ω circuit at a frequency of 884 MHz with a Q value of ~35. Considering the fact that the gap at the bottom of the MAGC also behaves like a capacitor, these tuning conditions suggest the inductance of the MAGC is less than 10 nanohenrys (nH), or $\frac{1}{3}$ that of the conventional coil. From a design point of view, it would be helpful to realize that the MAGC is topologically equivalent to a two-turn coil, but with the two coils connected in parallel, rather than in series as in their conventionally wound coil. This explains the lower inductance of the MAGC relative to a conventional coil: the inductances are predicted to be the ratio of 1/2, consistent with our observation.

III. RESULTS AND DISCUSSIONS

Figure 4 shows the MRFM spectra of the same cantilever/DPPH sample obtained with the two different rf coil designs at a constant rf power of 0.5 W. The amplitude of the oscillating current in the modulation coil is also kept constant near the optimal condition[10] which corresponds to $H_B^m \simeq 13$ G in the conventional coil experiment. In the MAGC experiment, the cantilever is about 4 mm away from the surface of the modulation coil (~10 mm i.d., ~20 mm o.d., and ~6 mm long) whereas it is ~1.5 mm away for the conventional coil experiment. We estimate that $H_{B,\mathrm{MAGC}}^m \simeq 0.9 H_{B,\mathrm{conventional}}^m \simeq 11.5$ G. This difference should not affect

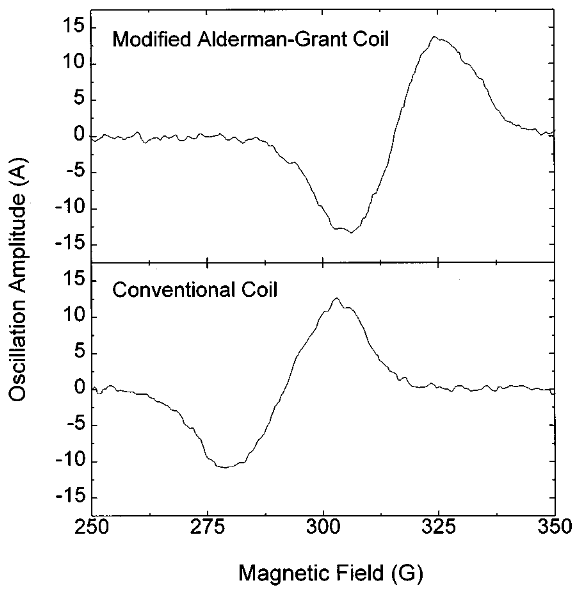

FIG. 4. The MRFM spectra of a DPPH particle using either the MAGC (top) or a conventional rf coil (bottom). The time averaged, applied rf power is constant at 0.5 W and is 100% amplitude modulated at 46.68 kHz. The bias field is ramped at 2 G/s and is modulated at 36.00 kHz with an amplitude of ~13 G.

the results significantly because the peak-to-peak amplitude in the MRFM spectra does not depend sensitively on H_B^m near the optimal condition.[10]

The peak-to-peak oscillation amplitude from the MAGC measurement was found to be slightly (~10%) larger than that from the conventional coil measurement. The rms amplitude of the thermally driven cantilever motion, on the other hand, is similar in the two cases (within 5%). The linewidth of the MRFM signal (see Fig. 4) is larger in the conventional coil measurement (~24 G) than in the MAGC measurement (~20 G) due to the larger modulation amplitude H_B^m in the former case.

Increasing the rf power increases the peak-to-peak oscillation amplitude significantly, a phenomena that has been well understood.[10] However, at each rf power the signal amplitudes for the two different coil designs are similar. This indicates that the amplitudes of the rf fields produced by the two coils are similar throughout the power range studied (0–1.5 W).

It is worth mentioning that in the initial Alderman–Grant coil design, a guard ring was used to screen out the electric voltage drop between the gap, thus reducing the electrical field leaking into the center volume which could cause a severe heating problem in the sample.[11] Such a design has not been employed in our current MAGC. As expected, we found that at a given rf power the thermal drifting of our optic fiber interferometer is more significant in the MAGC experiment than in the conventional two turn coil experiment. To further increase the rf power without inducing unacceptable heating, it will be necessary to modify the design to include such a guard ring as it is necessary to reduce the heating problem.

In conclusion, MRFM experiments were performed on a DPPH particle using a new rf coil design the MAGC design. For a similar coil size the magnetic field strength produced by the MAGC is similar to that of a conventional coil. However, the MAGC has a smaller inductance than a comparably sized conventional coil allowing the rf circuit to be operated at a higher rf resonant frequency, thus enhancing the MRFM signal by polarizing more electron spin moment from the sample. In addition, the special design of the MAGC also allows the sample to be placed at the center of the coil, making it possible to further reduce the size of the coil without reducing the strength of the rf field at the sample position as occurs in a conventional coil for which the sample must be outside the coil.

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