Constellation Coil Design

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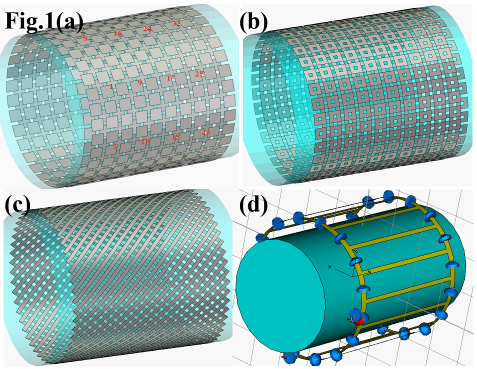
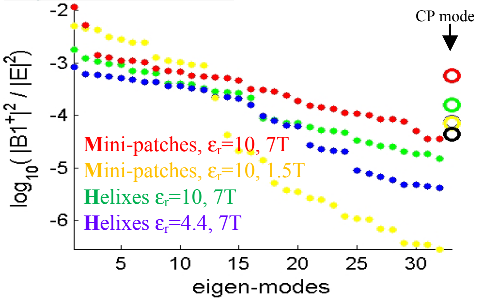
Introduction: While a radio-frequency magnetic field (B1) is employed to interact with spins and create MR signal, a necessarily accompanying electric field (E) induces RF loss inside scanned subject and caps transmit and receive performance with SAR and noise respectively. The essence of RF system performance optimization can be described as one of maximizing $|B1^{\pm}|/|E|$, quantities that track flip angle-to-√SAR ratio (spin excitation) and signal-to-noise ratio (signal detection). Further to this field-oriented perspective, we note that the RF current carried by the coil structure is the means by which an MR scanner implements / optimizes RF fields. Constellation coil [1], a new approach to MR RF coils, targets a supportive structure for ideal RF current patterns and thereby the ultimate performance. The new approach's intrinsic support for highly parallel transmit and receive can also play a central role in overall scan performance enhancement. The present study explores geometries and parameters for practical constellation coil implementation. FDTD simulations and parallel Tx / Rx MR experiments were used to evaluate prototypes.

Methods and Results: Among all EM field patterns inside the subject that are compatible with Maxwell's equations, some outperform others and register the ultimate performance allowed by electrodynamics. Clearly if a specific RF coil structure is capable of inducing only a subset of the patterns, due to, for example, geometrical constraints on current distribution, a gap may exist between the performance achievable with the structure and that of the ultimate. This is evidenced in examples of studying ultimate performance in excitation and detection[2]. A constellation coil's structure mimics an RF continuum, and tends to be more accommodating of all EM field patterns (Love's field equivalence theorem) than a conventional RF coil's discrete structure. To take advantage of the constellation coil concept, several aspects of implementation are envisioned: (I) Use of a structure that is substantially continuous at Larmor frequency, isotropic in carrying (conducting+displacement) current, and transparent to gradient, (II) Proper distribution of a significant number of ports, (III) Weighted combinations of the ports if #channels < #ports, and (IV) Two tailored sets of port use schemes, one for each of Tx and Rx.

Fig.1a-c show the geometry of several constellation coils modeled in FDTD simulations (CST Microwave Studio). **Fig.1c** shows a structure where a PCB with a grid pattern, formed by two layers of helixes sandwiching a 0.79mm-thick substrate of ε_r=4.4 (FR4), was wrapped around a ∅20cm cylindrical former. This modeled an eight-port prototype recently evaluated in 7T MR[1]. A variant to this version used a substrate of ε_r=10. **Fig.1a** shows a structure composed of two layers of mini patches sandwiching a 0.79mm-thick substrate of ε_r=10. The mini patches are of size 15mm x 15mm, and each is capacitively coupled to its four immediate neighbors on the other side of the substrate. Use of high dielectric-constant substrate strengthens the capacitive coupling, facilitating free flow of RF current. This geometry is more isotropic from the surface current's point of view and tends to reduce stray capacitance buildup. Further removing the center 1/3 x 1/3 of each patch led to a 2-layer mini-loop version shown in **Fig.1b**, which maintains the capacitive coupling and RF continuum while improving transparency for gradient field. Each design had 32 ports (Fig.1a) to cover the coil structure and to support implementation possibilities II-IV. **Fig.1d** shows a tuned and matched high-pass 7T birdcage coil that was used as a reference in evaluations. All coils in this study had an overall size of 20cm in diameter and ~20cm in length, and were each loaded with a cylinder phantom of ε_r=80 and σ=0.6S/m (see Fig.1d).

Fig.1(a) **(b)** **(c)** **(d)**





A metric[3] that tracks the ratio of $|B1^{+}|^2$ averaged over a region of interest to $\sigma|E|^2$ (RF power deposition) averaged over a lossy volume was used to assess Tx efficiency of the designs. In this study the region of interest and the lossy volume were, respectively, the center 57% and 100% of the phantom. Depending on the applied RF shimming weights, **w**, or parallel RF pulses, **w**(t), a multi-port coil operates at a range of efficiency levels, as quantified by the metric, equivalently expressed as $\eta = \mathbf{w}^H \mathbf{\Gamma}\, \mathbf{w} / \mathbf{w}^H \mathbf{\Phi}\, \mathbf{w}$. Maximum and minimum exist that bound the efficiency range. Recognizing that it is a generalized eigenvalue problem, one can approach efficiency assessment with the eigen-modes. The largest eigenvalue and its corresponding eigenvector represent, respectively, the maximum Tx efficiency and the corresponding driving weights **w**. Other modes deliver less efficiency and can also be readily identified. **Fig.2** shows the efficiency of the eigen-modes of four of the designs, indicating the 2-layer mini-patch design's tendency to outperform the others. This design was also characterized for 1.5T use - a large swing of efficiency was noticed, consistent with the observation that rather clean circularly polarized and anti-circularly polarized B1 can be produced at 1.5T (yielding, respectively, substantial and nearly zero average $|B1^{+}|$). For the individual designs, driving the first 8 ports in CP mode registered efficiency values marked by the circles. The black circle marks the efficiency of the birdcage in CP mode, which was lower than the others.

The constellation coil illustrated in Fig.1a was built (**Fig.3**). Parallel Tx and Rx MR using Ports 1-8 were conducted on a whole body Siemens 7 T scanner capable of 8-channel parallel Tx. Fig.3 shows example localizer images obtained in phantom imaging at a Tx voltage of 16V. Driving the first 8 ports in CP mode produced a $B1^{+}$ profile (**Fig.4b**) resembling that of a same-size birdcage. Fig.4a shows the $B1^{+}$ profiles corresponding to individual port driving. **Fig.5** further shows volunteer imaging results obtained with a GRE sequence without parallel Rx acceleration (Fig.5a) and with 2x acceleration (Fig.5b). Additional parameters include: 40V Tx voltage, TR=220ms, TE=5.4ms, slice thickness=4mm, NEX=1, 230x320 matrix and FOV=21.6x30.0cm^2.

Fig.3

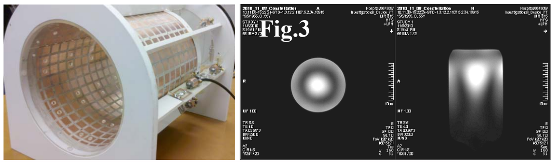
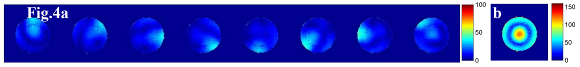
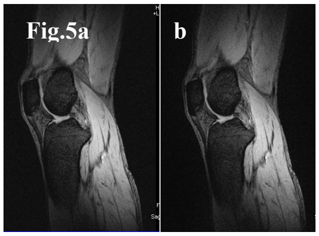


Fig.4a **b**



Discussions: In addition to supporting parallel Tx/Rx with a multitude of distinct B1 field profiles, each design, when driven in CP mode, appears to be capable of approximating B1 patterns similar to that of a conventional cylindrical volume coil. For multi-channel Tx/Rx, characterizing transmit efficiency is no longer possible with a scalar, yet remains tractable with an eigen-mode analysis which also facilitates evaluation/comparison. As an aside, CP mode was observed to give mid range efficiency - if use of single channel / a fixed B1 pattern is desired, there can be an advantage to use the max efficiency mode or a combination of higher efficiency modes, especially in high field MR where CP mode does not necessarily yield higher B1 homogeneity as is traditionally desired.

Fig.5a **b**



1. Y. Zhu, *18th ISMRM*, p 46, 2010. 2. R.Lattanzi, et al., *MRM*, 61:315-334, 2009. 3. Y. Zhu, *18th ISMRM*, p 1518, 2010.