Active Phased Array Techniques for High-Field MRI

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Abstract — This paper describes recent developments in high field Magnetic Resonance Imaging (MRI) concerning the application of active phased array techniques. The pulse amplitudes and phases of currents in Antenna (Coil) arrays are adjusted in order to improve the homogeneity of the magnetic flux density distribution inside the inhomogeneous patient’s body. This can be realized either by using the antenna elements combined with a Butler matrix which is excited by phase/amplitude steered power amplifiers or by connecting the antenna elements directly to the power amplifiers. An improved system includes a variable power combining stage for maximum utilization of installed transmit power.

I. INTRODUCTION

MRI is an imaging technique widely used to produce high quality images of the inside of the human body. The magnet system is used to produce an intense and homogeneous field in the region to be imaged to obtain images of good quality. In high-field MRI, RF power pulses of 1 kW peak per antenna element (coil) are common and the signal frequency is, e.g. 297 MHz for a 7 Tesla (bias) static and homogeneous magnetic flux density B₀. Antenna (coil) elements arrayed in a circle around the patient are employed for the generation of RF magnetic flux B₁ inside the patient’s body with circular polarization w.r.t the longitudinal axis of the MRI tube. The inhomogeneity of the patient’s body at this high frequency creates strong variations in the magnetic flux density produced by the antenna array, if we employ uniform current excitation. Therefore, adjustments of the phase and amplitude of the elements of a circular antenna (coil) arrays are required in order to improve the RF field homogeneity (called B₁ or RF shimming), [1].

II. METHODS FOR AMPLITUDE / PHASE CONTROL

We introduce two concepts borrowed from the phased array technology to control the phase and amplitude of antenna element (coil) arrays in an MRI system and after that a major improvement over both concepts will be introduced.

A. Butler Matrix Multi-Mode Feed Network

The first concept is the use of a Butler matrix [2], which is connected to the antenna elements on the output side and to the linear pulse power amplifiers (LPPAs) at the input side. Due to the inherent phase progression of the Butler matrix network the input signals from the amplifiers create phase modes (instead of “beams” in antenna arrays) of magnetic flux with circular polarization at the array elements which can be superimposed to counter the effects of the inhomogeneous patient’s body [3]. We can control the superposition by adjusting the input signal phase to the power amplifiers and connect each amplifier to one input port of the Butler matrix. This results in one of the power amplifiers to create the CP⁺¹-mode which exhibits 360° phase rotation of element current around the circular array while the next amplifier supplies its power to the CP⁻²-mode which exhibits 720° of phase shift, and so on. The concept is depicted in Fig. 1.

Fig.1 Concept of phase mode creation by Butler matrix; antenna (coil) elements connected to the Butler matrix output

1) Inherent limitations of this concept

- Only half of the input ports create the right handed circular polarization, the other half is opposite handed and less useful for transmission.
- The number of antenna elements (coils) must be equal to the number of power amplifiers. Given the number of LPPAs, which are the expensive components in the system, the “resolution” of the created field distribution is limited. Transmitting only through the right handed circular polarization ports of the matrix, this relation can be improved to allow twice as many antenna elements as there are transmitters.
- For optimum superposition, it may be necessary to adjust the amplitude of the various modes. However, when equal power amplifiers are employed, most amplifiers will operate below maximum, i.e., the installed power in general will be underutilized and the MRI image signal-to-noise ratio degraded. In particular, the first circular polarized phased mode CP⁺¹ can be considered the fundamental mode which should transmit most of the available power – this is not possible in the basic concept since all input ports of the Butler Matrix receive the same maximum power of a single LPPA.
2) Butler Matrix Realization

The realization of Butler matrix requires a combination of $90^\circ$ hybrid couplers (3dB) and fixed phase shifters. Line crossovers of conventional Butler matrix designs are one of the main drawbacks, since they may add several undesired effects. To overcome this problem, a new layout of an 8×8 Butler matrix was designed as Fig. 2 which uses ports at the edges as well as at the center of the matrix.

![Fig. 2 Planar 8×8 Butler matrix without any crossing and additional output phase shifters](image)

For the $90^\circ$ hybrid couplers, Branch-Line (BL) couplers were used because of their high power and high voltage handling capability. Our realization was based on microstrip technology and has been designed initially on RO4003 substrate with permittivity of 3.38, loss tangent of 0.0027 and a thickness of $h=1.524$ mm. This results in a branch line length of 13.59 cm, a series line length of 13.21 cm, and a total size of 14.7 cm × 16.2 cm for the BL coupler. To realize an 8×8 Butler matrix at 297 MHz, constructed from twelve BL couplers, the size of each coupler needed to be reduced. Therefore, a compact size BL coupler has been designed using chamfered bends to fold the branches and reduce the total size of the coupler, see Fig. 3. Using this method, the size of the BL coupler was reduced to 10.7 cm × 9 cm. This coupler has been implemented in the layout environment of the Agilent ADS software suite and has been optimized, realized, and tested. The full Butler matrix network as shown in Fig. 2 could be realized in just one board, but the physical dimensions of the Butler matrix would be 60 cm × 65 cm, which is difficult to manufacture and to accommodate in the bore of the MRI system. To reduce the total size of the manufactured Butler matrix, it was split into 6 substrates with cable connections. The output phase shifters and related BL couplers were realized on four separate substrates, with two substrates each stacked above and below the two main substrates (each main substrate includes four BL couplers), as shown in Fig. 4. The size of this Butler matrix was reduced to 28(length) × 22(width) × 18 (height) cm³ [4].

![Fig. 3 Realized Branch-Line coupler for 297 MHz](image)

![Fig. 4 Realized 8×8 Butler matrix in microstrip technology (split boards of RO4003) for 297 MHz](image)

B. Vector Modulator for Full Phase / Amplitude Control

The second concept is borrowed from technology of the fully active phased array: We connect each LPPA to one antenna element and we fully control the amplitude and phase of each amplifier using a Vector Modulator at the input (low power). The complete system, consisting of a long chain of Power Splitter, Vector Modulator, Power Amplifiers, Power combiner, Switches, Transmit Antenna Level Sensors (TALES), long Coaxial Cables and eight antenna elements (Coils), is sketched in Fig. 5. The eight transmit channels are controlled in phase and amplitude by the vector modulator; switches allow the transmit power to be optionally combined into one single channel and fed into a special single port antenna (e.g., bird cage coil) [5].

1) Limitations of this concept

- The optimum excitation of the antenna elements may demand a large variation of the output power of the individual LPPAs. Since the amplifiers are limited in power, most amplifiers have to be backed off from their maximum power such that their installed power is underutilized.
- The number of amplifiers must be exactly equal to the number of antenna elements which tends to seriously limit the “resolution” of the $B_1$ field control.
2) Vector Modulator Realization

Eight silicon RFIC quadrature modulators AD8345 and eight quad channel digital potentiometers AD8403 were employed in our design. Surface-mount high frequency relays were used as safety overrides and to switch the vector modulator in and out of the RF path. Relays and potentiometers are controlled by a PIC18F4550 Microcontroller. This I-Q type vector modulator yields 256×256 possible signal combinations, with each symbol representing 16 bits. Circuit boards used in the vector modulator are shown in Fig. 6. Using a GUI program written in MATLAB, the PIC18F4550 Microcontroller receives control data via a USB port, and the appropriate signals are sent to the potentiometers. Finally, the potentiometers produce controlling voltages for I and Q of the vector modulator.

All of the circuits for eight channels have been fabricated and integrated into one 19” chassis, see Fig. 7.

C. Improved Active Phased Array System for MRI

A major improvement over both concepts allows the flexible combination of power from several LPPAs to feed single phase modes of a Butler matrix. The novel feed network concept allows adjustment of all modes in phase and amplitude as required for B1 shimming and at the same time the (close to) full utilization of installed power of the LPPAs. This concept uses a first Butler matrix as a variable power combiner[6] and a second Butler matrix for the creation of phase modes at the coil array. The input signals to the power amplifiers are amplitude / phase controlled by a vector modulator and the output power signals are fed into the first Butler matrix. Depending on the setting of the vector modulators, this Butler matrix combines the input power into the output ports at prescribed amplitude and phase relations. The combined power then is fed to a second Butler matrix which produces the phase modes at the coil array. In this way, e.g., the first and most important CP-1 - mode can be fed the majority of power while other modes receive less power – while all power amplifiers can utilize their full installed power.

We realized this concept in our 7 Tesla MRI system [7] using an 8-channel amplifier bank, two 8x8 Butler matrices and an 8-element coil array, Fig. 8.
\[ B_j = k^8(S_{Tj1}A_1 + S_{Tj2}A_2 + \ldots + S_{TjN}A_N) = k^8 \sum_{i=1}^{N} S_{Tji}^* A_j \]  

(2)

In the case that all amplitudes \( A_i \) are chosen conjugate complex (negative phase and unit amplitude) of the corresponding coefficient, the summation gives \( N \). This means that all input power is condensed into the output power at port \( j \). In this way we have defined a characteristic vector of input signals which provide full signal combination into the \( j \)-th output port:

\[ A_j(j) = S_{Tji}^* \]  

(3)

All characteristic vectors combined into one matrix can be seen to be the transpose conjugate complex of our partial scattering matrix:

\[ A(i, j) = \begin{pmatrix} A_1(1) & \cdots & A_1(N) \\ \vdots & \ddots & \vdots \\ A_N(1) & \cdots & A_N(N) \end{pmatrix} \]  

(4)

We realize that each column represents the excitation (input) signal vector \( A(j) \) for complete signal combination into one output port. Due to the linearity of the superposition of wave signals within the network we may combine input signal vectors in order to superimpose output signals such that a required power distribution is realized.

Using the transmission partial scattering-matrix \( S_T \) to relate the outgoing waves \( B \) of the 8×8 Butler matrix to the incident waves \( A \), the required input signal phases were calculated based on the superposition of the characteristic input vectors using a genetic algorithm optimizer [8]. For a proof-of-concept demonstration, power levels of 50\%, 25\%, 12.5\% and 6.25\% for the first four output ports were arbitrarily chosen, using a genetic algorithm optimizer [8]. For a proof-of-concept demonstration, power levels of 50\%, 25\%, 12.5\% and 6.25\% for the first four output ports were arbitrarily chosen.

This coupler, fabricated on RO4003, has an attenuation loss of 0.15 dB and the isolation of -33 dB. The phase error of 0.41° has been found for this coupler. Fig. 10 shows the insertion loss values of the 8×8 Butler matrix when port 1 of Butler Matrix is fed. The 8-channel Butler matrix fabricated on RO4003 had an effective overall mode error of 1.91° at an overall attenuation loss of 0.72 dB. These results demonstrate the good performance in terms of accuracy and loss of the realized Butler matrix; considerable improvements in phase and amplitude accuracy and in attenuation loss are possible if cables are avoided and the matrix realized in one board. For operation of the Butler Matrix with 1 kW power level at the ports, we can use SMA connectors but for combined power from 8 amplifiers (8 kW) to drive, e.g. a multi coil array in birdcage mode, Type-N connectors for higher voltage handling are mandatory.

III. RESULTS

A. Branch Line Coupler and Butler Matrix

To examine the performance of realized BL coupler (Fig. 3) and Butler matrix (Fig. 4), measurements were carried out at 297 MHz using an Automatic Vector Network Analyzer (ANA). The measurement result for BL coupler is presented in Fig. 9.

![Fig. 9 (a) Measured S-parameters (b) Phase difference between the output ports of hybrid coupler](image)

Using the 8-bit potentiometers for the generation of the control voltages, the vector modulator produces 128 equal amplitude steps between the maximum and the minimum output signal for positive and 128 steps for negative sign. The size of these steps was verified in measurements for high to medium levels which means that the amplitude accuracy of the vector modulator is about 0.01; however, at the low levels around -30 dB, a residual signal (feed-through) degrades the level control. The recombination of level controlled I- and Q-signals produces the ultimate output signals of the vector modulator, such that the resolution is of the order 0.01 in amplitude and from 0.5° to 5° in angle for amplitudes in the 0 to -20 dB range. Note that the vector modulator electronic IC exhibits nonlinear characteristics when the input signal exceeds the compression point; therefore, an attenuator was placed at the input, see Fig 5. Using this vector modulator in our system, the final images from MRI were produced as in Fig. 11. Results show that the system is capable of full modulation.

B. Vector modulator

The vector modulator internally uses a poly-phase 90° phase shift filter for the creation of an in-phase (I) signal and a quadrature (Q) signal. The quadrature phase error was found to be just above 1° at 297 MHz. Both I- and Q-signals are controlled in amplitude by the differential d.c. voltages applied. The level range that can be controlled was found to be more than 30 dB at 297 MHz without extra zero-adjustment. Using the 8-bit potentiometers for the generation of the control voltages, the vector modulator produces 128 equal amplitude steps between the maximum and the minimum output signal for positive and 128 steps for negative sign. The size of these steps was verified in measurements for high to medium levels which means that the amplitude accuracy of the vector modulator is about 0.01; however, at the low levels around -30 dB, a residual signal (feed-through) degrades the level control. The recombination of level controlled I- and Q-signals produces the ultimate output signals of the vector modulator, such that the resolution is of the order 0.01 in amplitude and from 0.5° to 5° in angle for amplitudes in the 0 to -20 dB range. Note that the vector modulator electronic IC exhibits nonlinear characteristics when the input signal exceeds the compression point; therefore, an attenuator was placed at the input, see Fig 5. Using this vector modulator in our system, the final images from MRI were produced as in Fig. 11. Results show that the system is capable of full modulation.
C. Variable Power Combiner

First laboratory measurements of the variable power combiner (Fig. 8) with an ANA have been done by first splitting the excitation signal (TX) from the ANA into 8 equal parts and feeding these into the input ports of our matrix. The phase shift was realized using coaxial cables inserted into the connection paths. However, the cable lengths could not be realized precisely, so that an average phase error of 8° was achieved; see Fig. 12. The output signals from the matrix were measured by the ANA as $S_{12}$ transmission coefficients. Comparison of design levels and measured levels as plotted in Fig. 13 prove the concept although some amplitude error remains at the output ports. Finally, Fig. 14 shows the profiles of the modes produced by this variable power combiner Active Phased Coil Array system in MRI.

IV. CONCLUSIONS

In this paper we have described our recent work on high field MRI concerning the application of active phased array techniques, in particular, the use of the well-known Butler matrix feed system and the full amplitude / phase control of all channels. A major improvement was introduced by the use of the novel variable power combiner based on a Butler matrix and vector modulator control of signals. In this way, we can produce the fundamental and higher-order circularly polarized modes with prescribed power ratios. In general, arbitrary amplitude and phase shift for the created phase modes at the coil array can be prescribed and the control vectors can be generated by a genetic optimization routine which chooses amplitude and phase weights in such a way as to maximize the utilization of installed power for any combination of modes. Present work concerns the design of power combiners and 8x8 and 16x16 Butler matrices using our Microstrip Matrix Technology with the aim to realize insertion loss down to about 0.5 dB at 297 MHz for a 8x8 matrix using higher-permittivity dielectric substrate which also yields a smaller form factor.

ACKNOWLEDGMENT

The authors wish to thank M. E. Ladd, A. Bitz, S. Orzada (Erwin L. Hahn Institute for Magnetic Resonance Imaging, Essen, Germany), M. Vester (Siemens Medical Solutions, Erlangen, Germany) and R. Oppelt (Siemens Corporate Technology, Erlangen, Germany) for contributions to this paper.

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