# Modular and Versatile Multi-Row Transmit Array based on a Novel Decoupled Coil Element Design

Riccardo Stara[1], Simone A. Winkler[2], Ronald D Watkins[2], Alessandra Retico[3], Michela Tosetti[4], and Brian K Rutt[2]

[1]Dipartimento di Fisica, Università di Pisa, Pisa, Italy, [2]Department of Radiology, Stanford University, Stanford, CA, United States, [3]Istituto Nazionale di Fisica Nucleare, Pisa, Italy, [4]IRCCS Stella Maris, Pisa, Italy

**Target Audience:** RF engineers, MR physicists, electromagnetic community in MR.

**Purpose.** With increasing $B_0$-field intensity the wavelength of the $B_1$-field decreases proportionately leading to a number of challenges such as $B_1^+$ inhomogeneity, decreased power efficiency, and increased specific absorption rate (SAR). These problems are mitigated by careful RF coil design and software-related techniques such as RF shimming[1] and parallel transmission[2] for which a multi-channel transmit coil is required. Inter-element decoupling, dynamic disabling, and $B_1^+$ efficiency are the main challenges in the design of a transmit-only array.[3,4] Parallel transmission can also benefit from 3-D segmentation of the RF coil: this allows for a better acceleration in the z-direction and therefore improved RF shimming performance along this axis.[5] A novel semi-coaxial transmit element design, and a novel modular configuration, is presented here, which demonstrates improved intrinsic decoupling between elements without the need for additional circuitry. Each coil element, due to its geometry, is partially shielded against its neighboring coil elements. Multiple such elements can then be used for the construction of a modular transmit array, in a single-row or multi-row configuration, on a cylindrical surface or even on a more arbitrary surface. For this work, a transmit-only array consisting of 16 elements distributed on 2 rows of 8 elements each on a cylindrical shape, with dynamic disabling capability, has been simulated, built, and tested. Using only the 8 Tx channels available to us on our GE Discovery MR950 7.0T human system (GE Healthcare, Waukesha, WI, USA), the coil can be flexibly configured either as a 16-element array with z-segmentation, by using two Butler matrices, or as an 8-element array in one or the other single-row configurations.

**Methods.** The proposed transmit element consists of a semi-coaxial transmission line with a cylindrical center conductor and a semi-cylindrical outer shield, capacitively shortened at both ends. The element was built on a 3D-printed polycarbonate support frame; the length of each transmit element was 103 mm, while the shield radius was 26 mm (maximum radius possible with overlap in z-direction, see Fig.1). The shield material was 3M copper tape (0.04 mm thick) and the central conductor was made from hollow copper tubing (6.36 mm outer diameter, 1 mm wall thickness). The electrical circuit for each element is shown in Fig. 2: two symmetrically positioned capacitors ($C_{T1}$=10 pF, $C_{T2}$=8 pF) were used for tuning. Fine tuning was achieved with a small trimmer capacitor in parallel with $C_{T2}$. Impedance matching was realized with a parallel capacitor $C_m$=27 pF. For active decoupling of the coil, a diode $D_1$ (Microsemi HUM2020) was placed in series with the current path of the shield; this diode was forward-biased during transmission and reverse-biased during reception using a DC bias voltage present on the Tx line via an RF choke $L_c$=538 nH. The elements were arranged on two cylindrical rows of 8 elements each, spatially shifted by 22.5° with respect to each other for better isolation, and with some overlap in the z-direction (Fig. 1). The coil was tested in single-row configuration with 8 independent transmit channels and in two-row configuration with two Butler matrices (one per row). A Butler matrix was built using a combination of commercial quadrature hybrids (HE298MF, Florida RF labs) with coaxial cables used as phase shifters (UT-85C-Form, Microcoax) providing a fixed output phase distribution depending on the input port (mode) driven. The coil was analyzed via numerical simulations using Finite Difference Time Domain (SEMCAD, SPEAG, Zurich, Switzerland), and Method of Moments (FEKO, EMSS, Germany) software packages. Experimental testing was accomplished on the bench and in imaging mode, interfaced to a 7T scanner (GE Discovery MR950, GE Healthcare, Waukesha, WI).

**Results.** Simulations comparing planar vs. laterally (box) shielded vs. cylindrically shielded arrangements show that the proposed design reduces the spread of $B_1^+$-field in the lateral direction while the coupling with the sample was almost unperturbed (as demonstrated comparing the simulated $B_1^+$ profiles of Figs. 3 and the coupling between elements of Fig.4). Excellent agreement between the numerical simulations and the realized prototype was obtained in terms of reflection coefficient, considering that the required capacitor values agree with an error of less than 5%. As shown in Fig. 3, the cylindrical design demonstrates slightly lower $B_1^+$ efficiency compared to a more standard design (–5% compared to a flat shield element); however, it offers better decoupling (+3 dB) and better $B_1/E$ efficiency (+25%). It has been observed in the array simulations that the cylindrically shielded coil, with an inter-element decoupling of at least –13.5 dB, is suitable for modular array design, while the flat shield design shows resonance splitting. Measured S-matrices for matching and inter-element coupling demonstrated values below –13 dB for $S_{11}$ and –15 dB for $S_{12}$, indicating that the transmit array was well matched and decoupled. On the scanner, Bloch-Siegert $B_1$ maps[6] were acquired for all elements separately, operating in single-row mode, using a silicone phantom (Fig. 6) and demonstrate good isolation between channels and well behaved B1+ fields. An axial spoiled gradient echo image (Fig. 7) acquired in CP mode demonstrates good uniformity and signal-to-noise ratio.

**Discussion.** A 16-channel transmit coil based on a novel single-element design was built and first results show excellent intrinsic decoupling due to the improved Tx element geometry, without substantial decrease in $B_1^+$ efficiency. With this design, improved z-shimming capability is expected to lead to a better illumination of the lower brain region and to improve RF shimming and pTx in general. The single-element $B_1^+$ maps and the bench results show good performance in terms of decoupling, matching, and penetration depth.

**References.** [1] W. Mao, et al, Magn Reson Med 56(4):918 (2006). [2]U. Katscher, et al., Magn Reson Med 49(1):144 (2003). [3] N. Avdievich, et al, NMR in Biomedicine 26(11):1547 (2013). [4] E. Barberi, et al, Mag Reson Med 43(2):284 (2000). [5] K. M. Gilbert, et al, NMR in Biomedicine 24(7):815 (2011). [6]L. Sacolick, et al, Magn Reson Med 63(5):1315 (2010).

Fig 1: 16-channel Tx array prototype
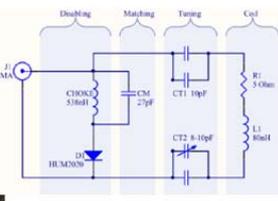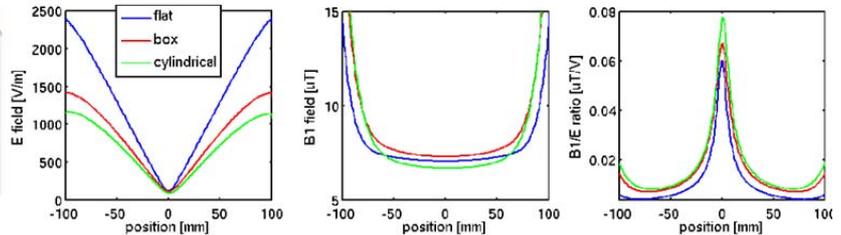


Fig 2: single element circuit diagram



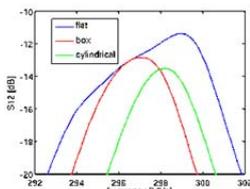Fig 3: Profiles for E (top) and $B_1$ field (middle) and $B_1/E$ plot (bottom) at x=0.



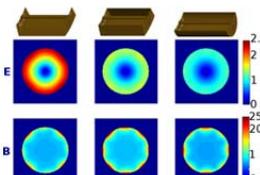Fig 4: MoM simulation of inter-element coupling ($S_{12}$) for three different coil element designs.



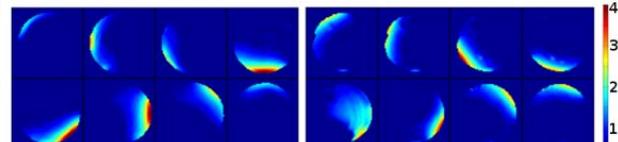Fig 5: Simulations of E-field in kV/m (top) and B-field in μT(bottom) (unloaded).



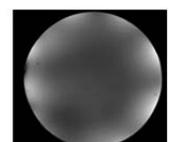Fig 6: Single-element, single-row $B_1$ maps in μT.



Fig 7: Single-row $B_1$-shimmed SPGR image using agar phantom.