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Planar Quadrature Coil Design Using Shielded-Loop Resonators

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The shielded-loop resonator is known to have a low capacitive sample loss due to a perfect balancing. In this paper, it is demonstrated that shielded-loop technology also can be used to improve design of planar quadrature coils. Both a dual-loop circuit and especially a dual-mode circuit may benefit from use of shielded-loop resonators. Observations in measurements agree with theory for both a dual-loop coil and a dual-mode coil. The coils were designed for use as transmit/receive coil for ^{1}H imaging and spectroscopy at 4.7 T in rat brain. © 1997 Academic Press

INTRODUCTION

A number of suggestions for design of planar quadrature resonators have been reported previously. The first useful design presented by Hyde (*1*) consists of a combination of a single loop and a planar pair. In the center, the RF fields of the planar pair and the single loop are perpendicular, and isolation is achieved by mechanical displacement of one of the coils in order to minimize the mutual induction. The major problem for this design is the separate electronics for the two coils. This gives no possibility for capacitively fine adjustment of the isolation, and cable traps are needed to eliminate ground loops via cable shields.

Boskamp (*2*) has presented an improved design (Fig. 1a) which consists of two identical single loops with the currents I_1 and I_2, which are partly overlapping. The isolation is primarily set by mechanical adjustment of the overlap between the coils, thus minimizing the mutual inductance. As the two coils have a common ground, it is possible to fine adjust the isolation by changing the electronic symmetry with capacitors. The common ground also eliminates the need for cable traps. Both the single-loop and planar-pair combination (*1*) and the dual-loop coil (*2*) are less suitable for a flexible design, since the mutual inductance, and accordingly also the isolation, depend on the bending angle of the coil.

Lee and Boskamp (*3, 4*) have described a dual-mode coil (Fig. 1b) which is especially suitable for a flexible design. This coil has two modes, the series mode I_1, and the parallel mode I_{2A} and I_{2B}. For this design, the mutual inductance is minimized for all coil shapes as long as the geometry of the coil is symmetric around the center conductor. The isolation between the modes can be finely adjusted by tuning the balance between C_1 and C_2. To maintain the isolation, the two connection points of the single loop to the center connector must be at virtual ground during operation. This is rather difficult to accomplish if a capacitive match circuit is used. In Ref. (*4*), two capacitive tune-and-match circuits are shown, a passive and an active circuit. Besides being rather complicated, both circuits suffer from the problem that there

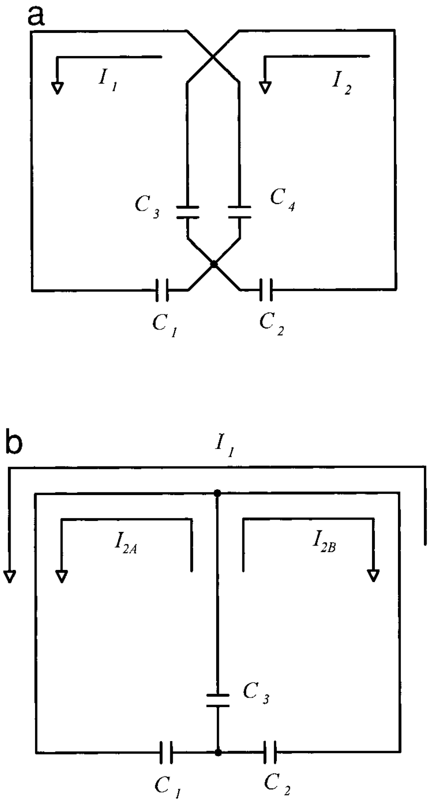

FIG. 1. (a) Dual-loop planar quadrature coil consisting of two identical single loops with the currents I_1 and I_2. The two coils partially overlap. The isolation is adjusted by this overlap and by capacitively changing the electric symmetry. (b) Dual-mode planar quadrature coil. This coil has two modes, the series mode I_1, and the parallel mode I_{2A} and I_{2B}. If the coil is symmetric around the center connection, and the two connection points of this connection to the outer loop are at virtual ground, the two modes are fully isolated. The isolation can be finely adjusted at the balance between C_1 and C_2.

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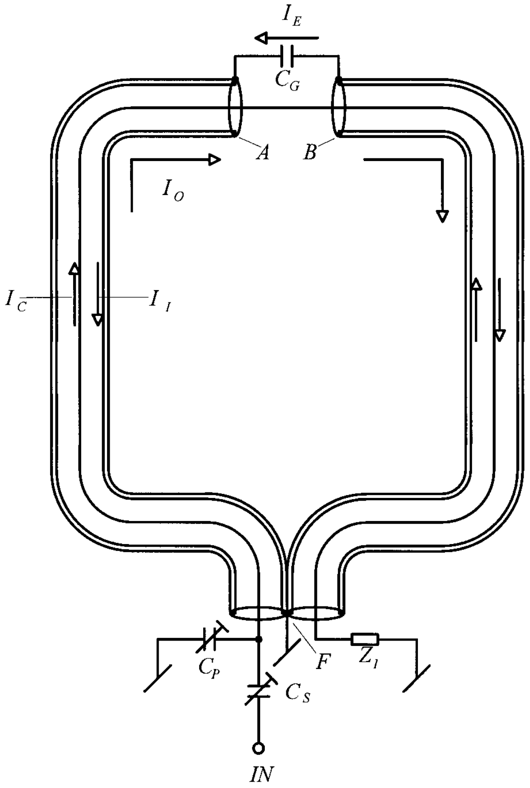

FIG. 2. Shielded-loop resonator consisting of a loop of coaxial cable. The two ends of the loop are connected to a common ground *F*. Opposite to the ground connection there is a tiny gap between *A* and *B*. C_G is mounted across the gap. The tune-and-match circuits C_P and C_S are connected to one end of the loop, and an impedance Z_1 is connected to the other. The electrical currents in the inner conductor, the inner side shield, the outer side shield, and the C_G are I_C, I_I, I_O and I_E respectively.

is no common ground for the two modes, which gives rise to Q problems. Also cable traps are needed to eliminate ground loops via the cable shield. If an inductive match circuit is used, establishing a virtual ground at the two connection points is quite easy. Inductive match, however, leads to an increase in inhomogeneity at high coil loads, and the solution is therefore not optimal.

The advantage of using shielded-loop resonators for surface coils has been described previously (*5, 6*). A shielded-loop resonator with an unbalanced tune-and-match circuit is balanced independently of the load.

In this paper, it will be demonstrated that the shielded-loop technique may also be used to improve the design of planar quadrature coils. A dual-mode resonator (*3*) designed with shielded-loop resonators has a simple tune-and-match circuit and a common ground for the modes; cable traps are thus not needed. A dual-loop resonator (*2*) can be designed with resonators balanced independently of loads.

METHOD

A shielded-loop resonator with one gap and unbalanced tune and match is shown in Fig. 2. This circuit, which has been analyzed in detail previously (*6*), consists of a loop of coax cable, where the two ends are connected to a common ground *F*. It has a tune-and-match circuit, C_P and C_S, at one end, and a termination, Z_1, at the other. This termination is typically a small capacitor or an open circuit. Opposite to the ground connection there is a tiny gap *A*,*B* in the shield. A current I_C flows in the inner conductor of the cable, and a current I_I of opposite direction flows in the inner side

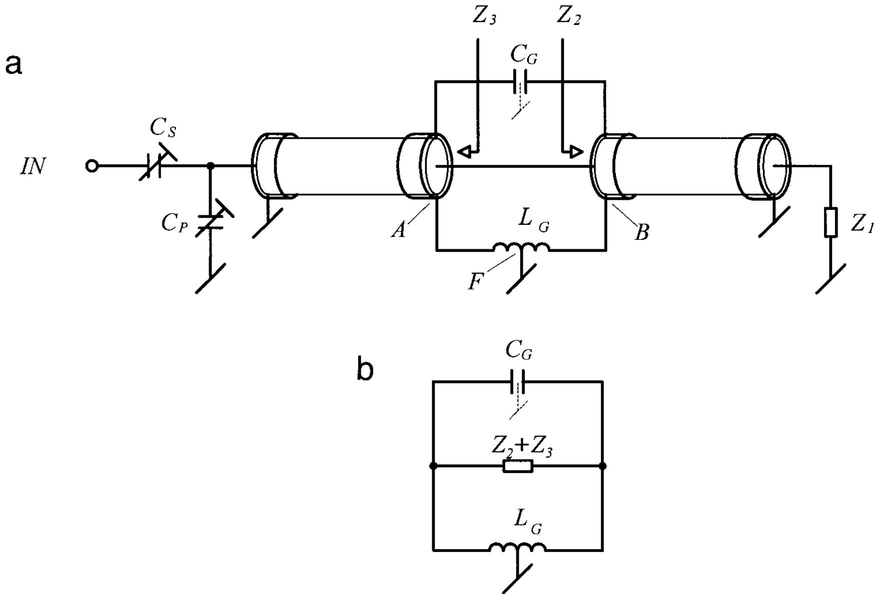

FIG. 3. (a) Equivalent electric circuit for the shielded-loop resonator in Fig. 2. The two cables are connected to C_G and L_G, where L_G is the inductance of the outer side of the loop. The cables are shown with both inner and outer side shields; both outer sides are broken since this current path is included in L_G. (b) Simplified circuit for Fig. 3a where the impedances Z_2 and Z_3 of the cables have been combined into one impedance across the gap.

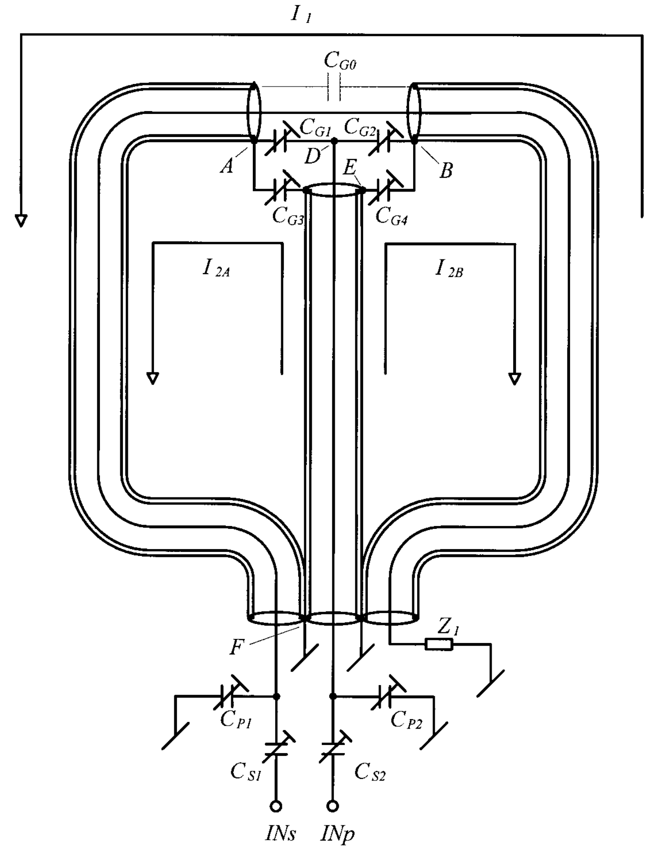

FIG. 4. Shielded-loop dual-mode quadrature circuit for $f < f_S(\text{loop})/2$. The series mode (I_1) has a tune-and-match circuit C_{P1} and C_{S1}, and the parallel mode (I_{2A} and I_{2B}) has the tune-and-match circuit C_{P2} and C_{S2}. Both modes have a common ground connection F, and due to the symmetry around the center cable and the series-mode virtual ground at D and E, there is isolation between the modes. The isolation can be finely adjusted by the balance between C_{G1}, C_{G2} and C_{G3}, C_{G4}.

of the cable shield, except, of course, in the gap region between A and B, where this current path is broken. The current I_I is forced to flow via the gap capacitor C_G (I_E), or via the outer side of the cable shield (I_O), which will function as an inductor L_G.

In Fig. 3a is shown the equivalent circuit for the shielded-loop resonator of Fig. 2. The two cables are shown with both the inner side and the outer side of the shield. The current paths on the outer side are broken, which is, of course, not the case for the resonator in Fig. 2. In the equivalent circuit, however, these current paths are included in the inductance L_G instead. In all other respects, the equivalent circuit exactly reflects the connections of the resonator in Fig. 2. The center of the inductor L_G is connected to ground, and because of the symmetrical geometry there is also a virtual ground at the center of the capacitor C_G. L_G and C_G are connected to the two impedances Z_2 and Z_3, which are the input impedances to the two cable ends. By combining Z_2 and Z_3, the equivalent circuit may be simplified to that shown in Fig. 3b. If the tune-and-match circuit is adjusted, Z_2 and Z_3 will change, and hereby the frequency or the Q factor of this circuit may be changed, but it will have no influence on the two ground potentials at the center of L_G or C_G. This effect makes the circuit suitable for use in the series mode of a dual-mode quadrature resonator.

For dual-mode operation, a center conductor and a tune-and-match circuit must be added to the circuit. The circuit in Fig. 4 may be used for this purpose. In this circuit, the gap capacitor is split into two pairs C_{G1}, C_{G2} and C_{G3}, C_{G4}, and a cable is added for the parallel mode. The inner conductor of the cable is connected to the center D of one pair of capacitors, and the shield is connected to the center E of the other pair. This circuit has two modes (*3*), the series mode I_1, and the parallel mode I_{2A} and I_{2B}. Both modes have a common ground connection F and unbalanced tune-and-match circuits. The isolation can be finely adjusted by tuning the balance between C_{G1}/C_{G2} and C_{G3}/C_{G4} in order to obtain a virtual ground at D and E. It is normally sufficient to make only one of the pairs adjustable. Whether it is necessary to adjust both pairs or only one will depend on the accuracy of the geometry, the components, and the requirements for the isolation. An optional capacitor C_{G0} is mounted directly across the gap A,B.

The equivalent circuit for the two modes is shown in Fig. 5. The series-mode equivalent circuit in Fig. 5a is almost the same as that shown in Fig. 3a. All the capacitors across the gap will add into one with a resulting value, C_G. The resonator is tuned locally by this capacitor C_G and the impedance Z_2, and remotely by C_{P1} and C_{S1}. The center cable is not included since it is connected to D and E, which are at virtual ground in the series mode. The parallel-mode equivalent circuit is shown in Fig. 5b. The inductors L_{P1} and L_{P2} are the inductances of the two coupled inner loops. The resonator is tuned locally by C_{G1}, C_{G2} and C_{G3}, C_{G4}, and remotely by C_{P2} and C_{S2}. The optional capacitor C_{G0} is not included in this circuit, since it is connected to A and B, which are at equal potential in the parallel mode.

While the series mode has a ground potential at the center of the loop, and consequently is well balanced, the voltage distribution in the loop pair of the parallel mode is more complicated. The loop pair also have a ground at F, but the mean voltage between E and A,B will depend on the inductance of the conductors ‘‘F to A,B’’ and ‘‘F to E’’ and their respective currents. The inductance of F to A,B will be higher than F to E for a planar pair, but the current in F to E will be twice as high as each of the currents in F to A,B. Therefore, it should be possible to balance the two inductors L_{P1} and L_{P2} as indicated in Fig. 5b. As the inductors are balanced, there will also be a virtual ground at the center of the capacitors C_{G3} and C_{G4}. If size requirements for the coil makes it slightly unbalanced, loss due to interaction with the sample will increase, but will not influence the isolation.

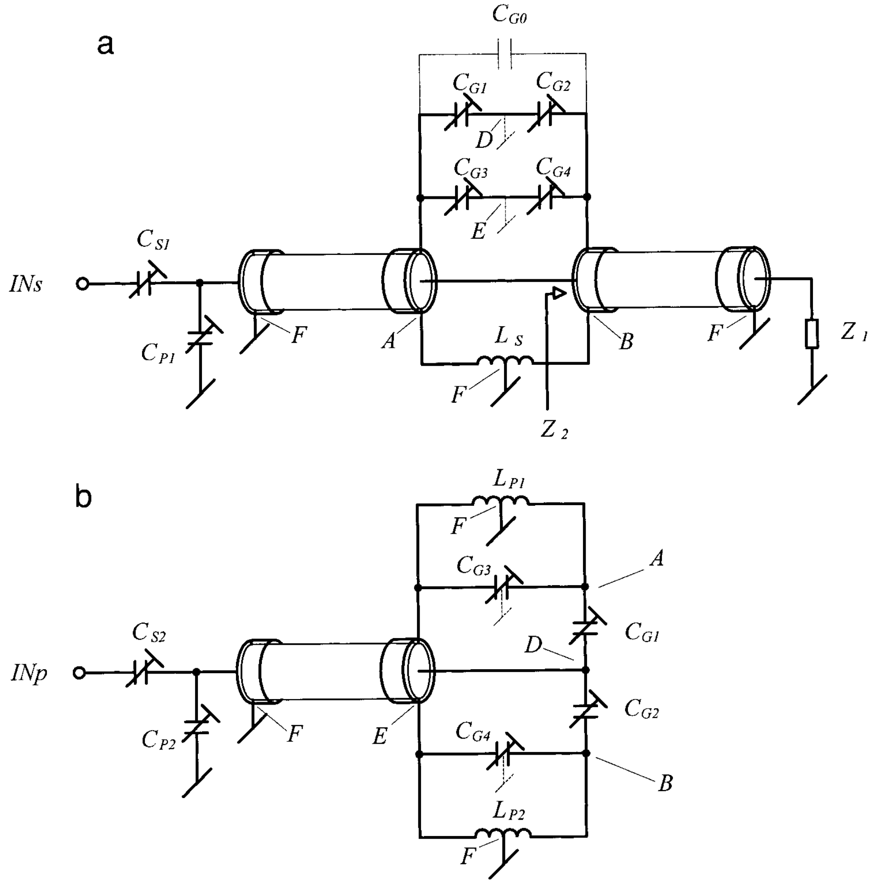

FIG. 5. (a) Equivalent electric circuit for the shielded-loop dual-mode resonators series mode in Fig. 4. Since all the capacitors C_{G0-4} combine into one resulting value C_G, this circuit is equivalent to that in Fig. 3a. (b) Equivalent electric circuit for the shielded-loop dual-mode resonator parallel mode in Fig. 4. The inductors L_{P1} and L_{P2} are the inductance of the two coupled inner loops. C_{G0} is not included in this circuit because there is equal potential at A and B.

With no external components mounted (C_{G0-4}, C_{P1}, C_{S1}, Z_1), the series mode has the resonance frequency f_S(loop). With this configuration, the resonance frequency f_P(loop) of the parallel mode is infinite, because D,E and A,B are not connected. At frequencies much smaller than f_S(loop), the resonances of the two modes depend primarily on the inductance of the loops and the values of the external capacitors, causing the resonances to be close to each other. The inductance of the series-mode loop is approximately twice as great as the induction in each of the parallel-mode loops. This is compensated for, as C_G from A to B is half the capacity of each of the parallel mode gaps E,A and E,B. The resonances can be finely adjusted independently by the two remote tuning circuits, although the divergence of the two modes resonances close to f_S(loop) restricts the use of this resonator circuit to frequencies below approximately f_S(loop)/2. The only component that makes it possible to tune the two modes independently, besides the remote tune-and-match circuit, is C_{G0}. Since C_{G0} will lower the resonance frequency of the series mode, this component is rarely used.

If the coil must be used at higher frequencies than f_S(loop)/2, it is necessary to add an inductor across the gap A,B in place of C_{G0}. This component will also only appear in the series-mode equivalent circuit due to equal potentials in the parallel mode, and will have a parallel resonance with the resulting gap capacitor C_G. This will make the resonance frequency of the series mode higher, and make adjustment to the same frequency as the parallel mode possible. For this inductor, it is possible to use a discrete component, but this will give a stray field, and also make the gap region rather crowded. This can be avoided by using a remote component. This is done by mounting a coax cable across the gap A,B and connecting the other end to a suitable impedance. By rearranging the connections in the gap region of the circuit in Fig. 4, it is possible to use the cable end connected to Z_1 for this purpose. The circuit is shown in Fig. 6. In this circuit, the inner conductor of the loop has been split into two, and each of the ends have been connected to the shield of the opposite cable ends A,B. One end is connected directly, and the other end is connected via a capacitor C_{GS}. The cable end

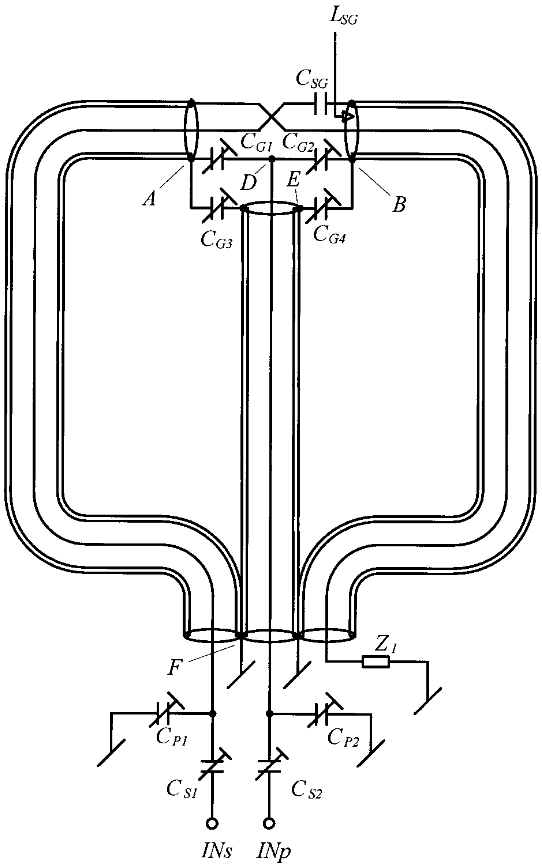

FIG. 6. Shielded-loop dual-mode quadrature circuit with no frequency limitation. In this circuit, the inner conductor of the loop has been split into two, and each of the ends has been connected to the shield of the opposite cable ends A, B. The cable end with Z_1 is connected across the gap A, B, giving the inductance L_{SG} over the gap.

with Z_1 is connected across the gap A, B, and by adjusting Z_1 and/or the length of the cable, it is possible to adjust for the inductance value L_{SG}, necessary for tuning the circuit to the desired frequency.

In Fig. 7, the equivalent circuit of that in Fig. 6 is shown. The parallel-mode equivalent circuits in Fig. 7b and Fig. 5b are identical, since only changes across the equal potential points A, B have been introduced. In the series-mode equivalent circuit in Fig. 7a, L_{SG} is in parallel with the gap capacitors, and C_{GS} is the local match capacitor. With this circuit, it is possible to tune the frequency of the two modes above the loop resonance f_S(loop) of the circuit shown in Fig. 4.

It is also possible to use shielded-loop technique for dual-loop quadrature resonators (*2*). This is very simply done by making two separate shielded-loop resonators with a common ground and partly overlapping loops. This will not normally be a good solution, due to the thickness of the coax cable used for the loops. This problem may be circumvented using foil elements instead of the cables opposite to the tune-and-match circuits. The circuit is shown in Fig. 8. This resonator has the same advantages of a dual-loop resonator, and some of the advantages of the shielded-loop resonator. The advantages maintained from the original circuit are common ground for the two loops, no need for cable traps, and capacitive fine adjustment of the isolation. The advantages added by using shielded-loop resonators are balancing of the resonators independently of load, and the possibility of a full shielding of the tune-and-match circuit.

RESULTS

One shielded-loop dual-mode resonator and one shielded-loop dual-loop resonator were made in order to test the theory. The coils were applied as transmit/receive coils for ^{1}H imaging and spectroscopy of rat brain at 4.7 T (200 MHz). The planar quadrature resonators could thus be compared with the existing coils for the scanner. At the present, two different coil systems are used for measurements in rat brain

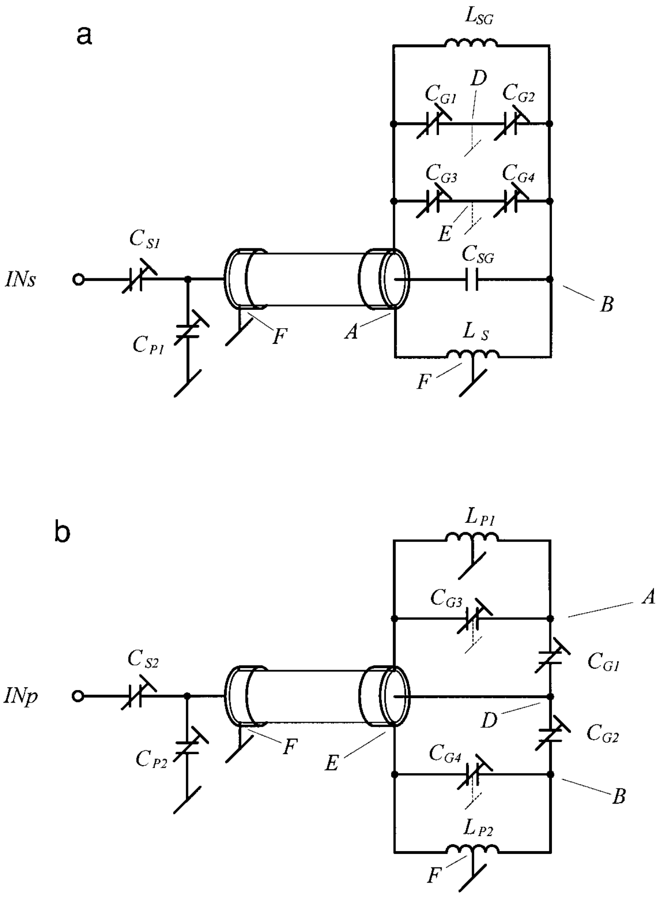

FIG. 7. (a) Equivalent electric circuit for the shielded-loop dual-mode resonators series mode in Fig. 6. L_{SG} is in parallel with the gap capacitors, which will give a higher frequency and make it possible to tune to the same frequency as the parallel-mode frequency. C_{SG} is the local match capacitor. (b) Equivalent electric circuit for the shielded-loop dual-mode-resonator parallel mode in Fig. 6. This circuit is equal to that in Fig. 5b.

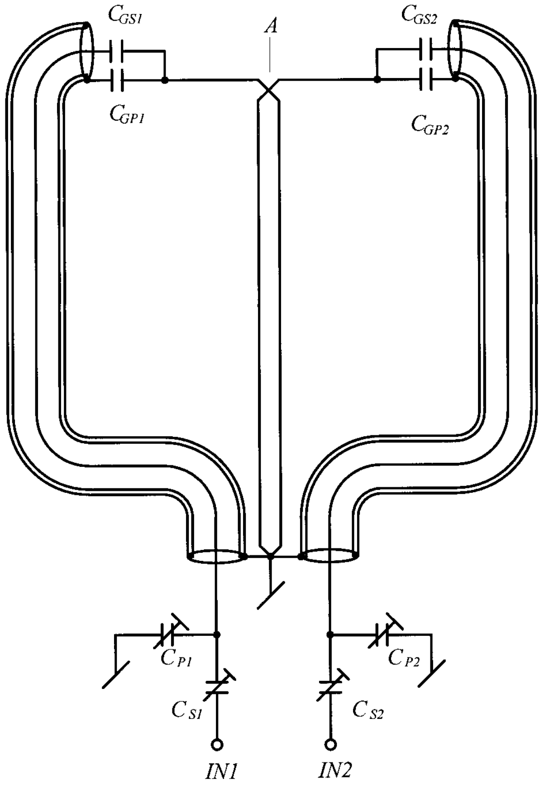

FIG. 8. Dual-loop quadrature circuit with shielded-loop resonators. The cable ends opposite to the tune-and-match circuits have been replaced with foil in order to control the overlap of the two loops. C_{GP1} and C_{GS1} are the local tune-and-match circuit of one resonator, and C_{GP2} and C_{GS2} are the local tune-and-match circuit of the other. As the circuit in Fig. 1b, this circuit has a common ground and no need for cable traps.

using this scanner. The first is a quadrature saddle head coil with a diameter and a length of 40 mm, and the second is a 24 mm diameter shielded-loop receive-only surface coil with a large saddle transmit coil (85 mm diameter and 130 mm length). The head coil has an almost perfect homogeneity over a full slice of the head of the rat, and in a length of ±10 mm from the center of the coil. The receive-only surface coil has a rather poor homogeneity, with a signal variation of approximately a factor of two over the rat brain. The coil sensitivity is approximately better by a factor of two in the central part of the brain, compared with the head coil.

Both planar quadrature coils were made 50 mm wide and 35 mm long. The coils are not fully planar, but are mounted on a section of a 50 mm diameter Teflon cylinder, in order to adapt to the anatomy of the animal. The distance between the loops and the tune-and-match circuit is approximately 60 mm. The materials used for the designs are $\frac{1}{4}$-in. copper foil, RG400 Teflon coaxial cable (1 mm inner conductor and 4 mm shield), ATC chip capacitors, and Voltronics trimmers. The size, and therefore the FOV, of the two planar quadrature coils is smaller than that of the head coil and much larger than that of the receive-only surface coil. If the sensitivity of the two planar quadrature coils was measured to be in between those obtained for the other two coils, it would indicate that the planar quadrature coils were performing according to the theory. Since the sizes of the two planar quadrature coils were similar, only a minor difference in sensitivity between the two coils should be expected, although there are differences in their B_1 profile.

The components used for the dual-mode coil (Fig. 6) were C_{P1}, C_{S1}, C_{P2}, and C_{S2}, 1–15 pF NMNT15E; C_{G1} and C_{G2}, 1–9 pF NMKP10HVNL; C_{G3} and C_{G4}, 10 pF/500V; and Z_1, 60 nH. With this design the electrical parameters measured were unloaded Q factor for series mode, 280; loaded Q factor for series mode, 110; unloaded Q factor for parallel mode, 250; loaded Q factor for parallel mode, 160; and isolation between the two channels, >20 dB. The components used for the dual-loop coil (Fig. 8) were C_{P1}, C_{S1}, C_{P2}, C_{S2}, 1–15 pF NMNT15E; C_{ISO}, 1–9 pF NMKP10HVNL; C_{P1}, C_{P2}, 10 pF/500V; and C_{S1}, C_{S2}, 3.3 pF/500V. The component C_{ISO} is added to the circuit in Fig. 8 for fine adjustment of the isolation. The best position for this capacitor was found to be between the foils at their crossing point (A).

With this design the electrical parameters measured were unloaded Q factor for right loop, 250; loaded Q factor for right loop, 100; unloaded Q factor for left loop, 250; loaded Q factor for left loop, 100; isolation between the two channels, >20 dB.

Both coils were relatively easy to manufacture and adjust, and both were also very uncomplicated to use during the magnetic resonance measurements. The homogeneity and sensitivity of the two coils were very similar. The homogeneity was evaluated with sagittal and axial spin-echo proton density and T_2-weighted imaging using the parameters TE = 16, 50 ms; TR = 1 s; NEX = 2; matrix = 128 × 128; FOV = 40 × 40 mm. Figure 9 is an image obtained with the dual-mode coil, and Fig. 10 is an image obtained with the dual-loop coil. The sensitivity was evaluated with a PRESS sequence. TR for the PRESS was 5 s, TE was 30, 50, 80, 132, and 272 ms, and eight acquisitions were obtained for each TE. The sensitivity of the two coils differed by less than 10% in the central part of the rat brain. Both the electric measurements and the magnetic resonance measurements were done with a 350 g, anaesthetized Sprague–Dawley rat as coil load.

The two planar quadrature coils were also compared with the performance of the two other coils. As expected, the planar quadrature coils did not improve sensitivity compared to the receive-only surface coil. The sensitivity in the central part of the brain was only on average approximately 20% better than the head coil, or 40% worse than the receive-only surface coil. The homogeneity of the two planar quadrature coils was slightly better than the homogeneity of the receive-only surface coil. In contrast to the two exciting

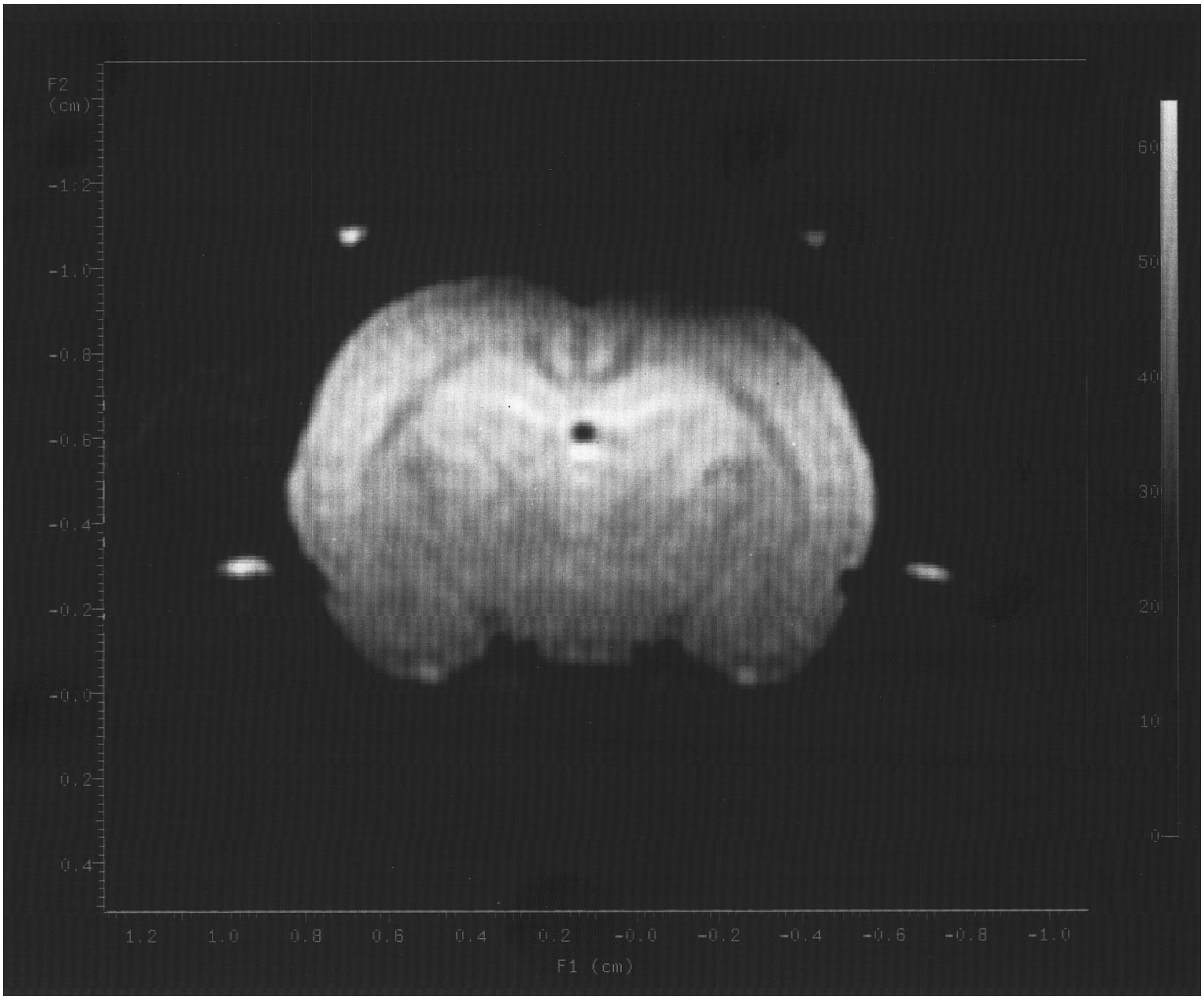

FIG. 9. Axial spin-echo T_2-weighted image obtained with a shielded-loop dual-mode planar quadrature coil (see Fig. 6). The image is obtained on a 4.7 T scanner with the coil used as transmit/receive.

coils, the two planar quadrature coils produce inhomogeneous excitation over their FOV, causing problems with adjustment of the transmit power.

DISCUSSION

It is known that shielded-loop resonators are suitable as surface coils, as their electrical interaction with lossy samples is minimal. In this paper, it is demonstrated that shielded-loop resonators may also be used to improve some of the already known planar quadrature coils. Both a dual-loop coil and a dual-mode coil gain in performance by using the shielded-loop technique, and especially the design of the dual-mode circuit may be much simpler than the original circuit.

The only limitation of using this technology is that it is mainly limited to a one-gap resonator. For a dual-mode coil, this is very important. Only in the one-gap resonator is the virtual ground at the center of the gap capacitor and the isolation accordingly independent of the tune-and-match circuit. For a dual-loop coil, the isolation is no problem, but if more than one gap is used for each loop, the balancing is no longer independent of the load. This behavior of the one-gap resonator is the only significant advantage of this circuit compared with the original circuit. Circuits using other than one-gap resonators are therefore not of interest. For large coil systems, where distributed capacity is vital, a design using shielded-loop resonators, with only two virtual grounds for each loop, will have a higher sample loss compared with a coil system with four or more virtual grounds. Planar quadrature coils using shielded-loop resonators are therefore best for relatively small coils.

A dual-mode coil and a dual-loop coil were made using shielded-loop resonators in order to test the theory. Both

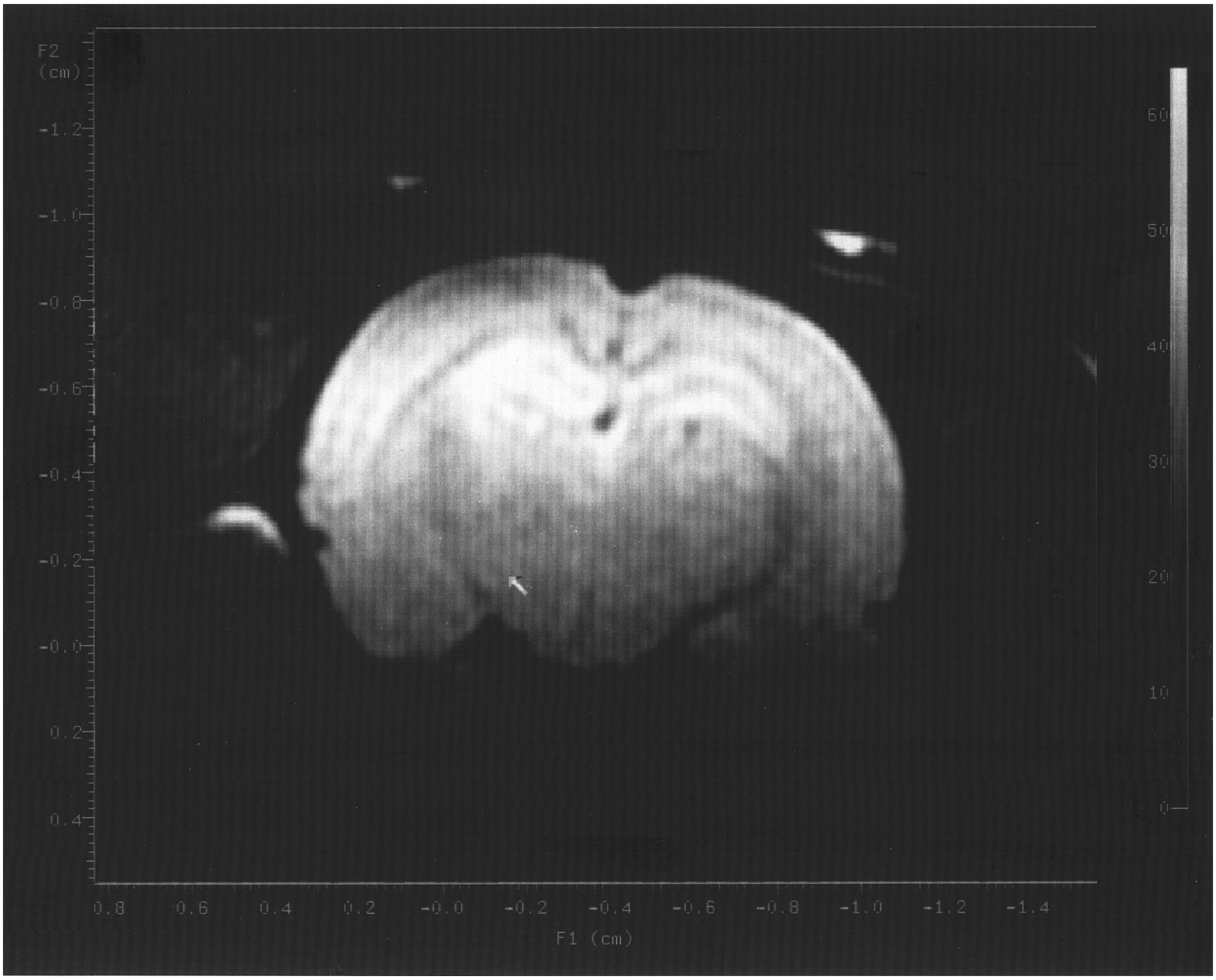

FIG. 10. Axial spin-echo T_2-weighted image obtained with a shielded-loop dual-loop planar quadrature coil (see Fig. 8). The image is obtained on a 4.7 T scanner with the coil used as transmit/receive.

coils were easy to use for magnetic resonance and had satisfactory performance. Although the two coils in the designs presented, as expected, did not improve upon the existing scanner coils, such an improvement might be attained if the planar quadrature coil were designed with smaller size, higher Q factor, and receive-only operation. As this kind of coil system is, however, quite complicated, posing other questions which are entirely outside the scope of this paper, such constructions were not attempted.

REFERENCES

1. J. S. Hyde, A. Jesmanowicz, T. M. Grist, W. Froncisz, and J. B. Kneeland, *Magn. Reson. Med.* **4,** 179–184 (1987).
2. E. Boskamp, J. S. Hyde, and M. Wolski, Abstracts of the Society of Magnetic Resonance in Medicine, p. 4006, 1992.
3. C. T. Lee, R. Pavlovich, and E. Boskamp, Abstracts of the Society of Magnetic Resonance in Medicine, p. 524, 1990.
4. E. Boskamp and C. T. Lee, U.S. Patent 5,030,915, 1991.
5. M. D. Harpen, *Magn. Reson. Med.* **32,** 785–788 (1994).
6. A. Stensgaard, *J. Magn. Reson. A* **122,** 120–125 (1996).