High Impedance Power Splitter for Transmitting Phased-Array Coils

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Introduction

Multi-channel phased-array coils currently dominate the market for RF MRI coils, although single channel birdcage design is still in use for select applications such as system built-in body coil and basic head and knee imaging. The advantage of the birdcage design is the field uniformity which is of critical importance in the transmission phase of an MRI scan determining the spin flip angles and the performance of chemical saturation pulses which cannot be corrected in the post processing phase. Why can't a phased-array coil be used as an equally uniform transmitter? One would assume that by feeding the proper power and phase of the RF signal to each of the loops forming a phased-array coil, one may reproduce to a great extent the uniformity of a birdcage design. This is, in fact, true, however, formidable technical challenges are faced in the practical performance of this task.

Problem

During a receive operation, intrinsic properties of the preamplifiers allow us to have both the best noise figure and good preamplifier decoupling between the loops. Unfortunately, preamplifiers are incompatible with the transmit operation which involves much higher RF voltages and currents. We are therefore left without the benefits of preamplifier decoupling while transmitting. Highly inductively coupled loops of a phased-array coil are unsuitable as high-power transmit antennas due to large cross-coupling, non-resonant operation, and different matching requirements when compared to the receive mode of operation. Even in the laboratory conditions, with extremely well decoupled loops, the effect of the coupling is detrimental to transmit operation because the effective worst-case coupling is proportional to the product of the coupling coefficient (k), quality factor of the loaded loop (Q), and the total number of channels (N). For example, a carefully decoupled 8 channel coil with coupling coefficients of less than 0.3% between any two loops, still leads to an effective worst-case coupling of k*Q*N = 0.3%*100*8 = 240%. Figure 1 illustrates highly non-uniform transmit field of this coil as evidenced by an inhomogeneous flip-angle map across an axial slice when the loops are driven from an 8-way, equal power Wilkinson power splitter followed by appropriate phase shifters for each channel. Consequently, no phased-array transmit coils have been commercialized to date. Transmission has been exclusively delegated to the system built-in body coil and the phased-array coils are used only for reception.

Motivation

There are many reasons why one would want to overcome the technical hurdle of inductive coupling in phased-array coils in order to enable transmit operation of the same. For example, body coil, although results in very uniform field, excites all the spins in the entire body of the patient within the magnet bore. This requires large amounts of RF energy leading to patient heating, pulse sequence limitations, and phase-wrapping image artifacts, while also putting a higher price tag on the system RF amplifiers which must be capable of delivering high RF power. Furthermore, dielectric resonance and dielectric loss effects may require multi-port driving of the transmit coil at high field strengths. These issues will only become more serious as the field strength is increased from 1.5T to 3T and higher.

Proposed Solution

As opposed to the conventional Wilkinson power splitter whose output impedances are matched to the load impedances we propose a power splitter circuit whose output impedances are much higher than the load impedances. Effectively, the high impedance power splitter (HIPS) acts as a current source delivering equal currents, as opposed to equal powers, to each loop. The block diagram of a 4 channel HIPS is shown in Fig. 2 where we use MN to denote a matching network, ϕ for a phase-delay line, and QH for a quadrature hybrid. The purpose of the MN's in row B is to match the impedance of the loops in row A to the characteristic impedance of the cables in row C which connect the coil to HIPS. The MN's in row D transform the cable impedance to higher impedance for parallel loading the resonant ring made out of delay lines ϕ in row E. The MN's in row F match the impedance of the two modes of the loaded ring with the output impedances of the driving hybrid QH.

Realization

A printed circuit board containing an 8 channel high impedance power splitter (HIPS), 8 transmit/receive (T/R) switches and 8 preamplifiers is shown in Fig. 3. We have experimentally determined that the semi-rigid coaxial cables provide significant advantages over shielded or unshielded lumped elements in terms of efficiency, shielding, and ease of tuning for the construction of the phase-delay lines. Furthermore, it was possible to absorb all the inductive components of the matching networks in rows D and F (Fig. 2) into the internal inductance of the semi-rigid lines, thus only capacitors and semi-rigid cables were required for the construction of most of the HIPS circuit (i.e. rows D, E, and F.)

Results

The resonant ring (row E in Fig. 2), plays a secondary role in achieving the goal of high output impedance. Its primary purpose is to provide correct phase shifts to each channel. A more detailed analysis and measurements indicate that the high impedance presented by the splitter to one of the loops has its origins in the loading provided by the remaining loops. Indeed, the theoretical expression for the output impedance of the HIPS is Rout = Z0*(N/η – 1) where Z0=50Ohms, N is the number of channels, and η is the power efficiency of the splitter. Indeed, for the 8 channel HIPS in Fig. 3 we have measured η=67% and Rout =550 Ohms, in excellent agreement with the theoretical expression. The highly uniform transmit field resulting from the use of HIPS is illustrated in Fig. 4 where a very uniform flip-angle map demonstrates the potential of the phased-array coils to be used as high quality transmitting MRI antennas.

Conclusions

We have developed a high impedance power splitter circuit capable of driving transmit/receive phased array coils and have demonstrated greatly improved transmit field uniformity when compared to matched Wilkinson power splitter drive.

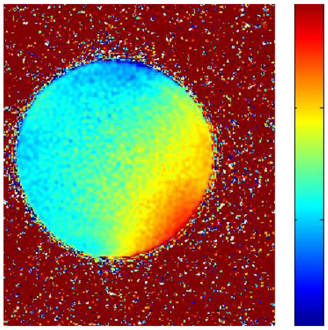

Fig.1 Flip-angle map when the phased-array coil is driven by a Wilkinson power splitter (colormap: blue=30°, red=45°.)

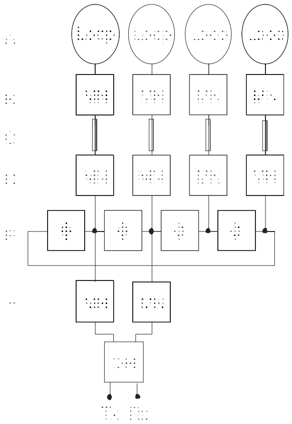

Fig.2 Block diagram of the high impedance power splitter circuit for a 4 channel coil.

Fig.3 An 8 channel high impedance power splitter with T/R switch and preamplifiers.

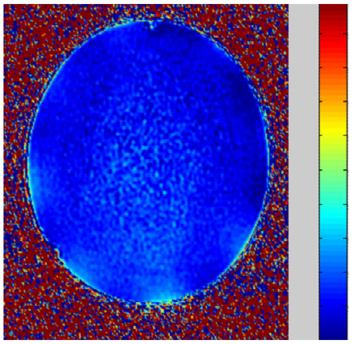

Fig.4 Flip-angle map when the phased-array coil is driven by a high impedance power splitter (colormap: blue=52.5°, red=57.5°.)