# Minimizing Mutual Inductance in NMR Phased Arrays: The Paddle End-Ring Design Revisited

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**Introduction:** The concept of NMR phased arrays has been traditionally linked to the use of overlapping coil loops in an attempt to null their mutual inductance [1]. Bloch et al. [2] first employed such a solution in crossed-coil, continuous wave probes, to remove residual inductive coupling. In this implementation scheme, a small sheet of metal was used, that was allowed to rotate about the probe. In the correct position, the eddy currents induced in the metal from the first coil, created an alternating magnetic field that coupled to the second coil, and cancelled the electromotive force induced by direct coupling. The metal sheet was effectively considered to 'steer' the magnetic field, and it was thus termed a 'paddle'. In analogy with such earlier work, numerous recent attempts [3, 4] proposed methods to decouple nearest neighbor coil loops using capacitive, inductive schemes, or decoupling networks [5] in coils arrays. Invariably, all such solutions use lossy lump components, often associated with increased power consumption and reduced array SNR performance, issues that can become challenging in clinical or research applications. Despite the existence of all such prior attempts introducing the implementation of specialized external circuits, appropriate overlap of adjacent array coils has become the standard practice nowadays to null mutual inductance in implemented arrays. Despite the incompleteness of this solution (finite mutual resistance), proper coil positioning is practically difficult to achieve, being position sensitive, and load dependent. This study theoretically investigates and proposes a closed-form formulation for the mutual inductance effects in planar phased arrays. It also proposes a solution that minimizes mutual inductance (maintaining adjacent coil loops in a non-overlapped configuration), based on the original idea of the fixed paddle design, using passive end-rings, in a manner that ameliorates the practical difficulties of overlapped phased array loops. The proposed concepts are validated through simulations and bench testing on a constructed 4x4 $cm^2$, two-coil planar array.

**Methods:** Mutual Inductance Effects in Phased Arrays: Assuming that the frequency of operation is within the low limit, and the coil circuits are made up of straight line segments, all of which are either parallel or perpendicular to each other, the mutual inductance between the coil loops *i. k*, $M_{ik}$ can be approximated as the summation of contributions from all the line segments, expressed as: $M_{ik} = \frac{\mu_o}{4\pi}\sum_i\sum_k \pm\int\int dl_i \bullet dl_k / |r_{ik}|$ where the integration is performed for each pair of mutually parallel or antiparallel segments $dl_i$, $dl_k$, and with $|r_{ik}|$ being the vector distance between a point on coil *i* and a point on coil *k*. Coil Development and Implementation: Two identical square resonating loops were designed (with a loop size of 4x4 $cm^2$) and implemented. Both loops were independently tuned to the Larmor resonant frequency of 300.5 MHz at the field strength of 7 T. The coils were designed and constructed with thin copper tape sheets of 6 mm in width and 0.02 mm in thickness (3M, USA). Circular ring paddles with different diameters, empirically chosen based on electrical testing, were used to null the mutual inductance. The coils were implemented as receive coils with non-magnetic ceramic capacitors (1-30pF, ATC Inc., NY, USA), Oxley variable capacitors (Oxley Inc., Cumbria, UK) for tuning and matching, and shielded half-wavelength (λ/2) RG58/59 co-axial cable (Belden Inc., USA). Electrical losses were minimized by distributing the total capacitance, through the introduction of a copper-track break. The end-ring paddles were passive and were constructed with the same copper tape. Their electrical separation with the planar phased array loops was achieved using insulating tape. Bench coil matching and tuning was achieved with the use of a 1.5 GHz Network Analyzer (Model E5061A, Agilent Inc., USA). Magnetic Field Simulations of Proposed Array Designs: Assessment of the performance of the two-coil arrays included $B_1$-field simulations of the transverse and total field components in free space XFdtd (Remcom Inc., PA, USA), in the: (a) conventional overlapped, (b) non-overlapped, and (c) non-overlapped with passive end-ring paddle configurations, and bench tests. For XFdtd simulations, the coil conductors were defined as perfect electric conductors. A 1 V sinusoidal feed was applied (in opposite polarity in the two loops), and the source and conductor impedances were set to 50 Ohms (pure resistive). Excitation was emulated using a 1.5 ms modulated gaussian pulse centered at the resonant frequency of 300.5 MHz. Simulations did not account for coil matching conditions, but accounted for the presence of the copper break and the presence of the variable capacitors used in the implemented designs. Mid-axial and sagittal $B_1$ (offset by 2 cm from centerline) field maps quantitatively assessed possible effects of the passive end-ring paddles on the modification of the flux distribution of the coils. In the non-overlapped coil configurations, adjacent coil conductors of the two coil loops were placed 1.5 mm apart, to prevent an undesired merging of the computational mesh models within the simulation environment. The reconstructed $B_1$-field grid from XFdtd simulations was spatially matched in the two non-overlapped coil configurations and encompassed [67-87]×[41-42] axial grids, and [41-42]×[123-139] sagittal grids (with cell sizes of 1-1.5 $mm^3$), for quantitative comparison purposes. Electrical Performance of Phased Array: Measurements of unloaded and loaded parameters ($S_{11}$, $S_{12}$, $S_{21}$, $S_{22}$), and the composite impedance (with and without the use of the passive end-ring paddles) were conducted on a 50 mL gel phantom, and on a 27 g male mouse post-mortem.

**Results and Discussion:** Figure 1 depicts the normalized magnetic coupling coefficient variation between planar square phased array coils (3x3-10x10 $cm^2$) as a function of the inter-coil distance *l*. The linear dependency of the overlap distance with the coil size (Coil Overlap Distance [cm]=0.16*Coil Size +0.1, $r^2$=1) allows the prediction of the exact overlap of any two-coil rectangular array on a planar geometry. Also shown are the constructed array and $B_1$ profiles from simulated results, in the three proposed configurations. Simulated $B_1$-field comparisons in the 2-coil array case (no paddle vs. paddle case) showed mean percentage differences of only 1.03% over the entire integration matrix. Measurable differences also exist in the $B_1$ response of the overlapped vs. non-overlapped cases, as shown. Electrical performance characteristics (coil loops in isolation) yielded unloaded and phantom loaded gains ($S_{11}$, $S_{22}$) for the 4x4 $cm^2$ two coil-loop phased array of -28.2/-18.0, and -28.7/-27.4 dB, respectively. Unloaded coil performance (in the non-overlapped configuration) yielded split resonances of 297.7 and 304.1MHz (Loop 1) and 296.2 and 304.1 MHz (Loop 2), due to mutual coupling effects. In the presence of the passive end-ring paddles, single resonance peaks were restored. Unloaded gains of -20.9 and -27.6 dB were recorded for the two array coil loops. Coil isolation under unloaded conditions was -10.1 and -10.5 dB, respectively Phantom and mouse loaded responses were -29.0dB/52.9-1.6j Ω;-32.3dB/49.8+2.9j Ω (Loop 1) and -29.9dB/54.9-1.6j Ω ;-24.3 dB/47.5-1.7j Ω (Loop 2), respectively.

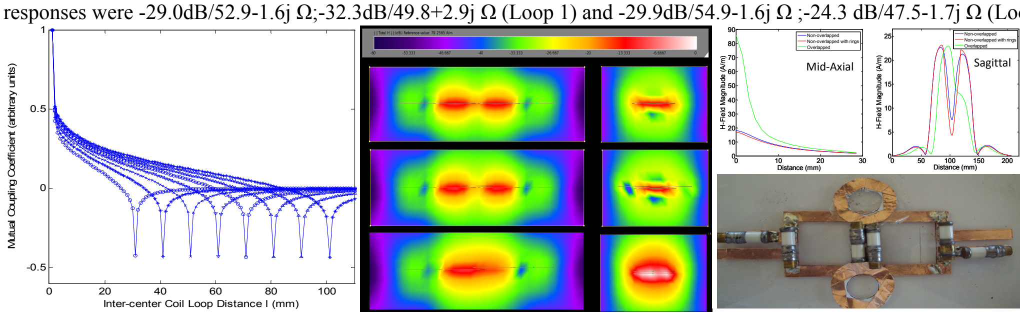


***Figure 1**: (Left to right) Mutual coupling coefficient variation of two planar square phased array coils with l, for centreline widths d=3-10 cm; $B_1$-field representations of two-coil phased arrays in sagittal (left) and mid-axial (right) orientations in (top) non-overlapped, (mid) non-overlapped with paddle, and (bottom) overlapped configurations driven by sources of similar polarity, and corresponding profiles; Schematic of a two-loop 4x4 $cm^2$ coplanar phased array.*

**Conclusion:** The present work and its findings introduce an easy and practical way to construct phased arrays with multiple coil loops. Such a methodology can support increased number of elements, addressing the complex mutual coupling issues of non-neighboring overlapping coil loops, in a spatially-efficient arrangement. Use of such passive ring paddles imposes, however, finite loading effects on the coil loop electrical responses, which can be easily adjusted through the use of the variable capacitors or half-paddle designs with adjustable knobs. Any residual mutual coupling will improve with the interface of the constructed array with low impedance preamplifiers. Once positioned, the array can be re-tuned and re-matched easily using the variable capacitors or adjustable knobs connected to the half-paddles, to attain proper resonance and loading characteristics.

**References: 1)** Roemer et al. MRM 16:192, 1990; **2)** Bloch F et al. Phys. Rev. 70:474, 1946, **3)** Duensing G et al. JMR Ser B 111:230, 1996, **4)** Zhang X et al. JMR 170:149, 2004, **5)** Mogatadakala et al. MRM 60:1498, 2008.**Acknowledgements:** Support was received from grant TEXNOLOGIA/0609(BE)/05 from the Research Promotion Foundation.