March 13, 2019 / Comprehensive Heart Failure Center (CHFC) / University Hospital Würzburg

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

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Agenda

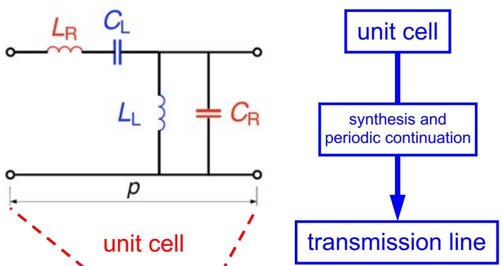
- **1D EM Metamaterials – CRLH «MetaLines»:**
  - – ZOR coil elements
  - – dual-resonant coil elements
  - – traveling-wave coil system «MetaBore»
- **2D EM Metamaterials – HIS «MetaSurfaces»:**
  - – elongated dipole elements on HIS ground plane
  - – 8-channel HIS coil system

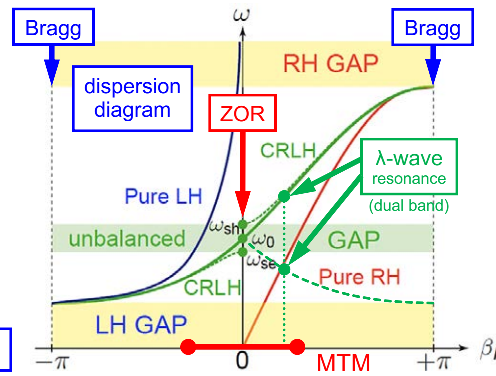
1D EM Metamaterials I

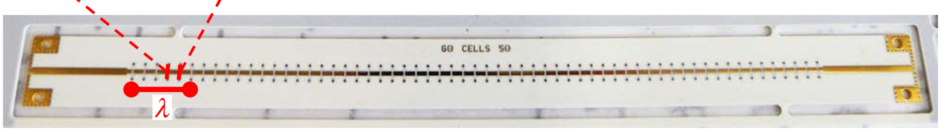
*) CRLH: composite right-/left-handed

Tailoring transmission lines

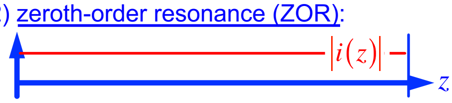
(1) Design of CRLH*) MetaLines:



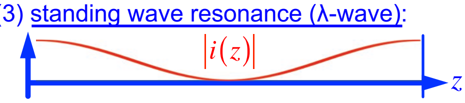




(2) zeroth-order resonance (ZOR):



(3) standing wave resonance (λ-wave):

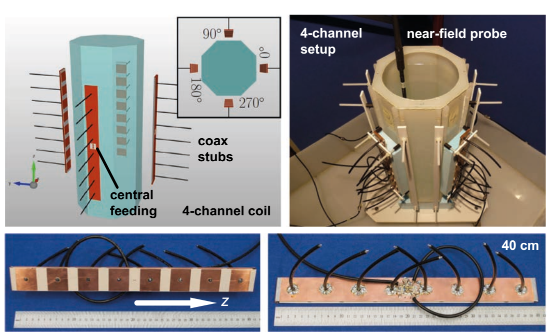


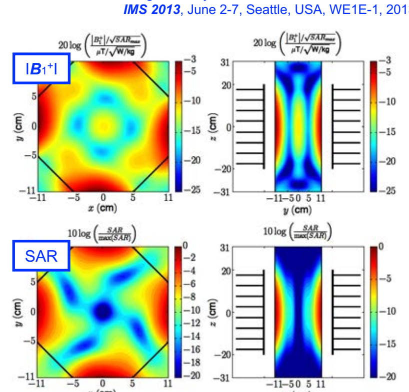
1D EM Metamaterials II

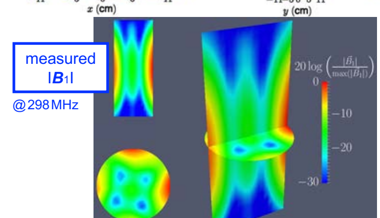
A. Rennings, J. T. Svejda, K. Solbach, and D. Erni, ***MAGMA***, vol. 26, no. suppl 1, pp. 183-185, Oct. 2013.

A. Rennings, J. Svejda, S. Otto, K. Solbach, and D. Erni, ***IMS 2013***, June 2-7, Seattle, USA, WE1E-1, 2013.

First multi-channel ZOR coil







- CRLH Metaline with coaxial stub lines as parallel inductors.
- short terminations yield a pronounced series resonance → uniform J_z over 40 cm!
- Performance: FoM: $|B_1^+|_{max}/\mathrm{sqrt}(SAR_{max}) = -2.6$ dB; decoupling: $S_{ij} \leq -30$ dB; SAR_{10g} ~70% of MSL dipole

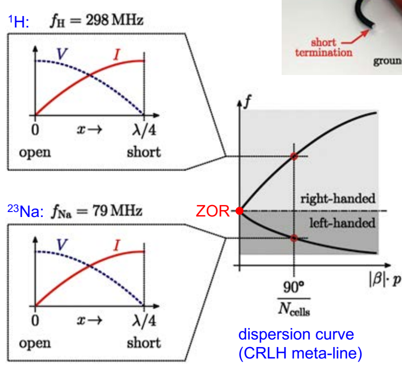
1D EM Metamaterials III

J. T. Svejda, A. Rennings, D. Erni, *tm – Technisches Messen*, vol. 84, no. 1, pp. 2-12, Jan. 2017,
MAGMA, vol. 29, no. suppl 1, pp. S309, Oct. 2016.

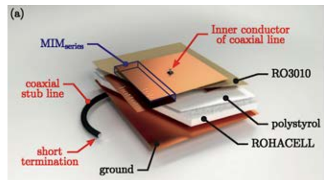
Dual-resonant coils for $^{23}Na/^{1}H$ high-field MRI

(1) Composite right-/left-handed (CRLH) MetaLine

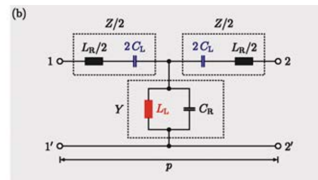
- multi-layer topology
- $\lambda/4$ resonance
- excitation of $^{23}Na/^{1}H$



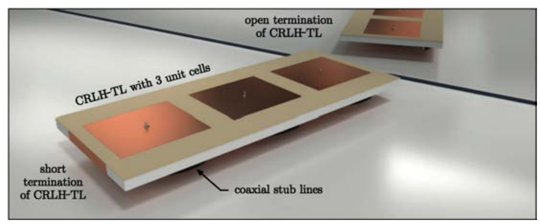
dispersion curve (CRLH meta-line)



triple-layer metallization



unit cell: varying L_L to meet the 2 resonances



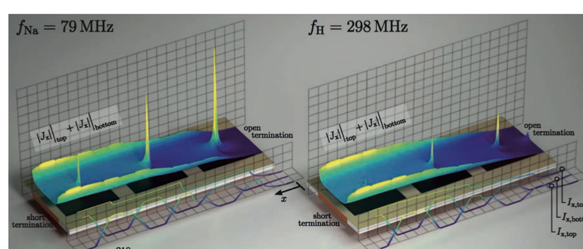
$\lambda/4$ resonant coil element consisting of a 3 section meta-line

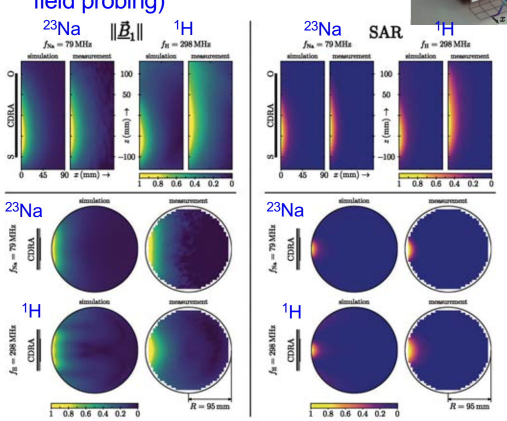
1D EM Meta…

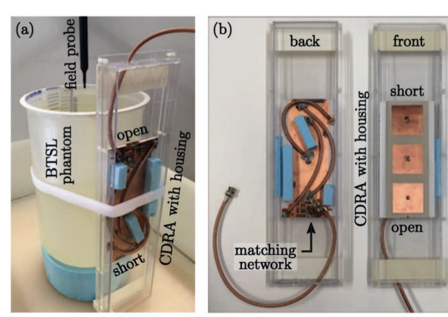
Dual-resonant coils …

(2) RF magnetic fields

- simulations vs. near-field measurements (i.e. near-field probing)







- cylindrical phantom for validation purposes

1D EM Metamaterials V

J. T. Svejda, A. Rennings, D. Erni, ***tm – Technisches Messen***, vol. 84, no. 1, pp. 2-12, Jan. 2017,
MAGMA, vol. 29, no. suppl 1, pp. S309, Oct. 2016.

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

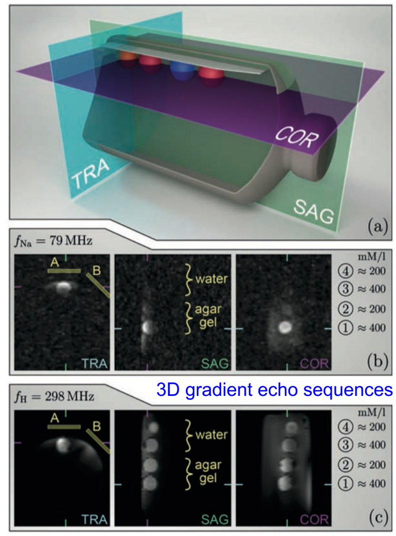
(3) Verification within a functional MRI scan

- 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 (→ increase Q_{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)

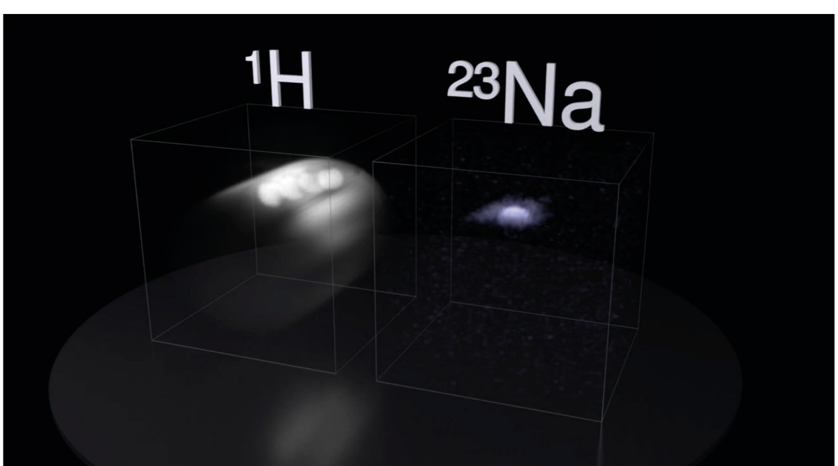


1D EM Metamaterials VI

Jan Taro Svejda, *Dual-frequente CRLH-Metaleitungs-Resonatoren für simultane ¹H/X-Kern MRT bei 7 Tesla.*
PhD Thesis, University of Duisburg-Essen, Duisburg, Feb. 4, 2019.

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

(3) Verification within a functional MRI scan

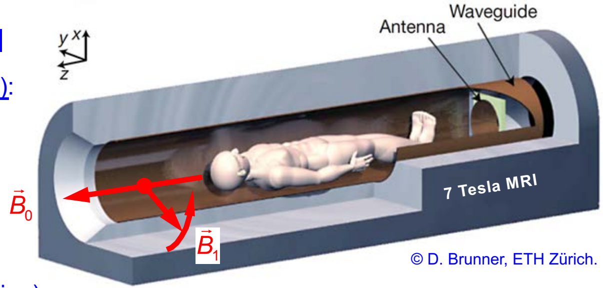


1D EM Metamaterials VII

Traveling-wave MRI

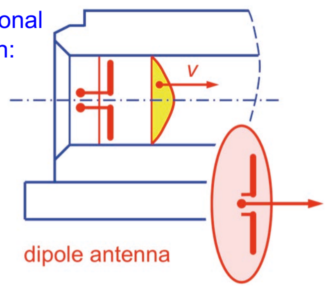
(1) Excitation concept (298 MHz):

- uniform $\boldsymbol{B}_1$ field along z
- unidirectional TE_{11} wave
- circularly polarized



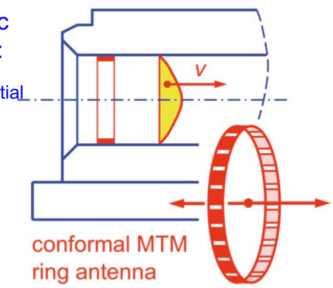
(2) Excitation antennas:
(simplified for linear polarization)

- conventional approach:



- ergonomic approach:

(circumferential full λ-wave resonance, quadrature excitation of circularly polarized fundamental TE_{11} mode).



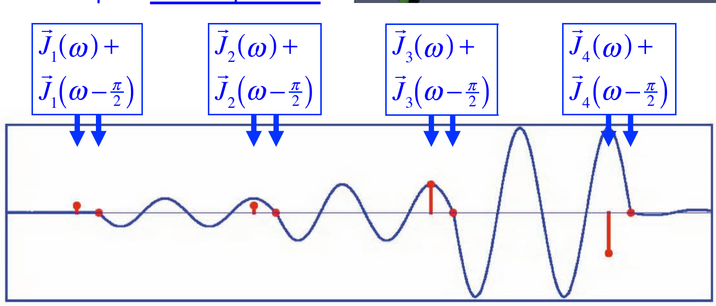
1D EM Metamaterial VIII

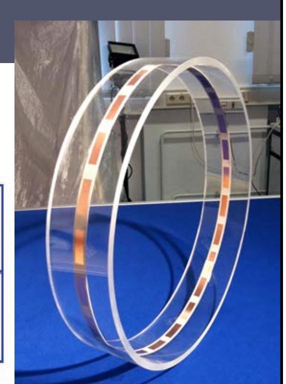
D. Erni, T. Liebig, A. Rennings, N. H. L. Koster, and J. Fröhlich, 33th *IEEE EMBS 2011*, Aug. 30 - Sept. 3, Boston, MA, USA, 2011.

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





The «MetaBore» Concept I

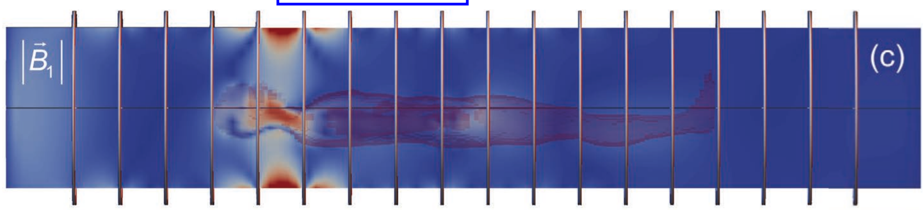
T. Liebig, J. T. Svejda, H. Yang, A. Rennings, T. Herrmann, J. Mallow, J. Bernarding, J. Froehlich, and D. Erni, ***ISMRM-ESMRMB 2014***, May 10-16, Milano, Italy, 2014.

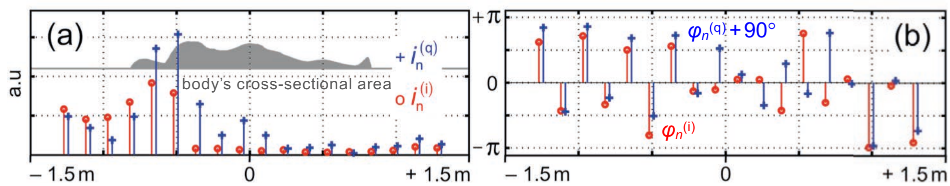
Test case: «Larynx illumination»

(1) Profiling scenario for confined illumination:
(while solving an inverse problem)

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

(c) total B_1 field $N = 18$ / $M = 137$





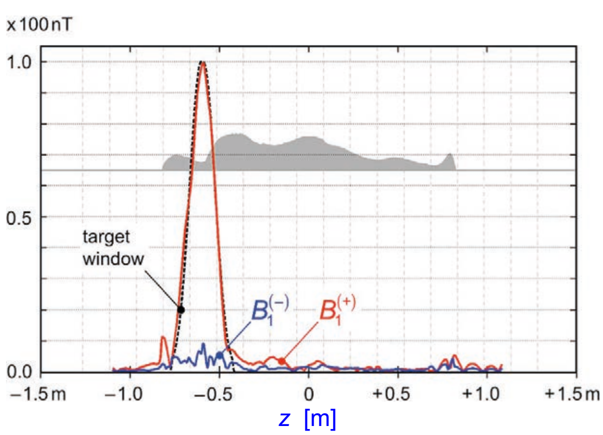
(a) current excitation amplitudes (b) current excitation phases

The «MetaBore» Concept II

T. Liebig, J. T. Svejda, H. Yang, A. Rennings, T. Herrmann, J. Mallow, J. Bernarding, J. Froehlich, and D. Erni, ***ISMRM-ESMRMB 2014***, May 10-16, Milano, Italy, 2014.

Test case: «Larynx illumination»

(2) Field amplitudes constituting the illumination profile :



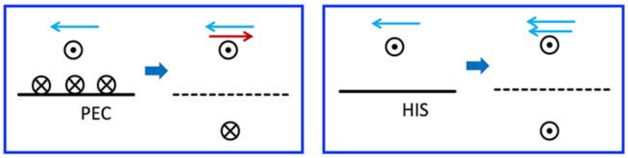
- Virtually purely circularly polarized B-fields ($B_1^{(+)}$).
- Undesired component $B_1^{(-)}$ is suppressed by 21dB.
- Conforms perfectly to the target profile.
- Achieved field confinement (FWHM = 15 cm) is much below the wavelength of the TE_{11} waveguide mode (2,6 m … 3,5 m)!
- No hotspots in the neck-shoulder region.

D. Erni, N. H. L. Koster, A. Rennings, T. Liebig, ***German Patent***, no. 10 2011 111 996, 2012.
D. Erni, N. H. L. Koster, A. Rennings, T. Liebig, ***German Patent***, no. 10 2010 010 189, 2013.

2D EM Metamaterials I

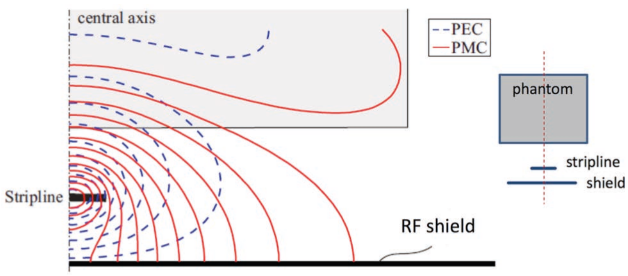
High Impedance Surfaces (HIS)

(1) Operation principle of the HIS shield:

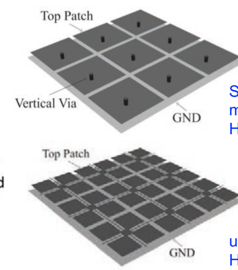


- PEC: induced out-of-phase currents → reduction of $\boldsymbol{B}_1$
- HIS: suppression of induced currents (only in-phase residuals).
- the HIS behaves similar to a PMC.

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



(3) Potential HIS structures:



Sievenpiper mushroom HIS surface

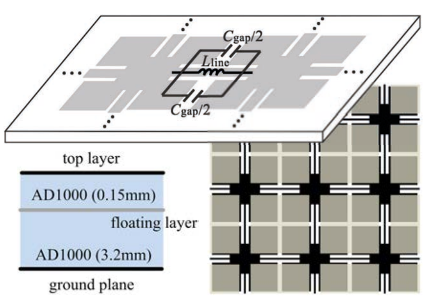
uni-planar HIS surface

2D EM Metamaterials II

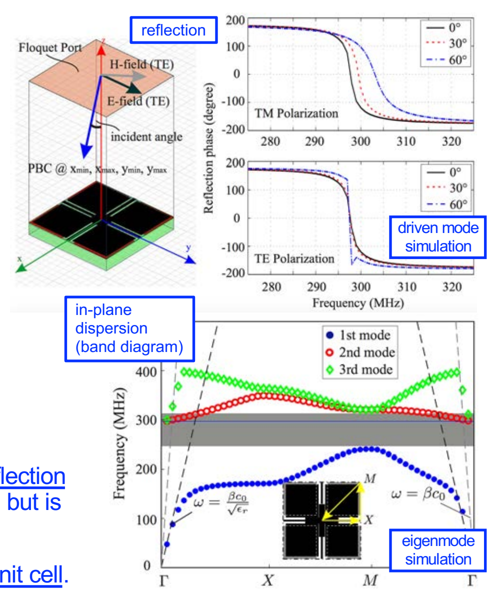
Z. Chen, K. Solbach, D. Erni, and A. Rennings, ***EuMC 2014.***, Oct. 6-9, Rome, Italy, 2014.

Uni-planar HIS surface

(1) Topology and frequency responses:



multilayer HIS surface



(2) Conclusions:

- 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 → additional DoFs, smaller unit cell.

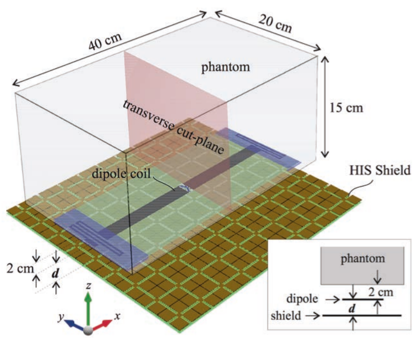
-15/19-

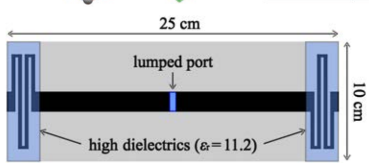
2D EM Metamaterials III

Z. Chen, K. Solbach, D. Erni, and A. Rennings, ***IEEE Trans. Microw. Theory Techn.***, vol. 64, no. 3, pp. 972-983, 2016.

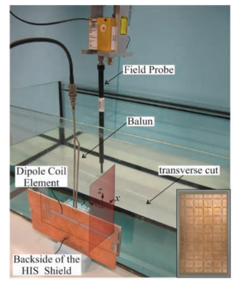
Dipole-based RF coil element

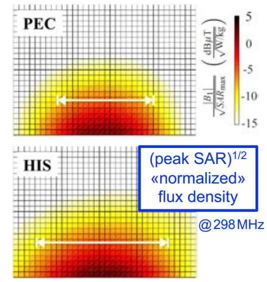
(2) HIS shielded dipole coil element:





(3) Elongated dielectric-loaded dipole:





- transversal flux profile broadening: 40%
- peak flux enhancement: 1.4% (d = 20 mm)
  26% (d = 5 mm)

(1) Elongated dielectrically-loaded dipole:

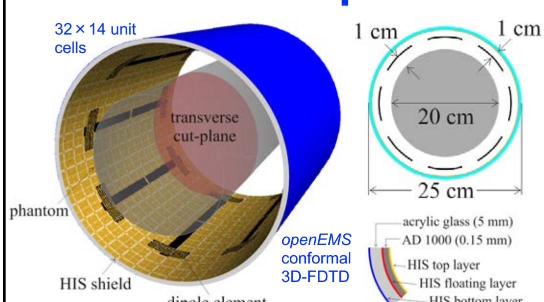
- Meander: geometrical compression/masking of the decreasing current distribution at the dipole end.
- Dielectric: increases the electrical length of the meander.

-16/19-

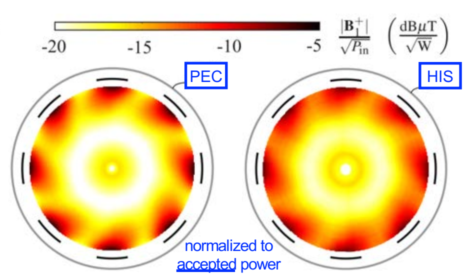
2D EM Metamaterials IV

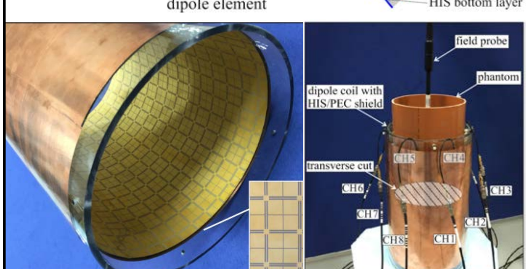
Z. Chen, J. T. Svejda, K. Solbach, D. Erni, A. Rennings, ***EDUHF-LAB MRI Workshop 2016***, May 19 Magdeburg, Gemany, 2016, (invited talk)

8-channel HIS dipole coil

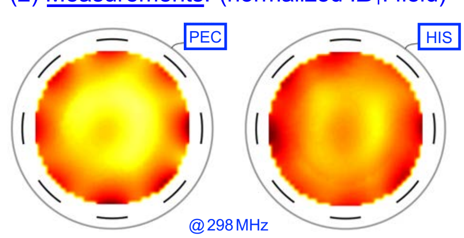


(1) Simulations: (normalized $|B_1^+|$ field)





(2) Measurements: (normalized $|B_1|$ field)



2D EM Metamaterials V

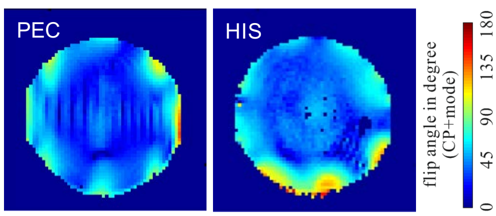
Zhichao Chen, ***Ph.D. Dissertation***, University of Duisburg-Essen, December 2016.
Z. Chen, K. Solbach, D. Erni, and A. Rennings, ***IEEE Trans. Biomed. Eng.***, vol. 64, no. 6, pp. 1297-1304, June. 2017.

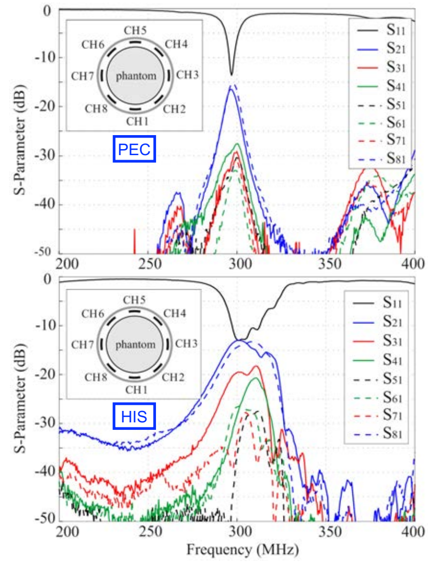
Coupling in 8-ch dipole coils

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

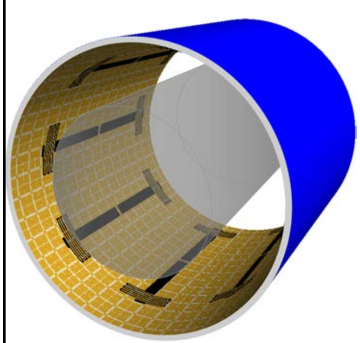
- Measurement: the HIS coil system shows the expected higher overall coupling compared to the PEC coil system.
- Measurement: the HIS coil system shows a 3dB stronger nearest neighbor element coupling compared to the PEC coil system (HIS: –13 dB, PEC: –16 dB).

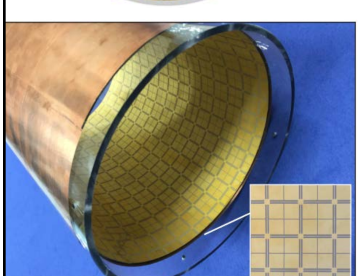
(1) 8-Channel HIS dipole coils – Flip-angle images:





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 $\boldsymbol{E}_{max}$ and peak SAR.
  - standing-wave resonances of tailored extent (i.e. wavelength λ via dispersion engineering).
  - intrinsic dual-band features for combined sodium/proton MRI.
- **Functionalizing HIS MetaSurfaces**:
  - HIS: suppression of image currents,
    Dipole (PEC → HIS): $\Delta|\boldsymbol{B}_1|_{av}$ = +20%; ΔCoV = –18%
    8-ch (PEC → HIS): $\Delta|\boldsymbol{B}_1|_{av}$ = +10%; ΔCoV = –13%
    azimuthal homogenization, better field penetration,
    but: higher cross-coupling.
- **Future work**:
  - exploring multi-band MetaLine-based coil elements (^{2}H, ^{19}F, ^{23}Na, ^{31}P).
  - Leaky-wave antenna-based broadband coil elements.

That's all – Thanks. www.ate.uni-due.de

Dr.-Ing. Andreas Rennings
- project leader MRI
- EM Metamaterials for high-field MRI

Dr.-Ing. Zhichao Chen
- former Ph.D. student
- elongated dipole elements over metamaterial ground planes, 8-channel coils

Dr.-Ing. Jan Taro Svejda
- scientist, MRI research
- dual-band metamaterial coils for X-nuclei MRI

Dipl.-Ing. Thorsten Liebig
- Ph.D. student
- MetaBore concept for traveling-wave MRI, openEMS (3D-EC-FDTD)

B.Sc. Benedikt Sievert
- M.Sc./Ph.D. student
- optimization of high-impedance surfaces (HIS)

Dr. sc. techn. Jürg Fröhlich
- visiting scientist, Fields at Work GmbH, ETH Zürich
- has pioneered the traveling-wave MRI approach