A Double-Row Transmit Array with Broadband Sheath-Wave Damping for 7T Human Head Imaging

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Purpose. Goal of the project was to design and build an eight-element, double-row, transmit (Tx) radio-frequency (RF) array coil for imaging the human head on a 7T scanner with an 8-channel parallel Tx system. Moreover, both rows should be tuned independently by the reflected power minimization approach [1]. Such arrays have been previously investigated by numerical simulations [1,2] and in practice [3,4]. Besides homogeneity of the RF magnetic field, B_1^+, good decoupling between both rows and to a receive (Rx) array and a good longitudinal coverage were important requirements. At high fields common mode problem presenting a source of loss as well as a potential safety issue. The problem is even worse with multi-channel coils.

Methods. Using printed circuit boards (PCBs), inexpensive, reliable, and reproducible 3D coil structures can be obtained by appropriate arrangement of 2D boards [5]. Only four different board types were required for the array (Fig. 1). One row was made of two rings (outer/inner diameter 390mm/280mm), connected by 108mm-long spacer boards. The ring segments carried the copper traces for the main loop with distributed capacitors and an active decoupling circuit. The metallized fingers of the spacers fitted into pairs of trough holes. Soldering provided electrical conduction as well as mechanical stability. Different spacers comprised one type to close the loops and another one with slight, twisted traces for the PIN diode bias. The second row was rotated by 45°. Recess areas on the ring segment boards permitted well-defined overlapping of both rings, adjusted by threaded rods and nuts to achieve minimal coupling between the rows (Fig. 2).

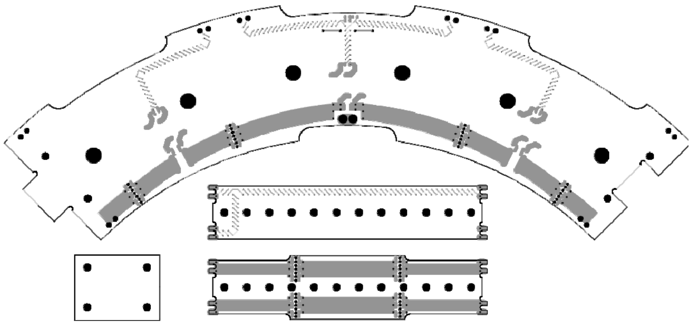

Fig. 1. The array is based on PCB design (standard double-sided FR4 material). Top copper layers are shown here for all 4 different elements.

The advantages of symmetric feed and remote tuning are well known [7,8]. In our design, the baluns were displaced from the active elements (loops) towards the distant matching unit (Fig. 3). Use of balanced lines was, hence, essential for the connection of the loops with the tune/match circuits. Pairs of hand-bendable coax cable (.141SRF-C-P-50, JYEBAO, Taipei Shien, Taiwan) were applied. For signal propagation, however, only the inner conductors of shielded symmetrical lines are relevant. Every unbalanced current along the shield is parasitic. If bypassed by lossy components (e.g. a resistor in range of 10-50 Ω), small gaps in the shield do not degrade a balanced signal but achieve damping of unwanted sheath waves. One gap in the λ/2 line to the top row and three gaps in the 2xλ/2 line to the bottom row, all placed near expected current antinodes, were sufficient to eliminate hand effects almost completely. All tune and match capacitors (NMNT10-6, Voltronics, Brookfield, CT) were bundled in a single shielded case (matching unit). Regarding the 4:1 impedance transformation provided by the λ/2 coax balun, all capacitor values had to be approx. four times larger compared to the 1:1 case. Every loop was divided into 14 segments by distributed capacitors (C_d=4.7 plus 3.3 pF; 2%, 1111 SMD footprint, 152 CHB series, Temex Ceramics, Pessac, France). A 4.7pF capacitor (C_f) was placed parallel to the feed line. Besides resonant sheath wave traps, PIN diode decoupling circuits are another possible cause of parasitic coupling. The simple series connection is broadband. To address limitations due to diode capacitance, four diodes (MA4PK2000, M/A-COM, Lowell, MA) were used per loop for adequate decoupling. By the use of printed twisted traces (Fig. 1) and bias tees in the matching unit no additional cabling was required. The coil shield was made of 8µm laminated aluminum foil (CLIMApac 2810, MetPro, Schwieberdingen, Germany) on a 400mm-diameter, 300mm-long acrylic tube with 5mm wall thickness.

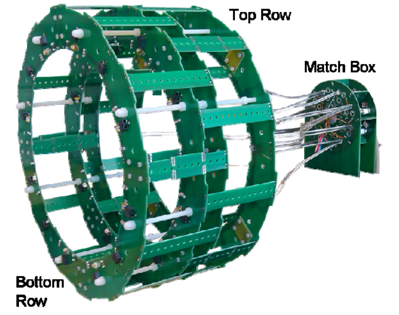

Fig. 2. Double-row array with matching unit. Shield and feed lines to the bottom row are not shown.

For initial performance tests, eight TxRx-switches permitted transceiver-operation of the double-row array. Usually the elements of an Rx array should be well decoupled. In contrast, a noticeable coupling is mandatory for the reflected power minimization approach. With a 400mm RG223 coax cable from the matching unit to the TxRx-switch and fine tuning (C_g in Fig. 4) a sufficient amount of preamp decoupling was adjustable (Fig. 5). For bench-top experiments an 8-channel vector network analyzer (ZVT 8, Rhode&Schwarz, Munich, Germany) was used. Imaging was performed on a MAGNETOM 7T (Siemens, Erlangen, Germany) with a cylindrical water phantom (160mm diameter, 7.3L volume, 1.24g $NiSO_4 \cdot 6H_2O$/2.62g NaCl per 1000g H_2O).

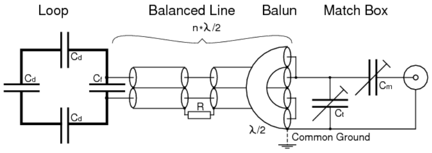

Fig. 3. Feed concept for a single channel.

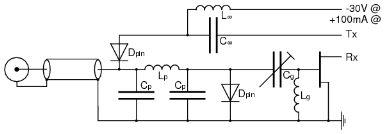

Fig. 4. TxRx-switch and preamplifier.

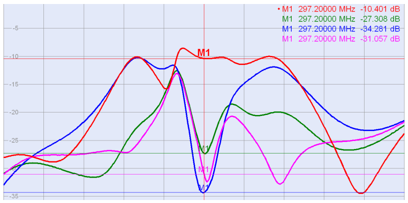

Fig. 5. Top row RX decoupling, frequency span 20 MHz. Loop 1 (red trace) is exited by a 5 mm diameter shielded loop probe.

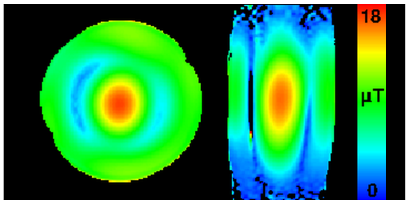

Fig. 6. The measured B1+ map for a rectangular pulse (800W, 7.3l cylindrical phantom, 0.52 S/m, 78 rel. permittivity).

Results and Discussion. Due to the precise PCB-based design and the use of high-quality capacitors, all initial resonance frequencies of the loops were within 450KHz deviation. The adjustment range allowed matching of the unloaded coil and when loaded with a human head. With the phantom, S_{21} of adjacent loops was −6.1dB and row-to-row decoupling was better than 20dB. The loaded bandwidths (S_{xx} = −7dB) were 4.14 and 4.39 MHz for the top and bottom rows, respectively, upon operation of a single loop. Once adjusted, the Rx loop decoupling was widely load independent. Notably, there were no parasitic common mode currents due to the combination of 1) balanced feeding, 2) balanced lines, and 3) resistor-bypassed line shield gaps. Moreover, no conventional sheath wave traps were required. Fig. 6 shows transmit performance of the array fed in circular polarized (CP). The transmit field of the array presents with desired radial symmetry and characteristic central brightening of CP mode (z position of slice: center of the array), and ample longitudinal coverage.

Conclusion. A PCB-based, double-row Tx array for human head imaging at 7 T was developed that achieves efficient excitation with good longitudinal coverage. The feed concept prevents sheath waves without a need of resonant traps and appears promising particularly for multi-element arrays. The reflected power minimization approach performed well even when combined with preamplifier decoupling.

References. [1] M. Kozlov, R. Turner. *J. Magn. Reson.* 200: 147-152 (2009). [2] M. Kozlov, R. Turner. *IEEE EMBS* 33: 547-553 (2011). [3] N. I. Avdievich et al. *Proc. ISMRM* 19: 328 (2011). [4] G. Shajan et al. *Magn Reson Med.* 24726 (2013). [5] R. Müller et al. *Proc. ISMRM* 21: 4366 (2013). [6] E.B. Boskamp et al. *Proc. ISMRM* 20: 2691 (2012). [7] F.D. Doty et al. *Proc. ISMRM* 11: 2361 (2003) [8] S. Hetzer et al. *J. Magn. Reson. Imaging* 29: 1414-1424 (2009).