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New resonator geometries for ICE decoupling of loop arrays

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Abstract

RF arrays with a large number of independent coil elements are advantageous for parallel transmission (pTx) and reception at high fields. One of the main challenges in designing RF arrays is to minimize the electromagnetic (EM) coupling between the coil elements. The induced current elimination (ICE) method, which uses additional resonator elements to cancel coils' mutual EM coupling, has proven to be a simple and efficient solution for decoupling microstrip, L/C loop, monopole and dipole arrays. However, in previous embodiments of conventional ICE decoupling, the decoupling elements acted as “magnetic-walls” with low transmit fields and consequently low MR signal near them. To solve this problem, new resonator geometries including overlapped and perpendicular decoupling loops are proposed. The new geometries were analyzed theoretically and validated in EM simulations, bench tests and MR experiments. The isolation between two closely-placed loops could be improved from about -5 dB to <-45 dB by using the new geometries.

Graphical abstract

Keywords

Magnetic Resonance Imaging; RF coils; Phased-arrays; decoupling; Induced current elimination; magnetic wall

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2. Introduction

With the advantages of increased signal-to-noise ratio (SNR), higher spatial resolution [1], and improved contrast in T2/T2*-weighted images, high field (≥ 7 T) MRI systems are becoming more widespread for human imaging. However, the high Larmor frequencies (≥ 300 MHz) of high field MRI lead to severe B_1 inhomogeneities in head and body imaging. The high Larmor frequencies also create technical difficulties in building large-sized volume resonators such as birdcage resonators. To overcome these problems, radiofrequency (RF) arrays are commonly used for transmission only or transmission and reception in high field MRI.

RF arrays with a large number of independent elements are desirable for both parallel transmission (pTx) and parallel reception. In parallel transmission, using more independent elements improves the ability to produce uniform flip angle patterns across the imaged volume while controlling global and local specific absorption rates (SAR) [2–6]. In parallel reception, increasing the number of elements reduces noise amplification and artifacts for a given scan acceleration factor [7–12]. One of the main challenges in designing RF arrays is to minimize the electromagnetic (EM) coupling between coil elements. In parallel transmission, coupled RF power is absorbed by circulators and wasted, which decreases transmit efficiency. Coil coupling also reduces degrees of freedom for shimming and excitation encoding capability since the coils' B_1 profiles become more similar. In parallel reception, coupling leads to noise correlations between the received signals across coils and degrades the g-factor. Strong coupling also reduces the distinction between the coils' B_1 profiles and thus degrades an array's spatial encoding capability.

Several methods have been proposed to decouple loop arrays. One traditional approach is to overlap neighboring loops to cancel their inductive coupling [13]. Other decoupling methods include transformers [14] and inter-connecting L/C networks between neighboring loops [15–19]. Generally, the coil coupling in heavy loading cases is less challenging compared to light loading cases because most of EM fields are localized near each coil in the heavy loading case. These traditional methods are effective in decoupling loop arrays in heavy loading cases, but less effective under light loading. This has implications for transmit arrays, which are usually placed at a distance from the body to leave space for receive arrays and to increase SAR efficiency [20], and are therefore often lightly loaded.

The induced current elimination (ICE) method, which uses additional resonator elements to cancel coils' mutual EM coupling, was first proposed for stripline arrays in Xie et al. [21–23] and Li et al. [24]. The method was later extended for L/C loop arrays [25], monopole arrays [26] and dipole arrays [27]. Compared to traditional decoupling methods that are challenged in light loading cases, ICE decoupling shows excellent decoupling performance in both heavy and light loading conditions [25,28]. Similar decoupling methods using other kinds of additional resonators have also been developed. In Avdievich et al. [29], a figure-of-eight (butterfly) resonator was demonstrated and termed Resonant Inductive Decoupling (RID). In Connell et al. [30], multiple small resonators were arranged periodically around the array and termed Magnetic Wall Distributed Filters.

The basic concept of these methods is to use the tailored induced current along the additional resonators to cancel the mutual coupling. The tailored current is achieved by tuning the self-resonant frequency and the geometry of the additional resonator (decoupling element). It should be noted that Avdievich et al. [29] first pointed out that both mutual resistance coupling and mutual reactance coupling could be cancelled out by additional resonators. Although the basic concepts of these methods are same, the implementations of the additional resonators, which play an important role on the coil performance and decoupling performance, are quite different. In ICE decoupling of loop arrays, the authors emphasized the use of a single L/C loop resonator without any lump inductors. In the RID approach, the authors emphasized the use of a “figure-of-eight” resonator with two lump inductors. In the magnetic wall distributed filters approach, the authors emphasized the use of periodical small distributed resonators. In this work, we refer to the method in Yan et al. [25] where a single L/C loop resonator is used as the decoupling element (referred to as a decoupling loop) as *conventional ICE decoupling*.

In previous embodiments of conventional ICE decoupling, the decoupling elements acted as “magnetic-walls” [31] which improves the local MR signal near coils but cancel MR signal near the elements. An additional requirement is that the decoupling element’s self-resonance frequency (ω_d) should be far away from the Larmor frequency (ω_0) to achieve robust coil performance in which the coils’ matching and decoupling are independent.

To minimize or eliminate the signal cancellation associated with ICE decoupling and to increase resonant frequency separation for robust coil performance, in this study new resonator geometries are proposed for decoupling loop arrays, including overlapped and perpendicular loops. The resonant frequency separation refers to the difference between the self-resonant frequency of the decoupling loop and the resonant frequency of the coil elements (i.e., the Larmor frequency), which has a significant impact on the robustness and matching performance in ICE decoupling. Similar to the conventional ICE decoupling, the new designs employ a single L/C loop resonator (without any lump inductors) as the decoupling loop. First, we theoretically analyzed the current distributions along the decoupling element and the relation between ω_d and ω_0 . Based on the theoretical analysis, we describe new resonator geometries and validated them in EM simulations. Finally, we built decoupled coil arrays using the new elements and validated their performance in bench tests and 7T MR imaging experiments.

3. Methods

3.1 Analysis of the current distributions and self-resonance frequency of the ICE decoupling element

Fig. 1 depicts a two-coil loop array with a decoupling element positioned symmetrically between the loops. Z_{ii} and Z_{ij} represent the self and mutual impedances of the two coil elements (element 1 and element 2) and the decoupling element (element d) respectively, where i, j, i and $j=1, 2, d$. V_i and I_i are the voltage and current across the ports of the coil elements and the decoupling element. The decoupling element is passive, so its voltage is zero and the matrix relating the voltages and currents in the system is

$$\begin{bmatrix} Z_{11} & Z_{12} & Z_{1d} \\ Z_{21} & Z_{22} & Z_{2d} \\ Z_{d1} & Z_{d2} & Z_{dd} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_d \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ 0 \end{bmatrix} \quad [1]$$

If $Z_{1d} = Z_{2d}$, the required self-impedance of the decoupling element is derived in the Appendix using the odd-even mode method to be:

$$Z_{dd} = Z_{1d}^2 / Z_{12} \quad [2]$$

Note that the two coils can be perfectly decoupled, i.e., both mutual resistance and mutual reactance can be cancelled out, so long as the decoupling condition in Eq. [2] is met. From Eqs. [1] and [2], the decoupling loop's current is equal to:

$$I_d = - (Z_{12} / Z_{1d})(I_1 + I_2) = - \eta(I_1 + I_2) \quad [3]$$

Where $\eta = Z_{12} / Z_{1d}$. Assuming $Z_{1d} = j\omega L_{1d} + R_{1d}$ and $Z_{dd} = j\omega L_d + 1/j\omega C_d + R_d$, where $j\omega L_{1d}$ and R_{1d} are the reactive (inductive coupling-dominated) and resistive parts of Z_{1d} , and L_d , C_d and R_d are the self-inductance, self-capacitance and self-resistance of Z_{dd} , the relation between ω_d and ω_0 can be derived to be:

$$\omega_d = 1 / \sqrt{L_d C_d} = \omega_0 \sqrt{1 - L_{1d} / (\eta L_d)} \quad [4]$$

3.2 New resonator geometries for ICE decoupling of loop arrays

In previous ICE-decoupled loop arrays the decoupling loop is positioned in the gap between loops (Fig. 2A), so η is positive so that $I_d \propto -I$ when one coil is excited with current I (based on Eq. [3]). Therefore the decoupling loop carries a current in the opposite direction of the coils and acts as a “magnetic-wall” that diminishes the total B_1 fields near it, leading to signal loss there. However, if the coils are instead overlapped and the decoupling loop is positioned in the coils' overlapped area (Fig. 2B), then η is negative and $I_d \propto I_1$. Thus the decoupling loop's current is in the same direction as the coil currents, which may enhance the MR signal near the decoupling loop rather than cancel it. If small perpendicular loops are inserted in the coils and the decoupling loop is placed between them and perpendicular as well (Fig. 2C), then the decoupling loop will carry current in a plane perpendicular to the coil currents, and may decouple the coils without affecting the MR-active EM fields. Note that the perpendicular loops inserted in the coils are wound with the same orientation to ensure that $Z_{1d} = Z_{2d}$, which is the assumption used to derive Eq. [2].

Compared to a conventional ICE decoupling loop, the magnitude of $\eta = Z_{12} / Z_{1d}$ is relatively smaller using overlapped and perpendicular decoupling loops. In the overlapped configuration, this is because Z_{12} has been partly reduced by the overlap to begin with. In the perpendicular configuration, it is because Z_{1d} is enhanced by the transformer effect.

Based on Eq. [4], ω_d of the overlapped and perpendicular decoupling loops is expected to be further away from ω_0 with smaller η . The sign of $L_1 d / \eta$ determines whether ω_d is higher or lower than ω_0 . For the overlapped decoupling loop, $L_1 d / \eta$ is negative so $\omega_d > \omega_0$. For the perpendicular decoupling loop, $L_1 d / \eta$ is positive so $\omega_d < \omega_0$.

3.3 Numerical simulations

To validate the proposed ICE decoupling geometries, a series of full-wave EM simulations were performed with HFSS (ANSYS, Canonsburg, PA, USA). Figs. 3A, 3B and 3C show the simulation models of arrays with conventional, overlapped and perpendicular decoupling loops, respectively. Each array consisted of two planar loops (dimensions $10.5 \times 15 \text{ cm}^2$) along the z-direction and a decoupling loop. The conventional decoupling loop had dimensions of $2.8 \times 15 \text{ cm}^2$ and eight distributed capacitors (to achieve a uniform current distribution). The overlapped and perpendicular decoupling loops were circular with diameter 1.6 cm, and only one capacitor was used. For the conventional ICE configuration, the two coils were placed 3.2 cm apart to make enough space for the decoupling loop. For the configurations using overlapped and perpendicular decoupling loops, the coils were placed 0.7 cm apart. With new geometries, the coils could be placed closer (gap 0.7 cm vs 3.2 cm) which is desirable for building denser arrays with more complete B_1 coverage. All these configurations would exhibit strong coupling if no decoupling loop were used.

A tank phantom (conductivity $\sigma = 0.6 \text{ S/m}$, relative permittivity $\epsilon_r = 78$) with dimensions $40 \times 25 \times 15 \text{ cm}^3$ was placed 4 cm below each array as an appropriate load. In all simulations, both coil elements were matched to 50Ω and tuned to 298 MHz (7T Larmor frequency). The distance between the simulation boundary and coils was more than a half-wavelength. Manual meshes were used to accelerate simulation convergence. The convergence condition S was set to 0.002 in first-stage simulation to generate S-parameter results, and set to 0.02 in the final simulation with lump capacitors. Values of all capacitors were obtained using the circuit co-simulation method [32].

3.4 Coil construction, Bench measurements and MR experiments

Three coil arrays with the different decoupling configurations were then built, as shown in Fig. 4. The coil dimensions and positions in each array were the same as in the simulation. All coil arrays were made of printed circuit boards (PCBs) and mounted on FR-4 boards (1.6 mm thick). The PCB conductors were 7.5 mm wide and 100 μm thick. Fixed capacitors (Series 1111C, Passive Plus, Huntington Station, NY) were used as the distributed capacitors and trimmer capacitors (52H02, Johanson Manufacturing corp., NJ, USA) were used to adjust the tuning, matching and decoupling. For each coil element, a shielded cable-trap circuit was used to suppress the common current at 298 MHz.

S-parameter plots including S_{11} and S_{21} of all arrays (loaded with the phantom) were measured by an Agilent 5071C network analyzer. A 4 cm thick foam layer was inserted between the coil arrays and the phantom. The phantom had dimensions of about $40 \times 25 \times 18 \text{ cm}^3$ and was made of 18-L distilled water and 5-L alcohol loaded with 21.1g $\text{CuSO}_4 \times 5\text{H}_2\text{O}$ and 51.3g NaCl. Low-flip-angle gradient-recalled echo (GRE) images were acquired on a 7T Philips Achieva scanner (Philips Healthcare, Best, Netherlands). The imaging

acquisition parameters were: flip angle (FA) = 10 degrees, TR = 100 ms, TE = 10 ms, field of view (FOV) = $400 \times 250 \text{ mm}^2$, in-plane resolution = $1.25 \times 1.25 \text{ mm}^2$, slice thickness = 5 mm, number of averages = 1.

4. Results

4.1 Simulation Results

Figs. 5A and 5B show the simulated S_{11} and S_{21} plots of the arrays without decoupling loops. As expected, the coil elements were strongly coupled with $S_{21} = -4.5 \text{ dB}$, -6.6 dB and -3.2 dB , corresponding to power cross-talks of 35%, 22% and 48%. Due to strong coupling, the resonance peaks (S_{11}) were asymmetric or even split in the perpendicular case, as shown in Fig. 5A. For the overlapped configurations, the two coils had relatively lower coupling (-6.6 dB vs. -4.5 dB) even though the two coil elements were placed closer (0.7 cm vs. 3.2 cm). This is because the coupling was partly cancelled by the magnetic flux in the overlapped area. When decoupling loops were added, the coil elements were well matched to 50Ω with $S_{11} < -30 \text{ dB}$ (power reflection $< 0.1\%$), and well decoupled with $S_{21} < -20 \text{ dB}$ (power cross-talk $< 1\%$) for all configurations, as shown in Fig. 5D. Note that the second dip in the S_{11} plots of Fig. 5C corresponds to the self-resonance frequency of the decoupling loops and is not caused by coils' coupling.

Fig. 5E shows the current vectors when only the left coil was excited with 1 Watt (clockwise current direction). As expected from Eq. [3], the current direction in the conventional decoupling loop was the opposite (counter-clockwise) while the current direction in the overlapped decoupling loop was the same as in the excited coil (clockwise).

Fig. 6 shows simulated B_1^+ fields of the different arrays, and Fig. 7 shows the differences between those fields and those of the ideal coils. For one coil excitation, the input power was set to 1 Watt. When both coils were excited, the input power to each coil was 1 Watt with the same phase. The conventional decoupling loop decreased nearby field strength (white arrows in Fig. 6B vs. Fig. 6A and dark arrows in Fig. 7B vs. Fig. 7A), reflecting its “magnetic wall” behavior. In contrast, the overlapped decoupling loop enhanced the nearby field (white arrows in Fig. 6C vs. Fig. 6A and dark arrows in Fig. 7C vs. Fig. 7A), and the perpendicular decoupling loop did not change the field strength of the coils driven in isolation (Fig. 6D vs. Fig. 6A and Fig. 7D vs. Fig. 7A).

4.2 Bench test and MR experiment results

Fig. 8 shows the measured S_{11} and S_{21} plots of the three arrays. All coil elements were well matched to 50Ω with $S_{11} < -30 \text{ dB}$, as shown in Fig. 8A. The measured isolations using the conventional, overlapped and perpendicular loops were -22.8 dB , -49.2 dB and -46.8 dB , as shown in Fig. 8B. Similar to the simulation results (Fig. 5C), the resonant frequencies of the overlapped (395 MHz) and perpendicular (212 MHz) decoupling loops were further away from Larmor frequency (298 MHz) compared to conventional ICE decoupling (341 MHz).

Fig. 9 shows experimentally acquired GRE images of the phantom obtained with these arrays (central sagittal slice). Since the B_1^+ and B_1^- fields have similar patterns in the central sagittal slice, the signal sensitivity profiles of low-flip angle GRE images can well

represent the B_1^+ profiles. As expected from the simulation results, the conventional decoupling loop caused nearby signal cancellation (Fig. 9A), which was avoided using the overlapped (Fig. 9B) and perpendicular decoupling loops (Fig. 9C).

5. Discussion

The measured isolations of the proposed ICE-decoupled loop arrays with new geometries were better than -45 dB (Fig. 8B), meaning that the power transfer from one loop to the other was less than 0.01%. As shown in Fig. 9A, the conventional decoupling loop led to MR signal loss nearby although it improves the MR signal near the coils. By using the new geometries, however, the MR signal loss near the decoupling element could be avoided (Figs. 9B and 9C).

Decoupling loops using the new geometries also have much smaller dimensions (circular, diameter 1.6 cm) compared to conventional ICE loops (rectangular, 2.8×15 cm²), making them more suitable for compact array designs. In spite of the small dimensions, their self-resonance frequencies (395 MHz and 212 MHz) were still far away from the Larmor frequency (298 MHz) due to overlapping (smaller Z_{12}) or transformer effects (larger Z_{1d}). By using a multi-turn design, the transformer effect of the perpendicular loop could be increased and its dimension might be further reduced.

Based on Eq. [1], the self-impedance of the coil elements will be changed in the presence of the decoupling element, which makes the matching and decoupling dependent on each other. This association is particularly strong when the decoupling loop resonates near the Larmor frequency. At high fields, the coils' matching performance have large variations with different subjects, and may need to be re-adjusted manually or remotely [33]. Therefore the new geometries are advantageous in ICE-decoupled loop arrays since they have more robust decoupling performance (larger $|\omega_d - \omega_0|$) compared to the conventional ICE decoupling method.

Supporting Figures S1 and S3 show simulated E fields (magnitude) of the different arrays in the axial and coronal planes, respectively. Supporting Figures S2 and S4 show differences between those fields and those of the ideal coils in the axial and coronal planes, respectively. When transmit arrays are designed for human imaging, simulated results of B_1 and SAR distributions are required to generate safety guidelines for RF shimming or pTx during transmission. Compared to ideal coils, the conventional and overlapped decoupling loops change the original EM fields (Fig. 6, Fig. S1 and Fig. S3). For these two configurations, therefore, real coil modes taking consideration of the decoupling loops should be used in EM simulations for safety. The perpendicular decoupling loop maintains the original EM distributions and meanwhile exhibits excellent coil isolation ($S_{21} < -45$ dB), so ideal coils might be accurate enough in EM simulations.

The “figure-of-eight” decoupling loop in Avdievich et al. [29] can also be seen as an optimized geometry for ICE decoupling of loop arrays. Based on their experimental results, the “figure-of-eight” decoupling loop has little impact on the original B_1^+ field, which is similar to the performance of the perpendicular decoupling loop proposed here. However,

the proposed perpendicular decoupling loop has a simpler geometry (single L/C loop resonator) and is easier to implement in practice. The perpendicular loops (inductors) of coils are wound in different directions in Avdievich et al. [29]. In that case, a “figure-of-eight” resonator is needed to meet the decoupling condition. In the perpendicular decoupling loop geometry proposed here, the perpendicular loops (inductors) of the coils are wound in the same direction and thus a single L/C loop resonator can meet the condition.

Besides the perpendicular decoupling loop, we also proposed an overlapped decoupling loop design, in which the B_1^+ in gap area is increased rather than decreased. Since these designs (conventional, overlapped and perpendicular) have different impacts on the original EM fields, they provide additional RF shimming capability as well as excellent decoupling capability. As shown in Fig. 6A, the B_1^+ field with two ideal coils driven is stronger at each coil's center but weaker near the gap area, leading to non-uniform B_1^+ along the z -direction. When the overlapped decoupling loop is employed, this B_1^+ uniformity along z -direction can be improved since the overlapped decoupling loop provides complementary B_1^+ patterns (Fig. 6C). Note that corresponding E-field is decreased when the overlapped decoupling loop is employed (Figs. S1–S4), indicating improved SAR efficiency in this specific case.

As shown in Fig. 5 and Fig. 8, the simulated S-parameter plots are slightly different from the measured plots. Especially, the measured S_{21} using the new decoupling loops (about -50 dB) is superior to the simulated S_{21} (about -30 dB) at the Larmor frequency. This difference can be attributed to the following several reasons. First, the excitation ports in the simulation are ideal and positioned exactly at one end the coils. In practice, however, there are cables and trap circuits which might change the frequency behavior in S-parameter plots. Second, capacitor values can be tuned continuously in practice but are tuned discontinuously in the simulation. Third, the meshes in the first-stage simulation (to generate S-parameter matrix) and final simulation are not exactly same.

The theoretical analysis in Section 3.1 is a general analysis that is based on self and mutual impedances, so it can also be extended for decoupling monopole or dipole arrays. Therefore perpendicular decoupling loops have the potential to minimize inter-element coupling in monopole and dipole arrays while maintaining their original EM fields. As mentioned above, one of key points in designing the decoupling element is to minimize the $\eta = Z_{12}/Z_{1d}$, so it might be best to position the decoupling loop near the points with maximum current in monopole and dipole antennae.

6. Conclusion

In conclusion, we propose new decoupling geometries for ICE-decoupled loop arrays and have validated them in simulations and experiments. Excellent decoupling performance can be achieved (< -45 dB) with the new geometries, and MR signal disturbances near the decoupling elements were reduced.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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9. Appendix

Any coupling between two coils can be decomposed into two basic modes, termed even and odd. In the even mode the currents on both coils have the same directions and amplitudes. In the odd mode, the currents on the two coils have the same amplitudes but opposite directions. The coupling between the coils is eliminated when the impedances associated with the odd and even modes are the same. For the odd mode, the voltages and currents of the two ports are: $V_1 = -V_2 = V$; $I_1 = -I_2 = I$. Thus Eq. [1] can be written as:

$$\begin{bmatrix} Z_{11} & Z_{12} & Z_{1d} \\ Z_{21} & Z_{22} & Z_{2d} \\ Z_{d1} & Z_{d2} & Z_{dd} \end{bmatrix} \begin{bmatrix} I \\ -I \\ I_d \end{bmatrix} = \begin{bmatrix} V \\ -V \\ 0 \end{bmatrix} \quad [5]$$

For the even mode, the voltages and currents of the two ports are: $V_1 = V_2 = V$; $I_1 = I_2 = I$. Thus Eq. [1] can be written as:

$$\begin{bmatrix} Z_{11} & Z_{12} & Z_{1d} \\ Z_{21} & Z_{22} & Z_{2d} \\ Z_{d1} & Z_{d2} & Z_{dd} \end{bmatrix} \begin{bmatrix} I \\ I \\ I_d \end{bmatrix} = \begin{bmatrix} V \\ V \\ 0 \end{bmatrix} \quad [6]$$

From Eqs. [5] and [6], the impedances of the odd-mode (Z_o) and even-mode (Z_e) can be derived as follows:

$$Z_o = \frac{V}{I} = Z_{11} - Z_{12} \quad [7]$$

$$Z_e = \frac{V}{I} = Z_{11} + Z_{12} - 2 \frac{z_{1d}^2}{z_{dd}} \quad [8]$$

If $Z_o = Z_e$, the elements are decoupled. Thus, based on Eqs. [7] and [8], the decoupling condition can be derived as

$$Z_{dd} = \frac{z_{1d}^2}{z_{12}}. \quad [9]$$

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Highlights of Manuscript Entitled “New resonator geometries for ICE decoupling of loop arrays” – JMR-16-343

- Current distribution and self-resonant frequency of decoupling elements in ICE-decoupled arrays are analyzed.
- New resonator geometries for the decoupling elements are proposed.
- Isolation between two closely-placed loops is improved from -5 dB to < -45 dB using new geometries.
- Self-resonant frequencies of new geometries are further away from the Larmor frequency.
- New geometries avoid the signal loss and also provide RF shimming capability.

Figure 1.

Illustration of two coil elements and a decoupling element. Z_{ij} and Z_{ji} represent the self and mutual impedances of the two coil elements (element 1 and element 2) and the decoupling element (element d), where i, j, d and $j=1, 2, d$. V_i and I_i are the voltage and current across the ports of the coil elements and the decoupling element.

Figure 2. Schematics of two-coil ICE-decoupled L/C loop arrays using a conventional ICE decoupling loop (**A**), and the proposed overlapped decoupling loop (**B**) and perpendicular decoupling loop geometries (**C**).

Figure 3. Simulation models of two-coil ICE-decoupling L/C loop arrays with a conventional ICE decoupling loop (A), and the proposed overlapped decoupling loop (B) and perpendicular decoupling geometries (C).

Figure 4. Photographs of the fabricated arrays with the three decoupling geometries. From left to right: the conventional decoupling loop, the overlapped decoupling loop and the perpendicular decoupling loop.

Figure 5.

Simulated results of two-channel ICE-decoupling arrays with different configurations. **A** and **B**: S_{11} and S_{21} plots without decoupling loops, with obvious coupling. **C** and **D**: S_{11} and S_{21} plots with decoupling loops, in which the two coils were well decoupled to <-20 dB in all configurations. Note that the second dip in the S_{11} plots corresponds to the resonance frequency of the decoupling loops and was not caused by coils' coupling. **E**: Current vector distributions when only the left loop was excited with clockwise current direction. The decoupling loops have different current directions when positioned in the gapped area (counter-clockwise) versus the overlapped area (clockwise).

Figure 6. Simulated B_1^+ maps using each array. Compared to the ideal single loop (Fig. 6A), the conventional ICE decoupling loop decreased nearby field strength (white arrows in Fig. 6B) while the overlapped decoupling loop enhanced nearby field strength (white arrows in Fig. 6C), and the perpendicular decoupling loop did not significantly change the individual coil fields (Fig. 6D).

Figure 7.
Residuals of the simulated B_1^+ maps compared to those of the ideal loops.

Figure 8.

Bench measurements of the constructed arrays. **A:** S_{11} plots. The resonance frequencies of the overlapped (395 MHz) and perpendicular (212 MHz) decoupling loops were further from the Larmor frequency (298 MHz) compared to conventional ICE decoupling (341 MHz). **B:** S_{21} plots. The S_{21} 's of the conventional, overlapped and perpendicular decoupled arrays were -22.8 dB, -49.2 dB and -46.8 dB, respectively.

Figure 9. Measured low-flip angle GRE image profiles using each array. Similar to the simulation results, the conventional decoupling loop canceled nearby signal (white arrows in Fig. 5A), but the overlapped (Fig. 5B) and perpendicular decoupling loops (Fig. 5C) maintained nearby signal.