Efficient Analysis of Dielectric Materials in Coupled RF Coil Configurations

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Purpose: MRI at high fields requires new approaches to RF coil design to maximize RF performance. Over the past years, various technologies have been developed, ranging from active control via parallel RF transmission (pTx), to passive approaches using dielectric materials. Previous work also indicates that the combination of both can yield further improvements.[1,2] However, the analysis of a dielectric shim in resonant coil structures such as surface arrays can involve long simulation times due to mutual coupling. This impedes a constructive analysis on the design of the dielectric in such scenarios.

A domain decomposition method has previously been presented which reduces the computational domain to that of the dielectric shim, allowing for much faster evaluation of its effect.[3] This approach is especially powerful in a decoupled scenario in which the coil's current distribution is minimally affected by the dielectric. In this work, we extend the domain decomposition method using circuit co-simulation techniques to account for tuned coil models as well as array configurations. Examples are shown for a tuned 7T birdcage analysis and a four-channel dipole array design study.

Methods: The effect of a dielectric in a background RF field generated by a port with index p can be formulated as a field 'perturbation' and solved for via domain decomposition as $E_p = (\mathbb{I} - \mathbb{G}^{E,J}\chi)^{-1} E_p^b$ where $\mathbb{G}^{E,J}$ denotes the Green's tensor for electric current density to electric field, χ denotes the electric susceptibility which characterizes the dielectric shim, and E_p^b is the background electric field generated without the dielectric whereas E_p denotes the final perturbed field. The computational complexity amounts to inverting the system matrix once, afterwards the resulting inverse can be reused on all ports for the given dielectric.

The perturbed B_1^+ fields as well as the port voltages and currents can then be obtained via direct evaluation of a set of matrix-vector products, given by

$$B_{1,p}^+ = B_{1,p}^{+,b} + \mathbb{G}^{B_1^+,J}\chi E_p \qquad V_p = V_p^b + \mathbb{G}^{V,J}\chi E_p \qquad I_p = I_p^b + \mathbb{G}^{I,J}\chi E_p$$

with $\mathbb{G}^{B_1^+,J}$, $\mathbb{G}^{V,J}$, and $\mathbb{G}^{I,J}$ denoting the Green's tensors for electric current density to B_1^+ field, port voltage and current, respectively. Using this set of voltage and current relations and EM fields, a circuit co-simulation analysis can be set up in a straightforward manner to evaluate the circuit domain relations.[4,5]

All Green's tensors have been evaluated using FDTD (XF7, Remcom inc., PA, USA) and customized codes have been developed in Matlab (R2016, Mathworks inc., MA, USA).

Results: To illustrate the utility of the method we present two analyses of scenarios which involve a multiport coil model. The first is a 16-rung high-pass birdcage transmit coil, loaded by a male head model.[6] A single dielectric pad of 18×18×1 cm is positioned on the left side of the head. Figure 1 shows the B field generated by a port in close vicinity to the dielectric pad, and illustrates the accuracy of the domain decomposition procedure. The resulting fields are then combined in the circuit domain to quadrature mode as shown in Fig. 2. The time required to evaluate the field perturbation and circuit-level combination was 20 s, whereas re-evaluation of the 34 portwise fields via FDTD would have taken 38 minutes.

The second scenario concerns the parametric optimization of a four-channel dipole array surrounding a dielectric cylinder (ε = 60, σ = 0.65 S/m) with a centered dielectric sleeve of 10 cm length and 1-cm thickness (Fig. 3a). The aim is to maximize the central transmit efficiency by changing the permittivity of the sleeve in conjunction with the length of the dipole and the position of the tuning inductor. This is achieved by segmenting a 35-cm dipole into 2.5 cm sections and combining these in the circuit domain via a topological arrangement of shorts, opens and tuning inductors. The resulting parametric variation is shown in Fig. 3b and Fig. 3c and shows an optimal relative permittivity for the sleeve of 100. Solving for the effect of the sleeve and running through the dipole design parameters in the circuit-domain took on average 35 s per value of the relative permittivity, compared to over an hour using FDTD.

Discussion and conclusion: An efficient method to analyse the effects of a dielectric in coupled coil models has been demonstrated. By combining the domain decomposition method to account for the dielectric with a circuit-domain model of the coil, fast evaluations can be performed for arbitrary circuit arrangements as well as arbitrary dielectric shim designs. The method can be applied to any linearized coil model, such as transmit coil arrays as well as receive arrays in an analogous manner.
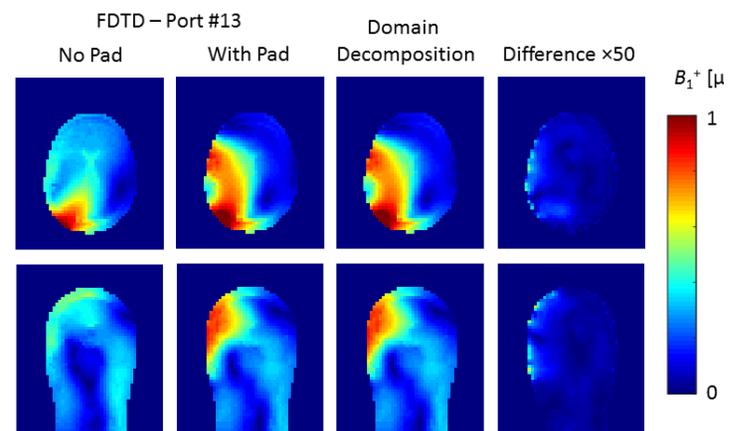
Figure 1. Accuracy of the domain decomposition method. Shown are B fields generated by port #13 of the birdcage model in close vicinity to the dielectric pad, with and without dielectric pad (ε_r = 300), illustrating the accuracy of the domain decomposition method.
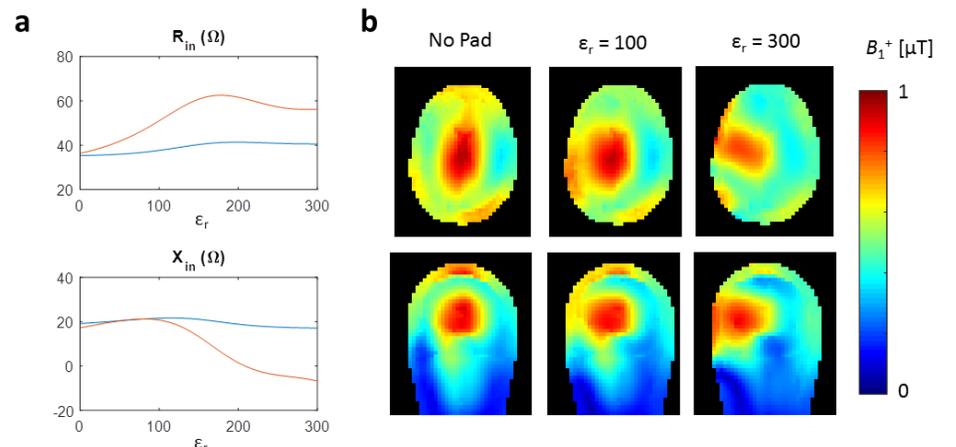

Figure 2. Analysis of the tuned birdcage model. a) The effect of the dielectric permittivity of a single dielectric pad on the impedance of the two channels of the coil. b) Resulting B_1^+ field distributions for selected values of ε_r.
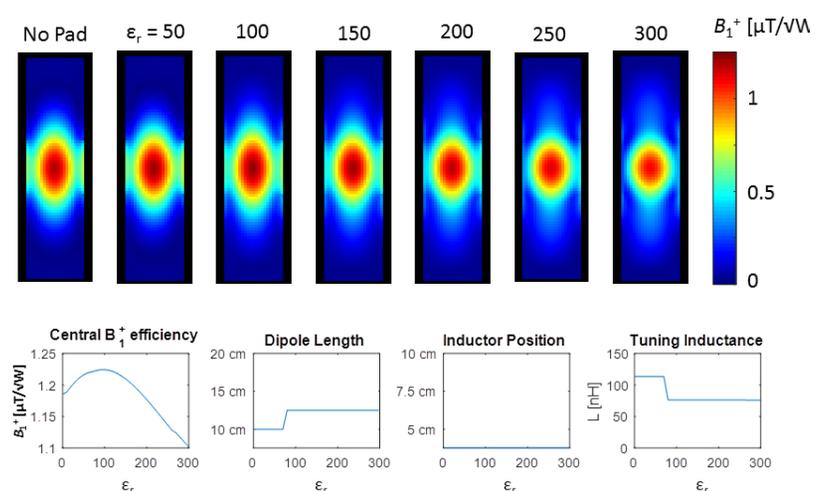

Figure 3. Parametric optimization of a four-channel dipole array. (top) B_1^+ field distributions for selected values of the sleeve permittivity. (bottom) Variational plots of the design parameters.

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