Unconventional Designs of RF Probes for High-Field MRI to Enhance Magnetic Field Uniformity

Navid P. Gandji, Bahram Seifi,
and Elena Semouchkina
Department of Electrical and Computer Engineering
Michigan Technological University
Houghton, MI, USA
esemouch@mtu.edu

Gangchea Lee[1], Seokwon Jung[2], Michael Lanagan[3],
and Thomas Neuberger[1,4]
[1]Department of Biomedical Engineering
[2]Department of Mechanical Engineering
[3]Department of Engineering Science and Mechanics
[4]The Huck Institutes of the Life Sciences
The Pennsylvania State University
University Park, PA, USA

***Abstract*—We present approaches to enhancing magnetic field uniformity produced by RF probes in high-field Magnetic Resonance Imaging (MRI) scanners by introducing compensating non-uniformities in the probe designs. Unconventional designs of RF probes for operating at 600 MHz in 14 T MRI scanners are demonstrated, including a solenoid coil with non-uniform wrapping and dielectric separators, a system of microstrip patch antennas with substrates engineered by using high permittivity inserts, and a system of specifically shaped patch antennas. The advantages of the proposed probe designs are discussed.**

I. Introduction

The main advantage of high-field Magnetic Resonance Imaging (MRI) scanners is their potential to provide higher signal-to-noise ratio and, consequently, improved spatial and/or temporal resolution. MRI systems that employ 14 T to 20 T static magnetic fields B_0 are expected to significantly advance preclinical imaging. Employing thus high magnetic fields requires radio frequency (RF) coils generating an oscillating magnetic field B_1 to operate at frequencies of 600 MHz to 850 MHz. The performance of conventional coil probes, however, degrades at higher frequencies, since the wavelength becomes small compared to coil dimensions, so that wave phenomena take place. As the results, obtaining a spatially homogeneous magnetic field over a larger field of view that is required for high image quality becomes extremely challenging [1].

In this work, we propose approaches to overcoming the non-uniformity of magnetic field distribution in RF probes for high-field MRI by introducing compensating non-uniformities in the probe designs. The developed approaches are first exemplified by a design of a solenoid coil with non-uniform wrapping suitable for 14 T MRI studies. Incorporating, in addition, dielectric separators inside the coil allowed for controlling its self-resonance frequency and for solving problems with designing the coil matching circuits. Then we present an alternative solution for RF probes operating in 14 T MRI scanners by comprising them from a system of two *vis-a-vis* placed microstrip patch antennas with non-uniform multi-dielectric substrates. Desired small dimensions of the antennas and characteristics of the fields were achieved due to engineering antenna substrates by using inserts of high permittivity dielectric materials. Finally, we propose a system of patch antennas, which have uniform substrates, however, are shaped to conform to the shape of the magnet bore and to equalize magnetic field distribution. Commercial software package CST Microwave Studio was used to perform full-wave electromagnetic simulations.

II. Design Specifics of Unconventional RF Probes for 14 T MRI Scanners

A. *Extended Solenoid Coil with Non-Uniform Wrapping and Dielectric Separators*

Increasing the length of solenoid coil probes, in order to accommodate extended samples, presents a problem in high-field MRI systems. In order to avoid strong non-uniformity and appearance of magnetic field zeros along the coil, its length should not exceed half wavelength of the current wave propagating along the wire. Even in this case, magnetic field distribution along the coil is non-uniform and has a bell-type shape. Another problem is that at increasing the number of turns, the self-resonance frequency of the coil decreases. When it appears below the operating frequency, i.e. below 600 MHz in 14 T systems, the coil has a capacitive type of reactance instead of an inductive one. The solution of the above two problems was found, first, in non-uniform coil wrapping to compensate for the magnetic field non-uniformity [2], and, second, in placing dielectric separators inside the coil, to decrease its total capacitance and increase the self-resonance frequency. A model of non-uniformly wrapped 14-turn coil with two dielectric separators is presented in Fig. 1.

The coil demonstrated magnetic field homogeneity of 73%, which was 30% higher than that for the uniformly wrapped 14-turn coil of the same 9 mm length along the coil axis. The new coil was confirmed to operate in inductive regime at 600 MHz that allowed for designing a conventional C-C matching circuit. Tunable circuit components allowed for mitigating the changes in coil responses after insertion of samples to be tested.

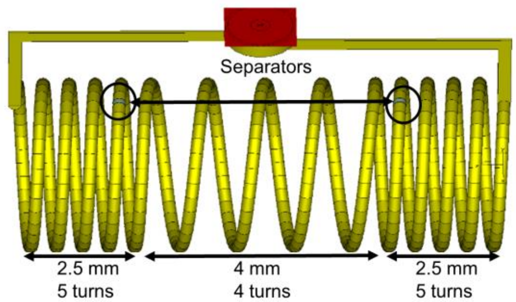

Fig. 1. Non-uniformly wrapped 14-turn coil with two separators. The coil diameter is 6 mm.

B. Patch Antennas with Multi-Dielectric Substrates

A conventional patch antenna with a typical substrate (such as Arlon substrate having ε_r=3) cannot be used as a 600 MHz probe, since its dimensions are too big to fit in the 14 T magnet bore with the diameter of 54 mm. With the purposes of antenna miniaturization and controlling magnetic field distribution above the patch [3], we used a combination of two dielectric materials with low and high permittivity in the antenna substrate. Based on the analysis of simulated near fields produced by the antenna, several designs of miniaturized antennas have been analyzed and the design with four round $SrTiO_3$ inserts (ε_r=300) in 1.6 mm thick FR-4 substrate (ε_r=4.4) has been selected for prototyping. The dimensions of inserts and the location of the feed were optimized to ensure antenna operation at 600 MHz with matched impedance. Fig. 2 presents the schematic of the simulated antenna and the photograph of the fabricated prototype before the feed connector soldering.

(a) (b) (c)

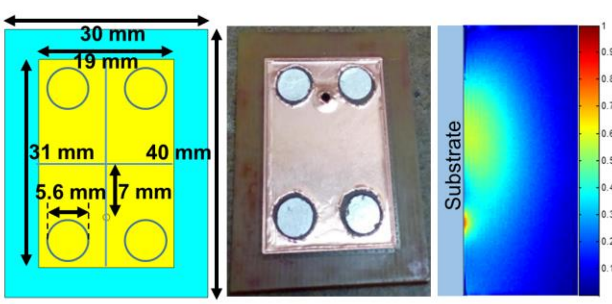

Fig. 2. (a) Schematic of the antenna design, (b) bare antenna before the feed connector soldering, and (c) normalized sagittal MR image of a water phantom.

As expected, the S_{11} measurements demonstrated a dip of -45 dB at the frequency of 600 MHz. The performed imaging (Fig. 2c) with the fully assembled antenna showed it suitability for MRI. To organize a volume of uniform magnetic field, two identical miniaturized patch antennas will be placed *vis-à-vis* in the magnet bore 20 mm apart. Feeding two antennas with 180^0 phase shift results in addition of their magnetic near fields and cancelling electric fields in inter-antenna space. Simulations showed that the uniformity of the magnetic field within the sampling volume with the dimensions $(10 \times 10 \times 10)$ mm^3 placed between two antennas will exceed 90%. Furthermore, the performed simulations demonstrated that due to the nature of the electromagnetic resonance in patch antennas, their operating frequency is practically not effected by the placement of a sample to be tested.

C. Patch Antennas with Curved Shape

The uniformity of magnetic near field of a patch antenna could be increased by modifying antenna shape. Since the shape of magnetic near field distribution in the plane normal to the antenna plane and to the direction of current oscillation in the patch at the half-wavelength resonance is close to cosine function, shaping antenna in a similar way can make the shape of field distribution flat. Fig. 3 presents field patterns above the cosine-shaped patch antenna with 1.6 thick alumina (ε_r=9.4) substrate, which demonstrate improved uniformity of magnetic fields. Field uniformity in an extended area in the yz-plane at half-wavelength resonance oscillation of current along z-axis is provided due to extended antenna dimension along this direction (along the axis of the bore). The two dimensions of the patch and the location of the coaxial feed were chosen to, respectively, fit the antenna to the bore, to ensure its resonance frequency of 600 MHz, and to match the impedance.

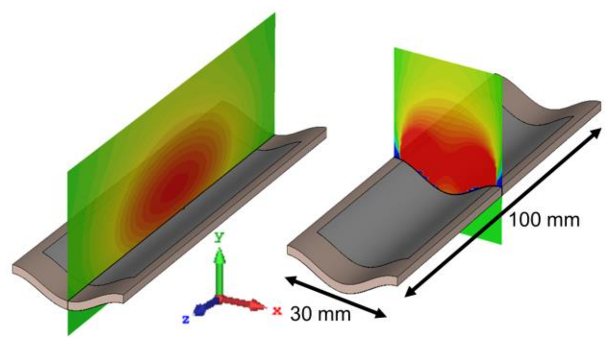

Fig. 3. Distribution of magnetic near field for the antenna with alumina substrate and curved shape.

Similar to the case with multi-dielectric substrates, two identical patch antennas with curved shapes fed with 180^0 phase shift were used to form the RF probe for 14 T MRI.

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