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RECEIVE-ONLY SURFACE COIL WITH IMPROVED DETUNING FOR PRE-CLINICAL MRI STUDIES*

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DISCLAIMER

Receive-Only Surface Coil with Improved Detuning for Pre-Clinical MRI Studies

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Abstract- Receive-only surface coils are typically detuned during the transmit phase using a PIN diode switch which opens the loop. A different detuning method described in this paper uses a blocking resonator, which has the advantage of moving the loss of the switching element off the signal path. A detuning coil using an optically actuated MOS switch (PhotoMOS) or a MEMS electrostatically actuated switch is described. The coil features an improved quality factor (Q) and better detuning performance. Test images obtained in a 9.4T MRI machine are presented.

I. Introduction

Surface receive-only coils for MRI are often used for high resolution MRI imaging to detect the signal produced by a larger (typically birdcage) coil. First described by G. Suryan in 1951 for NMR, a surface coil consists of a conductive loop (an inductor in the equivalent circuit model) creating a resonant circuit by means of one or more capacitors in series. The advantage of this configuration is that the receiving sensitivity is high (large filling factor, coil located near sample) while the excitation is very homogeneous.

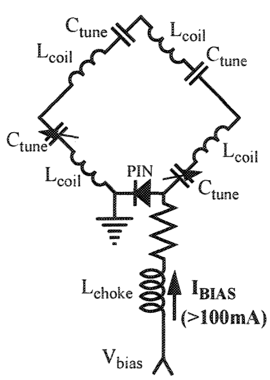

Fig. 1: Equivalent circuit of a typical receive-only surface coil. The coil is split into four section, so that the value of the capacitor creating the resonance falls into an acceptable range. The forward biased PIN diode presents a low impedance and closes the loop during the receive phase. The PIN diode needs to be biased at high current (~100mA) to reduce the loss of the tuned circuit.

Since receive and transmit coils have to be tuned at the same frequency, the coupling between them induces high currents in the surface coil during the transmit phase, which in turn create a magnetic field, thus distorting the B_1 field of the birdcage coil.

To detune the surface coil during transmission a switch is used to shift the resonant frequency away from the Larmor frequency.

A commonly used method is presented in Fig. 1. A PIN diode, forward biased in the receive phase (the coil normal mode of operation), closes the loop. Bias is removed in the transmit phase to open the loop. Other non-magnetic RF switching devices (MEMS switches, which are electrostatically activated, MOS, GaN or SiC transistors used as a switch) could be used, but they often present a higher RF impedance (order of a few ohms), thus spoiling the Q of the coil in tuned mode.

II. Blocking Resonator Detuning

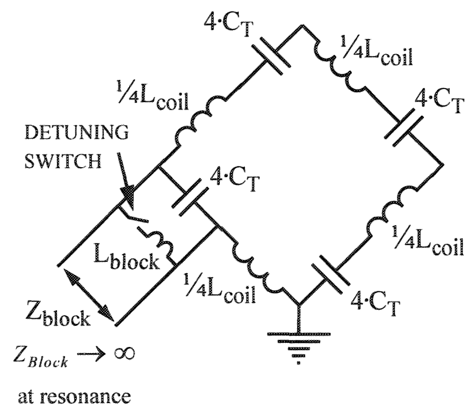

Fig. 2: Blocking resonator principle. It is necessary to detune the coil during the transmit phase to avoid large currents at resonance which distort the field. An inductor L_{block} is switched in parallel to one of the capacitors. The inductor is dimensioned to cancel the capacitor susceptance, thus opening the loop (i.e. introducing a large impedance) at the Larmor frequency.

To improve the quality factor (Q) of the resonant circuit and to allow for a wider selection of switching elements (with less strict low resistance requirements), it is advantageous to

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move the detuning switch off the signal path, which can be achieved using a blocking resonator.

With reference to Fig. 2, in tuned mode (switch in the OFF position), the condition for resonance at the Larmor angular frequency ω_L is:

$$\omega_{res} = \omega_L = \frac{1}{\sqrt{L_{COIL} \cdot C_T}}$$

The idea of a blocking resonator is to create a parallel resonant circuit which will feature a very high impedance (ideally infinite, an open circuit) at the resonant frequency.

For detuning, an inductor L_{block} is switched in parallel to one of the tuning capacitors. The impedance thus created is:

$$Z_{BLOCK} = \left(\frac{1}{j\omega C_T}\right) \text{parallel } (j\omega L_{BLOCK})$$

$$= \frac{j\omega L_{BLOCK}}{1 - \omega^2 L_{BLOCK} \cdot 4C_T} \rightarrow \infty \text{ for } L_{BLOCK} \rightarrow \frac{1}{4} C_T$$

III. Switches for High Magnetic Field MRI

Standard magnetic relays cannot be used in the presence of a magnetic field $\overline{B}$, but most electronic switches are unaffected.

PhotoMOS (also known as OptoMOS) and MEMS (Micro Electro Mechanical Systems) switches are particularly attractive. They feature:

- small size
- low power to activate
- galvanic isolation of the control and RF path
- acceptably low closed impedance (a few ohms, or less)

A. MEMS Switch

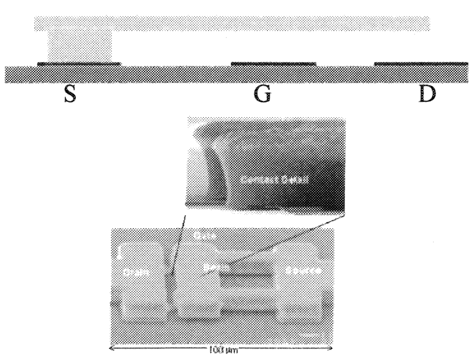

Fig. 3: 4: A MEMS (Micro Electro Mechanical System) switch is actuated by an electrostatic force, and thus capable of operation in a high magnetic field. (a) Principle of operation (b) Microphotograph of the contact and the thin gap over the gate for electrostatic operation.

A MEMS (Micro Electro Mechanical) switch is a relay actuated by an electrostatic force, and thus capable of operation in a high magnetic field. Fig. 4 shows the principle of operation: a cantilevered beam is deflected by a voltage applied on the gate terminal (90-100V) and closes the circuit between Source and Drain terminals. The microphotograph shows the contact detail. MEMS switches are capable of over one billion actuation cycles. The contact resistance is specified at <2Ω, with only a slight deterioration over the lifetime. The open impedance is almost ideal with very high ohmic resistance and a fraction of picofarad stray capacitance.

B. PhotoMOS Switch

A PhotoMOS switch is a MOS based optically activated switch which features full galvanic isolation between the control circuit and the switch itself. Fig. 3 illustrates the circuit: an LED, biased at I_L=1-2mA shines light on several photodiodes connected in series, which in turn provide the gate voltage to bias the DMOS switches on. Since the DMOS switch has a parasitic diode connected between its source and drain, two DMOS switches in series, with their source terminal connected together, are necessary for AC operation in order to have at least one of the two parasitic diodes in the reverse bias condition. For high frequency MRI coil, PhotoMOS with low parasitic output capacitance are necessary. The Panasonic AQY221N3M has an R_{ON}=4Ω and C_{out}<1pF.

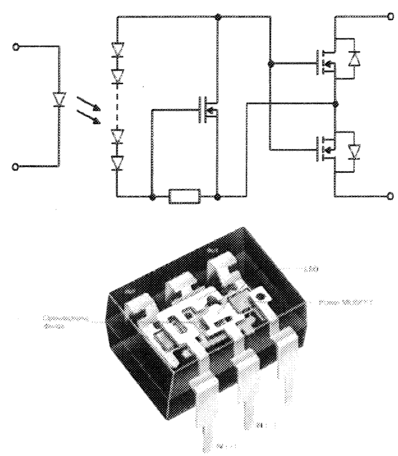

Fig. 4: PhotoMOS: an LED illuminates several photodiodes in series, which in turn create a control voltage for the output N-DMOS. Since the DMOS has an intrinsic parasitic diode connecting S-D, a second DMOS is necessary for AC operation. As shown in b) there is complete galvanic isolation between the control and the RF side. The Panasonic AQY221N3M has an R_{ON}=4Ω and C_{out}<1pF.
(Photo and circuit schematic from Panasonic datasheets [2]).

C. Comparison of Switches for MRI Coil Detuning

Table 1 compares the key characteristics of RF switches for detuning an MRI probe. Although the PIN diode still features the lowest RF impedance (just a fraction of an ohm at high bias current of 100-200mA) and is therefore the king for any switching operation involving the signal path, MEMS and MOS switches are suitable for switching in detuning circuit element. Their main advantage is the lower power and their galvanic isolation which allows for the removal of the RF choke necessary for biasing a PIN diode.

PIN DIODE	PHOTOMOS	MEMS
low DC R (~0.1Ω)	higher R (Ωs)	slightly higher(~0.5Ω)
very fast (ns)	fast (μs)	fast (~20ns)
can be used in signal path	cannot be used in signal path	can be used in signal path
choke required	no choke	no choke
high power (~100mW)	low power (mW)	No power (nW)
higher OFF C	small OFF C (~1pF)	negligible C
non isolated	isolated	isolated
small (but choke...)	small	very small
long lifetime	long lifetime	long lifetime (small degradation over 10^9 cycles)
low control V (high I)	low control V	high control V (~100V)

IV. Probe Construction and Characterization

Fig. 5 shows the 4cm surface probe with MEMS switch

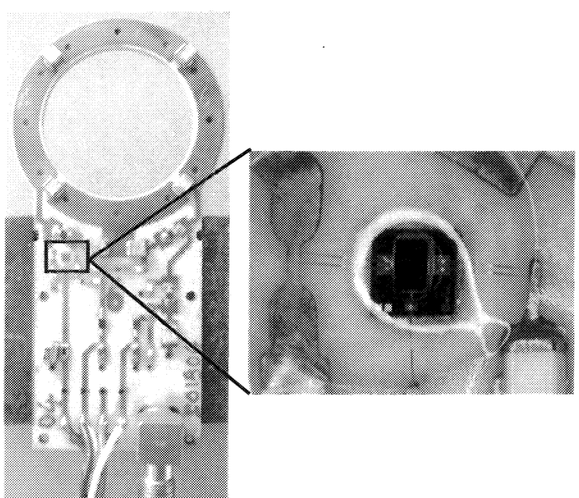

Fig. 5: Assembled 4cm surface probe with wire bonded MEMS switch.

detuning. It is constructed as a PCB on Rogers R3000 material. The MEMS (Radant MEMS RMSW101 [3] is wire bonded to the PCB and protected with a clear encapsulant. The construction of the PhotoMOS detuned probe is very similar, but assembly is easier since the switch is packaged (Panasonic AQY221N3M [2])

A. Tuning

Fig. 6 shows the unloaded (disconnected from 50Ω termination) quality factor Q measured by the two probe method. By removing the switch resistance off the signal path the Q is improved by about 30%.

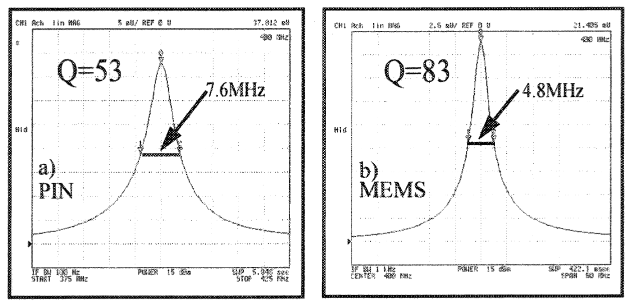

Fig. 6: Unloaded Q of: a) commercial PIN-diode detuned 4cm surface probe and b) MEMS switch detuned probe measured with the two probes method. By removing the switching element (and its small but finite resistance) off the signal path, the Q is improved by >30%.

B. Detuning

Thanks to a full galvanic isolation between the signal and control path and to an almost ideal switching characteristics (high OFF resistance, low stray capacitance) the resonance peak is moved more than 50MHz off the Larmor frequency, completely eliminating image artifacts due to non-uniform excitation field.

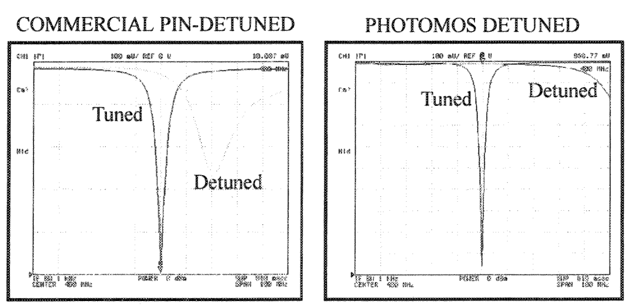

Fig. 7: 6: Tuned and detuned Γ (reflection coefficient) of:
a) PIN-detuned commercial probe and b) PhotoMOS detuned probe using a blocking resonator detune circuit. The energy coupled into the receive probe during transmission causes image artifacts. The blocking resonator method is virtually an open circuit at the Larmor frequency.

C. Comparison of MEMS and PhotoMOS Probes

Fig. 8 shows a phantom image obtained with both the MEMS switch detuned and the PhotoMOS detuned probes in a 9.4T MRI machine. Even a more detailed evaluation of the images confirms what is also apparent from the picture: that the two types of detuning methods are equally good and the probes performance is identical.

a: MEMS probe b: PhotoMOS probe

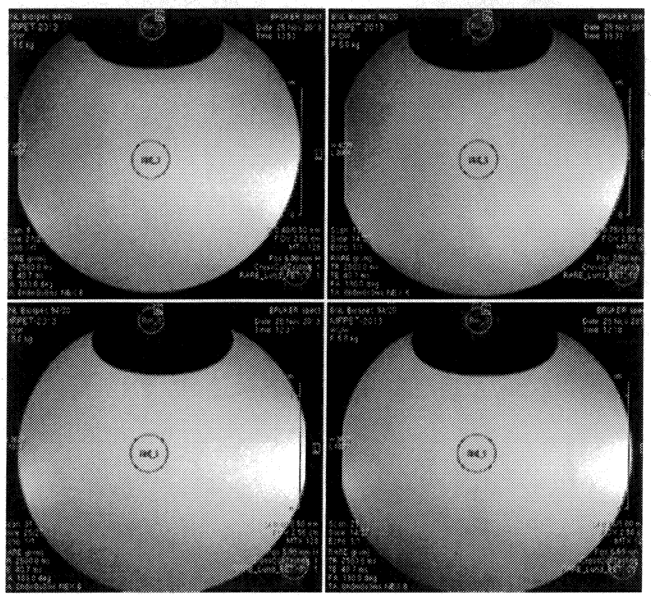

Fig. 8: Phantom images obtained with: a: the MEMS switch detuned probe and b: the PhotoMOS detuned one in a 9.4T MRI machine

D. Mouse Brain Test Images

Fig. 9 compares a mouse brain image taken with a reference high resolution 2cm coil with an image obtained with the 4cm PhotoMOS detuned coil. The 4cm coil shows the same resolution and level of detail of the smaller coil, with a wider field of view. No artifacts which were very noticeable with the commercial 4cm PIN detuned coil due to poor detuning characteristics are visible.

V. Conclusions

The blocking resonator detuning method (using either a PhotoMOS low-capacitance switch or a MEMS switch), has improved the detuning characteristics (and the Q) of a 4cm surface coil used for pre-clinical animal studies. The full galvanic isolation of the control and RF path allows the elimination of the bulky choke coil necessary to bias a PIN diode switch. The miniaturization of the control circuitry and the good performance demonstrated makes this method attractive for coil arrays which could further improve the S/N ratio and allow faster acquisition time. The two types of detuning devices perform equally well, and at the present stage the PhotoMOS, which consists of a packaged component, is more convenient to use than the MEMS switch, which needs to be wire bonded and encapsulated to protects the fragile bond wires.

a: 2cm HEX Probe b: 4cm PhotoMOS Probe

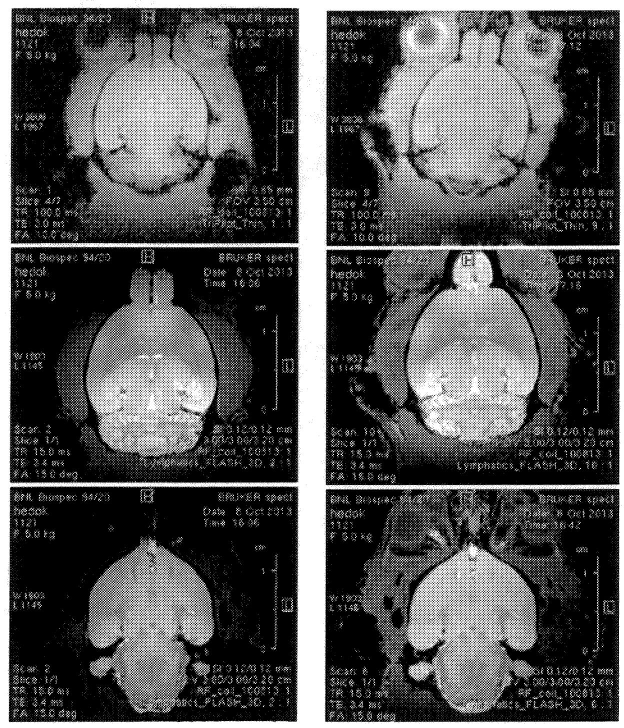

Fig. 9: Mouse brain imaged in a 9.4T MRI system under identical conditions. a: Reference 2cm hexagonal surface probe, PIN detuned; b: 4cm, PhotoMOS detuned

VI. Acknowledgments

The skillful help of John Triolo in assembling the probes and of Donald Pinelli in wire bonding and encapsulating the MEMS devices is gratefully acknowledged.

VII. References

[1] Suryan, G. "Nuclear resonance in flowing liquids." In Proceedings of the Indian Academy of Sciences-Section A, Vol. 33, No. 2.

[2] Radant MEMS RMSW221 datasheet, retrieved from http://www.radantmems.com/radantmems.data/Library/RMSW101.pdf on 22 Nov. 2013

[3] Panasonic AQY221N3M datasheet retrieved at http://pewa.panasonic.com/assets/pcsd/catalog/aqy-son-c-x-r5-catalog.pdf on 22 Nov. 2013