Performance consequences of broken cylindrical symmetry for a 7T head RF transmit array

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Purpose: FMRI studies are often benefitted by the provision of a window in the RF head coil, to enable visual presentation. Placing such a window in the dense geometry of 7T RF head arrays generally breaks the cylindrical symmetry of the coil transmit elements and the array shield. Since the human head is also asymmetrical, this results in different couplings between adjacent RF transmit array elements. Neither the penalties for broken cylindrical symmetry nor compensation strategies for this asymmetry have been reported in detail.

We performed a numerical simulation of the consequences of broken cylindrical symmetry on the transmit performance of an array excited in CP mode which was realistically tuned, matched and decoupled. While performance characteristics might be improved using RF shimming on a per-subject basis, this strategy is laborious and can cause significant delay in routine MRI examination.

Method: The arrays investigated were a transmit-only 8-channel 7T strip-line array (Vaughan, Minnesota), and several modified versions of this array. Because experimental optimization had resulted in a position-dependent range of actual values of the end capacitors, we simulated the influence of these end capacitor values on transmit performance. For a given geometry and end capacitor values, the array was tuned: a) by perfect matching of each array element together with minimization of the coupling between adjacent elements, using capacitor-based decoupling networks, b) matching of each array element without the addition of a dedicated decoupling network (the strategy for the array actually built), and c) minimization of the power reflected by the entire array (P_{array_refl}) without any dedicated decoupling network. After tuning, all arrays were excited in CP mode, applying 1W power to each port (array transmit power, $P_{transmit}$=8W), with a sequential geometry-based phase increment. We analyzed matching, coupling between adjacent elements, the power balance and current through each array element.

Results and discussion: In conditions “a” and “b”, the frequency dependence of element matching always showed a single resonance line, with a minumum below -40 dB at the Larmor frequency (F_{MRI}). The coupling between adjacent elements was better than -16 dB and -6 dB for conditions “a” and “b” respectively. When a decoupling network was used, coupling between adjacent elements was roughly equal and at a negligible level, but in condition “b” there is significant non-negligible variation (~4dB) in coupling. In condition “a”, the spatial separation required between the transmit-only array and the human load resulted in a small variation of element loading, such that the currents through the strip elements when jointly excited had the same amplitudes and very similar currents as with individual element excitation. In condition “b”, however, due to the asymmetric coupling, there is a very large difference in current amplitudes (up to 60%) across elements when all elements were jointly excited. This finding can be easily explained: when the coupling is non-negligible, constructive and destructive interference within the coil depend on the element excitation phases and the magnitude of coupling. When coupling is different between left and right adjacent elements, the interference results in different currents within each element. The larger the difference in non-negligible coupling, the larger the difference in currents, and hence the greater the asymmetry of the B1+ field in the transverse plane.

Increasing the values of end capacitors from 2.2 pF step by step to 3.7 pF influenced transmit performance in opposite directions: this was improved for condition “a” and worsened for condition “b”. When the end capacitor value was 3.7 pF, the currents through the strip line capacitors at each end of the coil were found to be equal, and the strip line generated magnetic fields which were symmetrical in the Z direction. When the strip line performance was close to optimal, the radiated power was significantly decreased. In condition “b”, the coupling between adjacent elements was then found to increase. To maintain coupling at a negligible level in condition “a”, the decoupling capacitor values had to be adjusted. The brain excitation efficiency, $B_1+_{brain}/\sqrt{P_{brain}}$, increased from 0.94 to 1.02 μT/√W and from 9.4 to 9.7 μT/√W for conditions “a” and “b” respectively.

In condition “a” the decrease in both radiation and tissue losses resulted in increased strip line current, and thus an increase in B_1+_{brain}. It should be noted that the optimization of a strip-line array in the direction of increasing current has natural limits, because this results in increased losses in lossy dielectric and capacitors.

In condition “b”, the increased coupling resulted in an increase of reflected power P_{array_refl} , as large as 38% of $P_{transmit}$, and a consequent decrease of B_1+_{brain}. Setting the values of the 1st and 5th end capacitors to 3.3 pF, with 2.2 pF for the other capacitors (as in the array built) reduced the variation in current amplitudes (2nd row of Fig. 1) and the asymmetry of B1+ field in the transverse plane.

In condition "c", P_{array_refl} was minimized to a value of zero (the 4th row of Fig. 4) but this did not equalize currents, because the non-negligible coupling remained asymmetric after applying this approach.

In all cases, improvement in current uniformity resulted in an improved symmetry of B1+ field in transverse plane. The transmit RF field inhomogeneity over the entire brain remained practically the same (about 29%).

Array developers attempt to avoid decoupling networks mainly because of increased array complexity and increased dependence of performance on load. Omitting the decoupling network improves independence of transmit performance from load at the cost of performance degradation, or problems with pTX excitation and RF shimming, for conditions “b” and “c” respectively.

Conclusion: Single (non-split) resonance lines for element matching can be obtained despite non-negligible levels (-6dB) of adjacent element coupling. However, broken cylindrical symmetry and non-negligible coupling result in significant variations of current through coil elements. Use of capacitors of different values improves current uniformity, but P_{array_refl} remains high, and transmit performance is sub-optimal. For CP mode excitation, transmit performance can be significantly improved by decoupling the array elements whilst simultaneously equalizing the currents through front and end capacitors, but this does not improve homogeneity. Minimization of P_{array_refl} cannot provide good current excitation uniformity for an array with broken cylindrical symmetry. When currents through both front and end capacitors of the strip-line are equalized radiation losses approach their minimum.

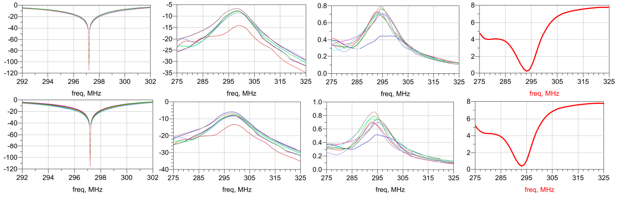

Fig.1 Column from left to right: 1st column S_{xx}, 2nd column S_{xy}, 3rd column I_{elem} , 4th column P_{array_refl}. Rows from top to bottom: 1st row - case "b" and C_{end}=2.2pF, 2nd row - case "b" and C_{end}=2.2/3.3pF

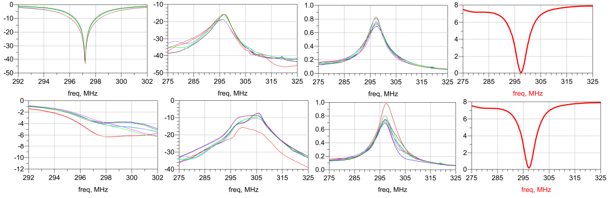

Fig.2 Column from left to right: 1st column S_{xx}, 2nd column S_{xy}, 3rd column I_{elem} , 4th column P_{array_refl}. Rows from top to bottom: 1st row - case "a" and C_{end}=3.7 pF, 2nd row - case "c" and C_{end}=3.7 pF.