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Study of two contact-less tuning principles for small monolithic radiofrequency MRI coils and development of an automated system based on piezoelectric motor

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ABSTRACT

The Multi-turn Transmission Line Resonator (MTLR) design allows for developing very small and highly sensitive radiofrequency (RF) coils for magnetic resonance imaging. However the monolithic feature and the small size of the developed coils, imposes to employ dedicated contact-free tuning techniques. In this work, we investigated two contact-free tuning principles for small monolithic RF coils: a dielectric tuning principle based on the interception of the electric field lines by a dielectric layer, and an inductive tuning principle based on the interception of magnetic field lines by a closed conducting ring. For both tuning principles, we used experimental measurements co-supported by electromagnetic simulation and analytical modelling to determine the accessible tuning range as a function of both the tuning element's characteristics and its distance to the RF coil. A maximal tuning range about 9% and 24% was achieved using the dielectric tuning principle and the inductive tuning principle, respectively. Contrarily to the dielectric tuning principle, the inductive tuning principle was found to strongly limit the quality factor of the coil. To implement the two investigated tuning principles, we have developed an automated system based on piezoelectric actuators that achieves microscopic displacements of the tuning elements. The automated system was also used to perform inductive impedance matching of the coil. For purposes of both tuning and matching, when starting from a strongly un-tuned or un-matched configuration, the automated system reaches convergence within a few tens of seconds. First MRI experiments were performed to evaluate the MRI compatibility of the automated system.

1. Introduction

Magnetic Resonance Imaging (MRI) provides anatomical and functional information in a non-invasive way and is an essential investigation tool for many biomedical applications.

However, when performing MRI at very high spatial resolution to observe structures at a microscopic scale, the amount of nuclear magnetic resonance (NMR) signal encoded in an elementary voxel is intrinsically low, and the sensitivity of the radio frequency (RF) detection coil is a critical issue, especially at clinical field strength [1]. This sensitivity-based limitation can be overcome by using small surface coils [2,3] compatible with a reduced voxel size while maintaining sufficiently high signal-to-noise ratio (SNR) per unit time [4]. Small surface coils present an improved RF sensitivity than large coils, because they detect both a higher NMR signal thanks to stronger magnetic coupling with the sample and a lower sample-induced noise due to the smaller volume of tissue viewed by the coil [5]. Monolithic designs, such as the Multi-turn Transmission Line Resonator (MTLR) [6,7], are of particular interest for development of small coils, since they overcome the miniaturization limit encountered with standard RF coil technology, which uses discrete capacitors soldered to the coil's winding [8]. Monolithic designs consist of conducting windings, setting the equivalent inductance of the coil, deposited on a low-loss dielectric substrate, acting as a continuously distributed capacitance. The monolithic structure operates as an equivalent self-resonant RLC circuit. Monolithic designs are also attractive to develop superconducting RF coils for which the use of a discrete capacitor and soldering would introduce additional losses that would limit the benefit of using supercon-

Abbreviations: FIT, finite integral technique; GUI, graphic user interface; LAN, local area network; MGE, Maxwell's grid equations; NMR, nuclear magnetic resonance; MRI, magnetic resonance imaging; MTLR, multi-turn transmission line resonator; Piezo-leg, piezoelectric leg; Piezo-motor, piezoelectric motor; RF, radiofrequency; SNR, signal to noise ratio; VISA, virtual instrument software architecture protocol.

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ducting material [1]. However, the development of MTLR makes it more difficult to achieve fine and reproducible post-fabrication adjustment of the resonance frequency [9]. In order to preserve the monolithic feature of the MTLR design and to avoid disruption of the resonance mode of the transmission line, dedicated contact-free tuning techniques must be employed instead of the standard tuning technique based on lumped trimmer capacitors.

Two main principles can be used to perform post-fabrication adjustment of the resonance frequency of an MTLR. The first tuning principle is based on the interception of the electric fringing field lines at the coil surface by a dielectric layer [10]. The presence of the dielectric layer modifies the overall permittivity of the media surrounding the coil, and consequently modifies the equivalent capacitance of the coil. Since common dielectric materials have higher permittivity than that of the air, this dielectric tuning principle can only increase the equivalent capacitance, and thus solely allows for decreasing the resonant frequency of the coil [11].

The second tuning principle exploits the modification of the equivalent inductance of the coil by intercepting magnetic field lines with a closed conducting ring placed near the coil. Since the magnetic energy is shared between the coil and the conducting loop, this inductive coupling principle can only reduce the equivalent inductance of the coil and can therefore only increase its resonance frequency.

While these two tuning principles have already proven to be efficient for tuning RF coils in MRI experiments [12], they remain hard to implement and their usability is limited for two main reasons. First, the lack of modelling and analytical tools makes it impossible to predict the achieved frequency shift, and no proper design of the tuning device can be found. Second, it was observed in a preliminary study [13] that displacements of a few microns of the tuning elements at the surface of the coil can produce frequency shifts up to tens of kHz and thus de-tune the coil. The need for precise adjustment of the resonance frequency of the coil imposes, therefore, fine control of the positioning of the tuning elements near the coil.

In this work, we investigated the two tuning principles described above in order to determine the accessible tuning range as a function of both the tuning element's characteristics and its distance to the RF coil. The coil's resonance frequency shift was determined using two complementary investigation tools. Numerical simulations were carried out using an electromagnetic solver based on the finite integral technique. Experimental characterization was performed using an inductive measurement technique to determine the actual performance, including resonance frequency shift and loss evaluation, of the proposed tuning techniques. Analytical modelling of the two tuning techniques was performed to allow for fast determination of the achievable tuning range as a function of the tuning element's characteristics.

To implement the two investigated tuning principles and meet the need of precise positioning of the tuning elements, we have developed an automated system based on piezoelectric actuators coupled to a linear translation rod that achieves microscopic displacements of the tuning elements. The displacement is controlled remotely and automatically via a dedicated graphic user interface (GUI) in order to reach a target resonance frequency. Besides the tuning purpose, the automated system was used to perform automatic impedance matching of the coil using an inductive coupling technique with a pick-up loop. The MRI compatibility of the developed automation system and the feasibility of using it in MRI, were evaluated experimentally by performing MRI experiments in a 4.7 T scanner.

The use of piezoelectric actuators for tuning the RF coil for MRI has been reported in a few experiments and has demonstrated reliable and precise adjustment of the coil's resonance frequency. However, as compared to the work presented here, these previous works were conducted using large-sized standard RF coils, based on lumped L-C elements, and piezoelectric actuators were used as voltage-controlled capacitors [14] or, more recently, as an automatic screw-driver to mechanically adjust the value of trimming capacitors [15]. Here, we investigated the use of piezoelectric actuators in the context of a small monolithic surface coil to be operated without contact.

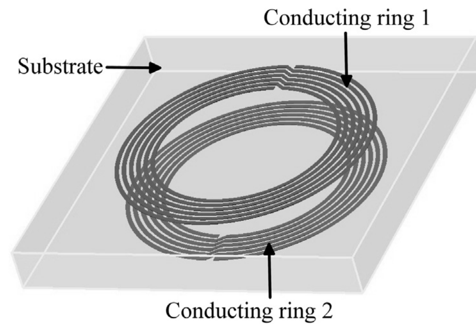

Fig. 1. Schematic of an MTLR: it consists of two sets of conducting split-rings connected in series and deposited on both sides of a dielectric substrate.

2. Material and methods

2.1. The RF coils

This work was carried out using small MTLRs as RF coils.

The basic scheme of an MTLR is shown in Fig. 1. It is composed of conducting split-rings connected in series and deposited on both sides of a dielectric substrate. The overall structure is a self-resonant transmission line capable of generating an external RF magnetic field. The resonant condition of an MTLR is determined using wave propagation analysis, based on differential current mode flowing in the transmission line, combined with lumped element model analysis based on common mode current and is expressed as [16]:

$$\frac{L\omega}{4Z_c}\tan\left(\omega\sqrt{\varepsilon}\frac{l_f}{4c}\right)=1 \tag{1}$$

where ω is the angular resonance frequency, l_f is the total length of the winding, L is the equivalent coil inductance, Z_C is the characteristic impedance of the transmission line, ε is the relative permittivity of the substrate, and c is the light velocity in free-space.

The characteristic impedance is set by the thickness and the permittivity of the substrate and by the width of the conducting strip. It is calculated using Wheeler's formula established for a parallel plate transmission line [17]. The equivalent inductance accounts for the self-inductance of each circular ring; it is determined using the empirical model proposed by Rayleigh and Niven [18] and for the mutual inductances between all rings it is calculated using the general Maxwell formula [19].

For evaluating on-the-bench the performances of the two studied tuning principles, we used an MTLR with a mean diameter of 14.6 mm, made of micro-moulded copper strips [20] (200 μm width, 15 μm thickness, 6 turns with 150 μm spacing) deposited on a 330 μm thick sapphire substrate. The size of this MTLR is small as compared to those of coils classically used for small animal MRI [21]. This MTLR was designed for proton imaging at 1.5 T. It exhibits a free resonance frequency of 67.8 MHz and an unloaded quality factor (Q-factor) of 117.

For MRI experiments, we used an MTLR coil specifically designed for H^1 imaging at 4.7 T (Larmor frequency of 199.8 MHz). It is composed of two copper windings deposited on both sides of a 510 μm thick Teflon substrate. Each winding has 6 turns (1.25 mm width,