Multi-functional RF coils for 7T MRI based on 1D/2D electromagnetic metamaterial engineering

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Agenda

- 1D EM Metamaterials – CRLH «MetaLines»:
  – ZOR coil elements
  – dual-resonant coil elements
  – traveling-wave coil system «MetaBore»

- 2D EM Metamaterials – HIS «MetaSurfaces»:
  – elongated dipole elements on HIS ground plane
  – 8-channel HIS coil system
1D EM Metamaterials I
Tailoring transmission lines
(1) Design of CRLH* MetaLines:

(2) zeroth-order resonance (ZOR):

(3) standing wave resonance (λ-wave):

1D EM Metamaterials II
First multi-channel ZOR coil

- CRLH Metaline with coaxial stub lines as parallel inductors.
- short terminations yield a pronounced series resonance → uniform J_r over 40cm!
- Performance: FoM: \( |\mathbf{B}|^2 \frac{I_{\text{max}}}{\sqrt{\text{SAR}_{\text{max}}}} = -2.6 \text{ dB} \); decoupling: \( S_{ij} \leq -30 \text{ dB} \); \( \text{SAR}_{100} \sim 70\% \) of MSL dipole
1D EM Metamaterials III

Dual-resonant coils for $^{23}\text{Na} / ^{1}\text{H}$ high-field MRI

1. Composite right-left-handed (CRLH) MetaLine
   - multi-layer topology
   - $\lambda/4$ resonance
   - excitation of $^{23}\text{Na} / ^{1}\text{H}$

   $^{1}\text{H}$: $f_h = 298\text{ MHz}$
   
   $^{23}\text{Na}$: $f_h = 79\text{ MHz}$

   $\lambda/4$ resonant coil element consisting of a 3 section meta-line

2. RF magnetic fields
   - simulations vs. near-field measurements (i.e. near-field probing)
   - cylindrical phantom for validation purposes
1D EM Metamaterials V

Dual-resonant coils for $^{23}\text{Na}/^1\text{H}$ high-field MRI

(3) Verification within a functional MRI scan

- There is an apparent selectivity between hydrogen and sodium images.
- Hydrogen images: reproduce the ping-pong ball insets due to the high SNR.
- Sodium images: are much less selective due to the low SNR ($\rightarrow$ increase $Q_{\text{unload}}$ @ 79 MHz).
- Sodium images are inhomogeneous due to the standing-wave nature of the quarter-wave resonance (in conjunction with the low SNR).

BTSL phantom with filled ping-pong ball insets (NaCl solution or NaCl agar mixtures)

Sodium images @ 79 MHz (still low SNR)

Hydrogen images @ 298 MHz (high SNR)

1D EM Metamaterials VI

Dual-resonant coils for $^{23}\text{Na}/^1\text{H}$ high-field MRI

(3) Verification within a functional MRI scan
1D EM Metamaterials VII

Traveling-wave MRI

(1) Excitation concept (298 MHz):
- uniform \( B_1 \) field along \( z \)
- unidirectional \( TE_{11} \) wave
- circularly polarized

(2) Excitation antennas:
(simplified for linear polarization)
- conventional approach:
- ergonomic approach:
  (circumferential full \( \lambda \) wave resonance, quadrature excitation of circularly polarized fundamental \( TE_{11} \) mode).

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1D EM Metamaterials VIII

Traveling-wave MRI excitation scheme

The «MetaBore» concept:
- Multiple MTM ring antennas
- Similar to active 2D EM MTM
- Optimizing current excitations
- Namely amplitudes & phases
- Sets up an inverse problem

\[
\begin{align*}
\bar{J}_1(\omega) + \bar{J}_1(\omega - \frac{\pi}{3}) \\
\bar{J}_2(\omega) + \bar{J}_2(\omega - \frac{\pi}{3}) \\
\bar{J}_3(\omega) + \bar{J}_3(\omega - \frac{\pi}{3}) \\
\bar{J}_4(\omega) + \bar{J}_4(\omega - \frac{\pi}{3})
\end{align*}
\]
The «MetaBore» Concept I

Test case: «Larynx illumination»

(1) Profiling scenario for confined illumination:
(while solving an inverse problem)
(c) total $B_1$ field

- 18 continuous circular current strips
  (width: 1 cm / pitch: 15 cm / $\phi$: 64 cm).
- Gaussian profile: FWHM = 15 cm

(a) current excitation amplitudes
(b) current excitation phases

The «MetaBore» Concept II

Test case: «Larynx illumination»

(2) Field amplitudes constituting the illumination profile:

- Virtually purely circularly polarized B-fields ($B_1^{(+)}$).
- Undesired component $B_1^{(-)}$ is suppressed by 21dB.
- Conforms perfectly to the target profile.
- Achieved field confinement (FWHM = 15 cm) is much below the wavelength of the $TE_{11}$ waveguide mode (2.6 m ... 3.5 m).
- No hotspots in the neck-shoulder region.
2D EM Metamaterials I

High Impedance Surfaces (HIS)

(1) Operation principle of the HIS shield:

- PEC: induced out-of-phase currents \( \rightarrow \) reduction of \( B_1 \)
- HIS: suppression of induced currents (only in-phase residuals)
- the HIS behaves similar to a PMC

(2) Comparison of \( B_1 \) field distributions (simulation):

(3) Potential HIS structures:

2D EM Metamaterials II

Uni-planar HIS surface

(1) Topology and frequency responses:

- the uni-planar HIS surface has a smaller reflection bandwidth compared to the mushroom HIS, but is much easier to fabricate (no vias).
- multilayer HIS \( \rightarrow \) additional DoFs, smaller unit cell
2D EM Metamaterials III

Dipole-based RF coil element

(2) HIS shielded dipole coil element:

(3) Elongated dielectric-loaded dipole:

- Transversal flux profile broadening: 40%
- Peak flux enhancement: $1.4\% \ (d = 20 \text{ mm})$
- $26\% \ (d = 5 \text{ mm})$

(1) Elongated dielectrically-loaded dipole:

- Meander: geometrical compression/masking of the decreasing current distribution at the dipole end.
- Dielectric: increases the electrical length of the meander.

2D EM Metamaterials IV

8-channel HIS dipole coil

(1) Simulations: (normalized $IB_1$ field)

(2) Measurements: (normalized $IB_1$ field)
2D EM Metamaterials V

Coupling in 8-ch dipole coils

(2) 8-Channel HIS dipole coils – coupling:

- **Measurement**: the HIS coil system shows the expected higher overall coupling compared to the PEC coil system.
- **Measurement**: the HIS coil system shows a 3dB stronger nearest neighbor element coupling compared to the PEC coil system (HIS: –13dB, PEC: –16dB).

(1) 8-Channel HIS dipole coils – Flip-angle images:

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Summary

- **Functionalizing CRLH MetaLines:**
  - zeroth-order resonance (ZOR) that aims at
    - large uniform, longitudinal field-of-views (FoVs)
    - whole-body MRI
    - lower peak electrical field $E_{\text{max}}$ and peak SAR.
  - standing-wave resonances of tailored extent (i.e. wavelength $\lambda$ via dispersion engineering).
  - intrinsic dual-band features for combined sodium/proton MRI.

- **Functionalizing HIS MetaSurfaces:**
  - HIS: suppression of image currents,
    - Dipole (PEC → HIS): $\Delta I_{\text{avg}} = +20\%$; $\Delta \text{CoV} = -18\%$
    - 8-ch (PEC → HIS): $\Delta I_{\text{avg}} = +10\%$; $\Delta \text{CoV} = -13\%$
  - azimuthal homogenization, better field penetration, but: higher cross-coupling.

- **Future work:**
  - exploring multi-band MetaLine-based coil elements ($^1\text{H}$, $^{19}\text{F}$, $^{23}\text{Na}$, $^{31}\text{P}$).
  - Leaky-wave antenna-based broadband coil elements.
That’s all – Thanks. www.ate.uni-due.de

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