Shielded Current Sensors for Monitoring Parallel Transmission

Karl Edler[1], Marie-France Hang[1], Alexis Amadon[1], Nicolas Boulant[1], Martijn A Cloos[1], and Christopher J Wiggins[1]
[1]*NeuroSpin/I2BM/DSV/CEA, Gif-sur-Yvette, France*

Introduction

An accepted strategy for producing a uniform spin excitation at magnetic field strengths at and above 7 T is to produce the $B1^+$ field using multiple coil elements in a parallel transmission array. A uniform excitation can be achieved by a judicious choice of current waveforms for the various coil elements [1-2]. As in all RF-excitation pulses, care must be taken to limit the SAR and temperature rise of the patient's tissues both locally and globally. However in the case of parallel transmission, the multiplicity of coil elements and their interactions complicates the situation. If the transmit field deviates appreciably from the calculations that were used to ensure patient safety – possibly because the patient has made an extreme and unforeseen move within the coil or the coil has been somehow damaged – then an injury may result. For this reason it is desirable to stop the scan if the currents transmitted into the coil elements deviate appreciably from their intended values. Due to inter-element coupling, however, the outputs of the RF amplifiers are not a direct measure of these currents. Thus, as a first step towards continuous RF current monitoring on a parallel transmit array, we have used inductive current sensors connected directly to loop coil elements and the existing receivers to simultaneously monitor the currents during transmission on a Siemens 7 T MRI.

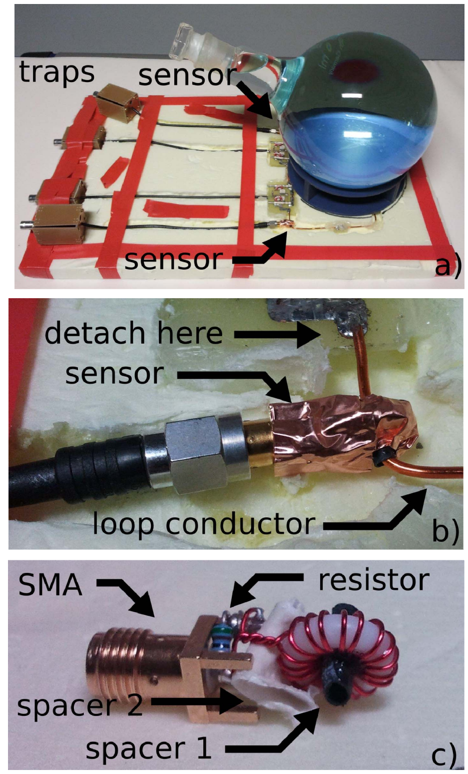

Figure 1: Part a) shows the both transceiver loops with the phantom and cable traps. Part b) is a close-up of a sensor connected to its loop and part c) shows a sensor without its shield.

Materials and Methods

Two loop coil transceiver elements were constructed as shown in figure 1a) with lattice baluns integrated into their matching circuits and tunable cable traps placed approximately λ/4 from the coils. The loop elements were geometrically decoupled by adjusting their overlap in the presence of a phantom until the mutual coupling reached a minimum at -21dB – thus using both mutual inductance between elements and mutual capacitance through the phantom to achieve decoupling. Later phantom placements produced couplings of less than -19 dB.

The toroidal sensing elements [3] shown in figure 1b-c) were each produced by winding 18 turns of AWG 25 magnet wire around a Teflon ring and soldering the winding in parallel with a 50 Ω resistor to a non-magnetic SMA connector. A piece of heat shrink tubing (spacer 1) was then glued in the center of the toroid to provide further insulation from the loop conductor and to ensure mechanical stability; spacer 2 protects the toroid from rubbing against the SMA connector's centre pin. Finally the toroid was shielded with copper tape grounded to the SMA connector's chassis such that only the heat shrink tubing was exposed. To attach the sensor to the coil, the coil's conductor was detached and threaded through the heat shrink tubing. The advantages of this sensor design are that it is easy to attach, it is approximately matched to 50 Ω, and it is strongly coupled to the coil conductor but only weakly coupled to anything else; both the toroidal nature of the winding and the copper shielding reduce external couplings. Tunable cable traps were used on both the loop transceiver elements and the sensor cables to minimize common mode couplings.

a) Measured Port Impedances

$f_0 = 297.18$ MHz	Loop 1	Loop 2	Sensor 1	Sensor 2
Input Impedance Ω	$51.8 - 0.11j$	$52.0 + 1.7j$	$52.4 - 6.2j$	$58.6 - 9.0j$

b) Measured Couplings

$f_0 = 297.18$ MHz	Loop 1	Loop 2	Sensor 1	Sensor 2
Loop 1		−21.7 dB	−21.6 dB	−46.5 dB
Loop 2			−42.8 dB	−24.3 dB
Sensor 1				−67.3 dB

c) Computed from Measurements in b)

Loop 1 to Sensor 2	-21.7 dB $- 24.3$ dB $= -46.0$ dB
Loop 2 to Sensor 1	-21.7 dB $- 21.6$ dB $= -43.3$ dB
Sensor 1 to Sensor 2	-21.7 dB $- 21.6$ dB $- 24.3$ dB $= -67.6$ dB

Table 1: Parts a) and b) show the impedances and couplings as measured with a network analyzer while part c) gives the calculated sensor interactions assuming that a sensor only has a direct coupling to its associated loop.

Results & Discussion

Table 1 gives the measured coupling coefficients between the loop elements and their sensors in the presence of a phantom. If we assume that the sensors only respond to current in their respective loops then any coupling between sensors or between a loop and a sensor on another loop must be mediated solely by the interaction between loops. Table 1c) shows the indirect couplings computed using this assumption and the results agree with the measured values to within 0.5 dB. As a qualitative evaluation of the sensors' shielding, we measured S_{21} at 297.18 MHz between a sensor's cable trap connection and a 1 cm magnetic loop probe placed directly on the sensor's shield. This coupling was always below -50 dB but was between -60 and -70 dB for most loop orientations. For comparison, the coupling from the same loop to the outside of a RG58 cable terminated with a 50 Ω load was always below -60 dB but usually between -70 and -80 dB. Thus the sensor's shielding is only somewhat worse than that of RG58 cable.

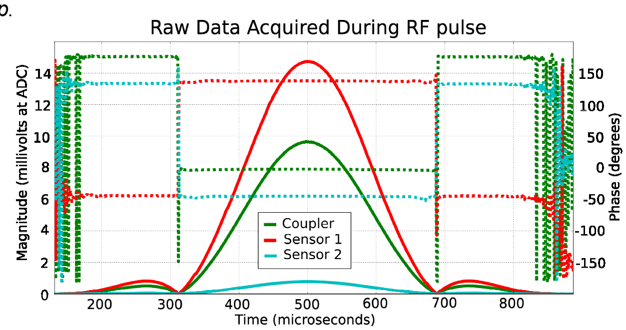

Figure 2: Signals acquired during the transmission of a sinc pulse on loop 1.

The loop coil elements were connected to a Siemens 7 T MRI as transceiver coils through the usual combination of a TR switch and preamplifier. However on the sensor channels the TR switches were set to the receive state and the preamplifiers were replaced with -50 dB attenuators which adjusted the sensed signal into the dynamic range of the analog to digital converters. For comparison with these sensor signals, the forward power was also detected with a directional coupler integrated into an RF power amplifier and was digitized with a free receiver channel. Figure 2 shows the digitized signal from the directional coupler compared with those from each sensor. Note that currents flow in both loops despite power only being applied to loop 1 and that the sensor signals are not distorted – as can be verified by scaling them to the same magnitude.

In most – if not all – MR coils, the number of receive channels is greater to or equal than the number of transmit channels but the receivers are not needed during transmission. Thus in the future, receiver channels could be used to monitor current sensors during transmission as well as to collect the MR signal through the preamplifiers.

References

1. Zhu, *Magnetic Resonance in Medicine*, **51** 775-784 (2004)
2. Ulrich Katscher, Peter Börnert, Christoph Leussler, and Johan S. van den Brink, *Magnetic Resonance in Medicine*, **49** 144-150 (2003)
3. D. I. Hoult, D. Foreman, G. Kolansky, and D. Kripiakevich, *Magnetic Resonance Materials in Physics, Biology, and Medicine* **21** 15-29 (2008)