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Noise-Immune Coil for Unshielded Magnetic Resonance Measurements

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A modified split-loop resonator that is electrically balanced and that has no magnetic dipole moment is shown to be relatively immune to environmental noise. Using a magnetic resonance surface coil of this design for ^{14}N NQR at 3.4 MHz, it is demonstrated that magnetic resonance measurements can be made in the laboratory without additional RF shielding and with less than a 2 dB increase in the rms noise. Compared to more traditional designs, the modified split-loop resonator showed a net 17-dB gain in sensitivity for unshielded measurements.

Key Words: **NQR; noise pickup; surface coil; split-loop resonator; RDX.**

INTRODUCTION

Magnetic resonance has been found to be useful in detecting quantitatively the presence of specific substances within an inhomogeneous sample. In particular, NQR has been shown to be a promising technique for the detection of nitrogen-containing explosive materials (*1*). To obtain maximum sensitivity, magnetic resonance spectrometers normally employ extensive RF shielding to keep nonthermal noise, both man-made and naturally occurring, from entering the system. For measurements in the field or on particularly large ''samples,'' extensive RF shielding can be quite cumbersome, if not impractical.

The work reported here is the result of a study into the feasibility of performing magnetic resonance measurements in the absence of traditional RF shielding by designing magnetic resonance detection coils which are largely immune to external noise sources but still provide a usable magnetic resonance signal. The results are applicable anywhere the burden of providing extensive RF shielding is excessive, including materials detection in the field and possibly some NMR imaging applications.

The specific coil design presented here is an extension of the optimized shielded-loop resonators recently presented by Stensgaard (*2, 3*) for use as NMR imaging surface coils. A detailed theory of shielded-loop resonators has been described by Harpen (*4*). The discussion here is limited to the case where the coil size is much smaller than the RF wavelength.

After a brief discussion of the theory, we present a design for a noise-immune (surface) coil and demonstrate ^{14}N NQR detection in an unshielded laboratory environment. We show that the environmental noise entering the system has been reduced by more than 20 dB. In this case the resulting environmental noise is comparable in size to the normal thermal (plus amplifier) noise in the system, with only a small decrease in signal strength compared to a more traditional magnetic resonance coil with similar dimensions.

THEORY

Figure 1 illustrates three simple coil designs. Figure 1a shows a single-turn loop with tuning (C) and matching (C') capacitances on the input connections. Figure 1b shows a single-turn split-loop resonator made from a length of (coaxial) transmission line as discussed by Stensgaard (*2*). Figure 1c shows the specific noise-immune coil discussed here. The coil in Fig. 1c is electrically very similar to the coil in Fig. 1b; however, it has been folded into a gradiometer coil as discussed below. The shape of the gradiometer coil resembles a question mark and for brevity we refer to it as the ''?-coil'' (pronounced ''question mark coil''). For the coils in Figs. 1b and 1c, the ''extra'' tuning capacitor, C'', should be as small as is practical (i.e., $C'' \ll C$) (*2*).

Figure 2 illustrates an electrical model for the coils in Figs. 1b and c, valid when the RF wavelength is long compared to the coil dimensions. The results below are not dependent on this assumption; however, that assumption simplifies the discussion. In Fig. 2, L_c represents the inductance of the inner conductor of the transmission line, L_i is the inductance of the inner surface of the shield, and L_s is the inductance

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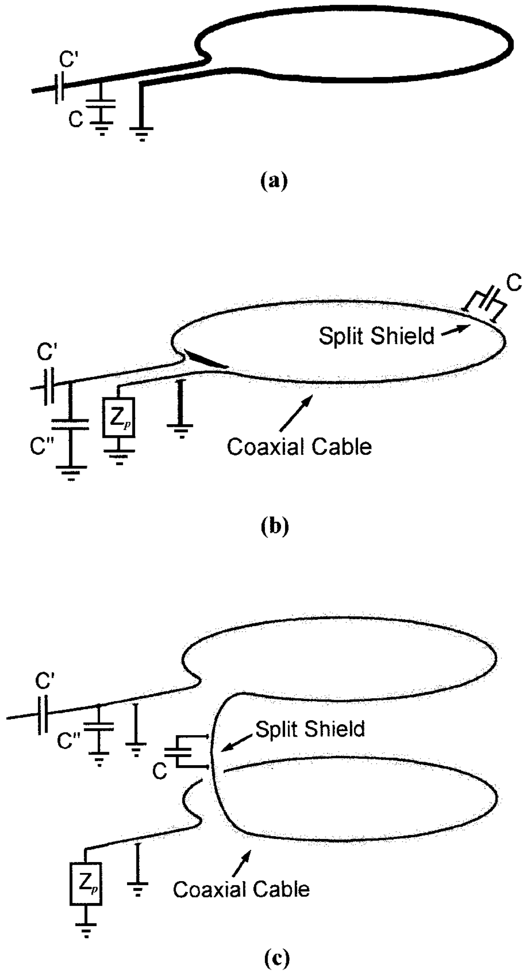

FIG. 1. A perspective view of the three coils discussed here including (a) a simple single circular turn, (b) a single-turn split-loop resonator as discussed by Stensgaard (*2*), and (c) a two-turn, noise-immune split-loop resonator. Due to its shape, the coil in (c) is referred to as a ''question mark coil,'' abbreviated ?-coil.

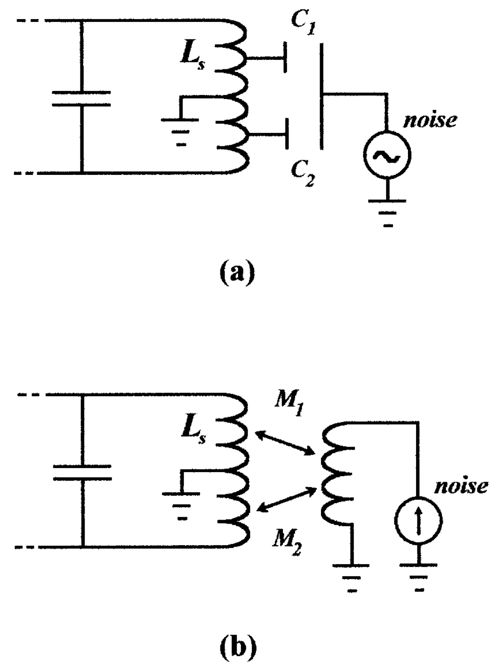

FIG. 3. Simplified electrical model for environmental noise pickup by the two split-loop resonators of Fig. 1 for (a) RF electric fields and (b) RF magnetic fields. For the single-turn split-loop resonator, $M_1 \approx M_2$, and for the two-turn resonator, $M_1 \approx -M_2$.

of the outer surface of the shield. As discussed by Stensgaard (*2*), the RF skin effect causes the inside and outside of the shield to act as separate conducting paths. Since currents and charges on the inner conductor and the inside of the shield are equal and opposite, the interaction of the coil with the external environment is only via interaction with L_s. The most significant difference between the coils in Figs. 1b and 1c is the sign of the mutual inductance, M, between the two halves of the coil. The mutual inductance, M, is secondary to the discussion of noise immunity.

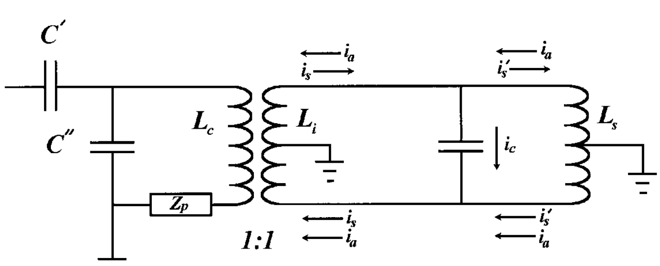

FIG. 2. Simplified electrical model for the two split-loop resonators in Fig. 1.

The branch currents in Fig. 2 are drawn using symmetric, i_s and i'_s, and antisymmetric, i_a, combinations as shown. The symmetric current, $i_s = i'_s + i_c$, will couple through the transformer and on to the NMR spectrometer, whereas the antisymmetric current, i_a, will not. Note that for the antisymmetric currents the tuning capacitor, C, is effectively out of the circuit. The strategy employed here for noise reduction is to ensure that, to the extent possible, environmental RF fields produce only the antisymmetric currents and hence do not produce a measurable signal.

In principle, the induced currents due to environmental noise can be caused both by electric and/or by magnetic couplings. Figure 3 illustrates simple electrical models for the two types of interactions. In Fig. 3a the electric coupling via the distributed capacitance of the coil (with respect to a distant ground) is modeled using a single discrete effective capacitance for each half of the coil. In Fig. 3b the magnetic coupling is modeled using a (nonideal) transformer with small mutual inductances to each half of the coil. For both split-loop resonators, $C_1 \approx C_2$, provided that the source of the electric field is at a distance large compared to the coil size. For the simple split-loop resonator, $M_1 \approx M_2$ and for the ?-coil version $M_1 \approx -M_2$. When $C_1 = C_2$ there is electrical balance and only the current i_a is produced. The advantages of electrical balance are well known (5). When $M_1 = M_2$ the environmental magnetic fields produce currents, i_s, which will interfere with the desired signal. When $M_1 = -M_2$, the magnetic field coupling produces only currents, i_a, which do not interfere with the signal. It is straightforward to show that for typical values of the stray capacitances and mutual inductances

$$i_s \approx A(C_1 - C_2) + B(M_1 + M_2)$$

for suitable choices of the constants A and B.

The coupling between the coil and the environment can also be described in terms of multipole moments. The goal is to make the lower order electrical multipole moments as small as possible and this is achieved with good electrical balance and a symmetrical geometry. The two counterrotating currents of the ?-coil eliminate the coil's magnetic dipole moment, making it insensitive to uniform (RF) magnetic fields, but sensitive to RF magnetic field gradients. Since fields associated with the higher multipoles fall off rapidly with distance, noise pickup from distant environmental sources is minimized while signal pickup from a nearby sample is still practical. The electric field pickup of the ?-coil can be further reduced by adding Faraday shielding between the two coils as shown in Fig. 4. The extra shielding, resembling teeth, increases the capacitance between the two loops and between each loop and the environment in a way that increases higher order electric multipoles at the expense of lower order multipoles. As discussed below, most of the noise pickup (in a laboratory environment) is magnetic and it is not clear whether adding teeth to the ?-coil is worth the effort.

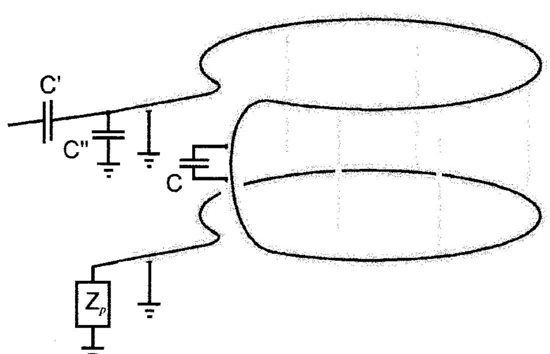

FIG. 4. The addition of Faraday shielding between the two loops of the coil in Fig. 1c can improve the coil's immunity to RF electric fields.

Stensgaard's quadrature coil (3) operated in the parallel-tuned mode ideally would have noise immunity similar to that of the ?-coil. The ?-coil has two significant advantages. The series feed of the ?-coil makes it much less sensitive to the imbalance produced when the two loops are unequally loaded by the sample and the ?-coil is much easier to adjust. We note also that the ?-coil discussed here has two coaxial loops; however, there is no particular requirement that the two loops share a common axis. When used as a surface coil, it may be advantageous to have the two loops coplanar, in a figure eight, so that signal is acquired by both loops, while noise is rejected. A simpler figure eight arrangement designed to reduce interference was recently presented by Trushkin *et al.* for ground water NMR measurements in Earth's magnetic field (6).

EXPERIMENTAL

Three coils, corresponding to the three shown in Fig. 1, were constructed. The simple single-loop coil was constructed using 0.25-inch (0.635-cm) nominal outside diameter copper pipe. The two split-loop resonators were constructed using RG401/U semirigid coax. In each case a loop diameter of 20 cm was used. The spacing between the two loops of the ?-coil was maintained at 5 cm using a small number of supports made from double-sided copper circuit board. Except at the feed point, one end of each of the circuit boards was etched and the unetched ends were alternately soldered to the top and bottom loops respectively to provide teeth as is illustrated in Fig. 4. A total of six teeth were used to provide additional Faraday shielding as discussed above.

All three coils were tuned to 3.4 MHz using multiple fixed high-Q capacitors in parallel with nominal total values shown in Table 1. The free space wavelength, λ, at 3.4 MHz is 88 m, much larger than any coil dimension. The coils were matched to 50 Ω using a small air variable capacitor for C'. The additional tuning capacitance, C'', was not used here. For the two split-loop resonators $Z_p = 0$ (a short) was used since this lowered the total tuning capacitance required. The matching components and RF connections were enclosed in a small aluminum box for shielding. The free space loaded Q's of the three coils were comparable and in the range of 150 to 200. Shielded measurements were made in an RF-tight enclosure with inside dimensions large compared to the coil dimensions (0.93 m wide, 1.40 m high, and 1.83 m long).

Noise measurements were made in a variety of ways. The values reported here were obtained using an NMR spectrometer and a single pulse experiment (with the power amplifier turned off). The rms noise voltage was calculated using 1000 points of acquired data. The noise figure for the spectrometer was measured to be about 1.2

TABLE 1
Tuning Capacitance, *C*, and Representative Relative rms Noise Measurements for a 50-Ω Resistive Load and the Three 20-cm-Diameter Coils Tuned and Matched at 3.4 MHz

Coil	*C*	rms noise shielded (arb. units)	rms noise unshielded (arb. units)	Ratio of unshielded to shielded (dB)
50-Ω resistive load	—	23.5	24.2	0.25 ± 0.4
Single loop	5.0 nF	22.7	386	25 ± 2
Split-loop resonator	5.2 nF	21.6	314	23 ± 2
?-coil	3.4 nF	20.4	24.6	1.6 ± 0.4

± 0.2 dB for a 50-Ω load at room temperature. Noise measurements were made at a variety of coil locations and coil orientations within the laboratory. Representative values are shown in Table 1. Additional measurements (not shown) were made using various forms of electrostatic shielding, which were found to have little effect on noise pickup. It was determined that the largest contribution to the environmental noise pickup was due to RF magnetic fields. This latter result is not too surprising for loop coils which are small compared to the free space radiation wavelength, λ, though it should be remembered that in the laboratory the sources of noise are only a fraction of a wavelength away. Furthermore, in a laboratory the various electrical conductors present can distort the fields from sources which are far away. Such a laboratory environment is actually rather challenging for a gradiometer coil, since the interfering fields will have the character of near field, rather than far field, sources.

Figure 5 shows single-pulse Fourier transform measurements using the ?-coil for both excitation and detection for one of the ^{14}N NQR transitions of RDX (cyclo-1,3,5-trimethylene-2,4,6-trinitramine), an explosive material, both inside the RF-tight shield and out in the laboratory. The extra noise for the unshielded measurement is roughly 1 to 2 dB. In each case the sample was located on axis, just below one of the two loops, appropriate for use as a simple surface coil. The slight distortion of the lineshape in the unshielded measurement is probably due to thermal gradients introduced when the sample was moved from the shield and out into the room.

The ?-coil will be somewhat less sensitive to the induced NQR signals than the other coils. For the coils here, all of which are the same diameter, the B_1 field produced for the same RF power input can be used as a simple estimate of receive sensitivity to the NQR signal. The B_1 field produced was measured using a small pickup coil and it was found that the maximum B_1 field for the ?-coil was one-half that of the other two. Hence, there is a loss of about 6 dB in the sensitivity to the NQR signal. Combining this with the noise reduction, the ?-coil has a net gain in the signal-to-noise ratio of about 17 dB compared to the other two coils when measurements are made in an unshielded laboratory environment. A figure eight arrangement for the coils would be expected to improve the sensitivity to the NQR signal.

Thus, it has been demonstrated that practical noise-immune magnetic resonance coils can be constructed and used for NQR measurements in the absence of RF shielding. This is done by balancing the electric and magnetic field pickup from environmental noise sources in a

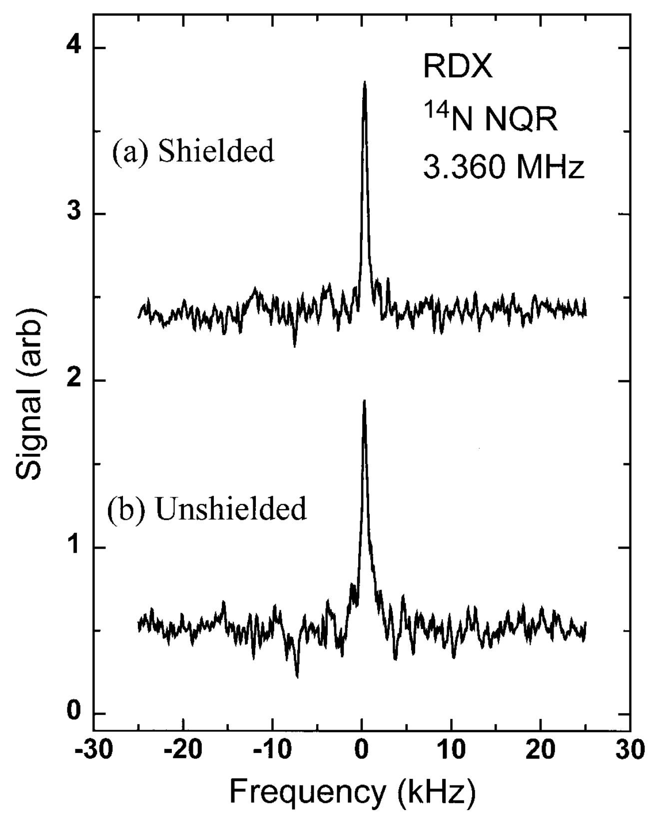

FIG. 5. Experimental ^{14}N NQR measurements using the noise-immune coil of Fig. 1c for RDX both (a) inside an RF-tight enclosure and (b) out in the laboratory with no additional RF shielding.

way which results in no net measurable signal from interfering sources.

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REFERENCES

1. A. N. Garroway, M. L. Buess, J. P. Yesinowski, J. B. Miller, and R. A. Krauss, *SPIE Conf. Proc.* **2276,** 139 (1994).
2. A. Stensgaard, *J. Magn. Reson. A* **122,** 120 (1996).
3. A. Stensgaard, *J. Magn. Reson.* **128,** 84 (1997).
4. M. D. Harpen, *Magn. Reson. Med.* **32,** 785 (1994).
5. For example, see C.-N. Chen and D. I. Hoult, ''Biomedical Magnetic Resonance Technology,'' p. 136 ff., IOP Pub., New York (1989).
6. D. V. Trushkin, O. A. Shushakov, and A. V. Legchenko, *Geophys. Prospect.* **42,** 855 (1994).