Design of Distributed Spiral Resonators for the Decoupling of MRI Array Coils

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Abstract— **This paper describes a distributed filter layout for the decoupling of 7T Radio Frequency (RF) Magnetic Resonance Imaging (MRI) ^{1}H planar array coils based on miniaturized spiral resonators as unit-cells. The spirals, opportunely designed in terms of resonant frequency and with an optimized layout to minimize their number, are placed on the same dielectric substrate of the RF coils. We demonstrated through numerical simulations the decoupling effectiveness of the distributed filter, observing a decoupling greater than -20 dB and satisfying matching levels (-30 dB) for the RF coils. The possibility to print on the same substrate both the coils and the filter results in practical advantages like excellent mechanical robustness and less sensibility to potential fabrication tolerances.**

Index Terms— **Array, Decoupling, Distributed Magnetic Traps (DMTs), spiral resonator, MRI coils.**

I. INTRODUCTION

Planar arrays of RF loops, resonant at the same Larmor frequency, are commonly used in Magnetic Resonance Imaging technique. Indeed, the possibility to transmit and receive signals from multiple coils is very attractive to enhance the Signal-to-Noise Ratio (SNR) and to reduce the total examination scan time. Nonetheless, the proximity between RF loops is responsible for a strong mutual coupling which is particularly detrimental for the image quality. As a matter of facts, mutual coupling degrades the SNR and leads to image artifacts; therefore, it represents a major issue to face for the planar arrays implementation [1]-[3].

Hence, currently, a significant effort is still directed to face and mitigate such phenomenon among the scientific and industrial MRI community. As a consequence, different technical solutions have been proposed in the literature that enhance the decoupling of closely spaced RF coils. To the best of our knowledge, the overlapping technique, thanks to its straightforward implementation, is one of the most common and applied decoupling method [1]. In a few words, it consists in a partial overlap between adjacent coils, choosing the point where the mutual coupling is compensated. However, a certain Field of View (FoV) reduction is observed, thus pushing the research to find further solutions.

Another popular and effective proposal is the Induced Current Elimination (ICE) technique, based on an eigenvectors and eigenvalues approach [4]. More recently, the Magnetic Wall decoupling method was successfully developed and satisfying decoupling levels in ^{1}H RF arrays were observed [5]. In addition, also interleaving other reactive and resonant elements between RF MRI coils was demonstrated as a viable solution [6].

In this paper, we propose the implementation of a distributed filter for the decoupling of 7 T RF MRI array ^{1}H coils based on miniaturized spiral resonators as unit-cells. We developed a design framework, based on analytical assumptions, to choose the appropriate geometry and the minimum number of unit-cells required to achieve a good decoupling level, thus optimizing the system in terms of mechanical strength, fabrication tolerances robustness and electrical losses.

In Section II, we first describe the analytical assumptions and the general filter design flowchart. Afterwards, we present a numerical study to demonstrate the feasibility and the effectiveness of the proposed approach on a simple array, chosen as test-case. Finally, conclusions follow.

II. MATERIALS AND METHODS

A. Mutual coupling estimation

In order to quantify the interactions between each couple of RF coils in an array, it is required to evaluate the corresponding mutual coupling. This is possible through a magneto-static hypothesis, using Biot-Savart law to compute the magnetic field produced by a coil and evaluating the flux concatenating in the other [7]:

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int \frac{I\vec{dl}\times\vec{r}'}{\left|\vec{r}'\right|^3} \tag{1}$$

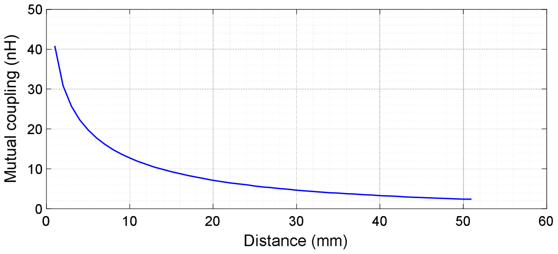


Fig. 1. Mutual coupling between two loops versus their gap distance: it is evident the rapid decrease for increasing gaps.

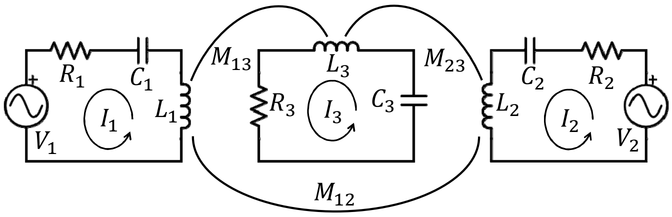


Fig. 2. Equivalent schematic circuit representing the proposed system, describing the two coils (circuit 1 and 2) and the filter (circuit 3).

The same approach can be also followed to evaluate the coupling between the filter unit-cell (i.e., the spiral resonator) and the RF coils, thus completely characterizing the system.

In a planar array, mutual coupling between coils, as a function of their distance, is a rapidly decreasing function (Fig. 1). For this reason we will concentrate in the design of a filter that reduces the first-nearest neighbors coupling neglecting, in a first approximation, the smaller next-nearest neighbors coupling.

B. Design framework

Under the previous assumptions, we can represent our system as an ensemble consisting of two MRI RF adjacent coils (reported in Fig. 2 as elements 1 and 2) with a decoupling structure interacting with them (element 3).

Then, we developed the following design framework, whose various steps are reported graphically in Fig. 3. After the mutual coupling coefficients are estimated as reported in Section II.A, we perform an analysis on the system (Fig. 2) impedances matrix. In particular, we optimize the number and the reactance that ideal spiral resonators must retain to minimize the two MRI RF coils coupling. Specifically, the impedance value that the spiral resonators must present in order to compensate the inductive coupling between RF loops and their minimum number necessary to satisfy the aforementioned condition is determined by the analytical approach based on the equivalent circuit depicted in Fig. 2.

Subsequently, we design appropriate spiral resonators, matching the requisites of the previous step and also satisfying the system geometrical constraints. Specifically, the accurate RLC extraction of the spiral resonator is carried out as reported in [8].

Finally, targeted full-wave simulations are carried out to evaluate the filter performances and, eventually, to refine the SRs geometry until the desired decoupling level is accomplished.

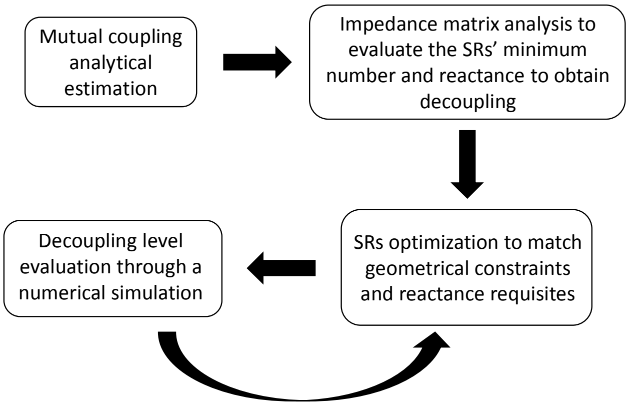


Fig. 3. Flow chart of the proposed decoupling approach.

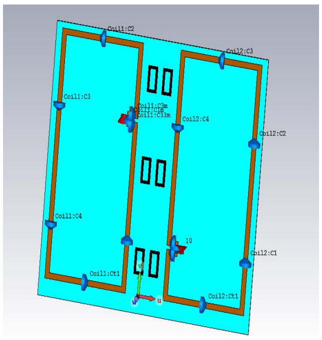
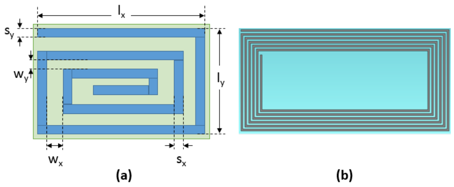


Fig. 4. CST Microwave Studio CAD model of the test-case.



(a) (b)

Fig. 5. Adopted spiral resonator geometry (drawing not in scale).

III. TEST-CASE

A. Numerical design

We designed a test-case to evaluate the developed framework through CST Microwave Studio (Darmstadt). It consisted in two RF loops, both resonant at the proton Larmor frequency for 7 T MRI (about 298 MHz). The loops are rectangular (6.5 cm × 13 cm) and they are printed on a low losses 0.8 mm thick dielectric substrate (Arlon, ε_r=3.45). The strip width is 3.2 mm and the two RF coils are separated by 2.5 cm (Fig. 4). We interleaved between them 6 spiral resonators, designed to fulfill the RF coils coupling minimization condition. The adopted spirals are depicted in Fig. 5; they are characterized by a rectangular shape (6.7 mm × 13.7 mm), consisting of 6 turns. The spirals are printed on the same dielectric substrate of the RF loops; their strip width and the gap between two adjacent branches are equal (0.127 mm). After the impedance characterization, their resonant frequency resulted 300 MHz with a residual

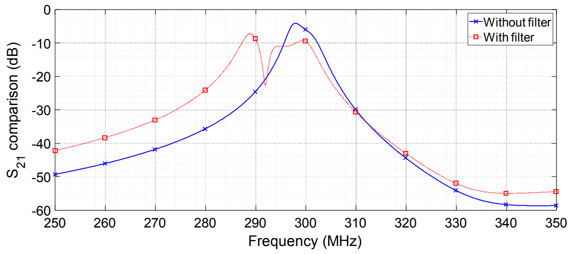


Fig. 6. Simulated S_{21} with and without the filter presence between the two adopted RF coils. The filter is responsible for a significant decoupling improvement.

reactive component at 298 MHz of -19.7 nH.

B. Results

We performed numerical simulations of the RF coils without and with the distributed filter presence. In both cases, we obtained a good tuning and matching level (around -30 dB) of the coils with appropriate capacitive loads.

We reported the decoupling results in Fig. 6, where we compared the two configurations. As can be seen from the figure, the decoupling level was significantly improved (it passed from -5 to -23 dB) with the filter, demonstrating the effectiveness of our design. However, it must be pointed out that the system in presence of the spiral resonators requires a further fine tuning procedure to be exactly centered at 298 MHz.

IV. CONCLUSIONS

In this paper we proposed a design framework for the decoupling of RF planar array coils for 7 T MRI based on miniaturized spiral resonators acting as filtering unit-cell. Our technique is based on an analytical approach thanks to which we are able to estimate the mutual coupling coefficients between RF coils and between each RF coil and the adopted decoupling spiral resonators. We calculate the required minimum number and the impedance value that the spiral resonators must retain in order to compensate the inductive coupling between RF loops. Then, it is possible to perform few and targeted full-wave simulations to verify the performance of the developed filter and, eventually, refining the spiral resonators geometry until the desired decoupling level is achieved.

We numerically designed a test-case to evaluate the effectiveness of the proposed approach, obtaining a good decoupling level (-23 dB) together with a satisfying matching (around -30 dB) around the desired working frequency.

The next steps will be directed to improve the analytical formulation and extend the study for the case of multiple adjacent coils, thus including the next-nearest neighbors' coupling in the model.

REFERENCES

[1] P. B. Roemer et al., "The NMR phased-array", *Magn. Reson. Med.*, vol. 16, pp. 192-225, 1990.

[2] G. Adriany et al., "A 32-channel lattice transmission line array for parallel transmit and receive MRI at 7 Tesla", *Magn. Reson. Med.*, vol. 63, pp. 1478–1485, 2010.

[3] J. A. de Zwart et al., "Signal-to-noise ratio and parallel imaging performance of a 16-channel receive-only brain coil array at 3.0 Tesla", *Magn. Reson. Med.*, vol. 51, pp. 22–26, 2004.

[4] Y. Li et al., "ICE decoupling technique for RF coil array designs", *Med. Phys*., vol. 38, pp. 4086-4093, 2011.

[5] I. R. O. Connell et al., "Design of a parallel transmit head coil at 7T with magnetic wall distributed filters", *IEEE Trans. Med. Imag.*, vol. 34, pp. 836–845, 2015.

[6] A. Abuelhaija, S. Orzada, K. Solbach, "Parasitic Element Based Decoupling of 7 Tesla MRI Coil Array", *Antennas & Propagation Conference (LAPC)*, Loughborough, 2015.

[7] Y. Cheng and Y. Shu, "A new analytical calculation of the mutual inductance of the coaxial spiral rectangular coils," *IEEE Trans. Magn.*, vol. 50, no. 4, pp. 1–6, 2014.

[8] D. Brizi et al., "Accurate Extraction of Equivalent Circuit Parameters of Spiral Resonators for the Design of Metamaterials", *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 2, pp. 626-633, Feb. 2019.