

# Variable Power Combiner for a 7T Butler Matrix Coil Array

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## Introduction

Butler matrix networks [1] are used for the excitation of phase modes of MRI coil arrays. The standard excitation method is to connect each power amplifier output to one of the (input) mode ports of a Butler matrix. This allows all phase modes of the coil array to be excited at equal power level. However, not all modes are equally useful, since the lowest-order Circularly Polarized (CP) mode or  $CP^+$  is the dominant mode, while higher  $CP^+$  modes are less important to excite and  $CP^-$  modes may be completely unnecessary to excite (yet useful in receive). Power utilization in a multi-TX Power Amplifier MRI system should therefore try to direct most of the available power into  $CP^+$  and less power into the other, higher modes. This requires the power amplifiers to be combined into specific sum powers first before feeding the matrix. A fixed ratio of power levels for the different modes is not suitable for practical work, and thus we require a variable power combiner system for pre-combination of the power amplifiers. In this work an eight-channel variable power combiner has been designed and fabricated using an 8x8 Butler Matrix network. To find the optimal design of the variable power combiner, an optimization based on Genetic Algorithms [2] has been defined. Finally, this variable power combiner was integrated with an 8-TX power amplifier array to excite the coil array in a 7 Tesla MRI system.

## Methods

An 8x8 Butler matrix was constructed from 90° hybrid couplers and phase shifters, Fig. 1, using Microstrip Matrix Technology. The prototype eight-port, high-power compact-sized Butler matrix has been designed for 300 MHz (7T) and is shown in Fig. 2. This Butler matrix consists of integrated hybrid couplers on six substrate boards. The concept for a variable power combiner [3] is sketched in Fig. 3. The low-level RF signal is split into N parts and is fed to the input ports of RF Power Amplifiers (PA). The phase of each input signal is individually varied by a Phase Shifter (PS). The high-power output signals from the PAs are fed into the NxN Butler matrix, which combines the power from the amplifiers at its output ports. The portion of power at the various output ports can be controlled at a basic level by the phase shifters on the low-power side of the amplifiers; because no switch or attenuator is needed at the high-power combining stage, power loss is minimized. Using the transmission partial scattering-matrix  $S_T$  to relate the outgoing waves **B** of the 8x8 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. For a proof-of-concept demonstration, power levels of 50%, 25%, 12.5% and 12.5% for the first four output ports were arbitrarily chosen, and the phase weightings were calculated. Next, the variable power combiner unit was integrated with 8-Tx Power Amplifier 7 T system as shown in Fig. 4. The eight power amplifiers, each with 1 kW output power, were connected to the power combiner matrix with the calculated phase shift provided by cables of appropriate length inserted in to the path. The output signals No.1 to No.4 of the combiner were coupled into the  $CP^+$  mode ports of a Butler matrix feeding an 8-element coil array. The other ports were loaded and Tx/Rx duplexers were inserted at the coil ports in order to receive all of the available response signals.

## Results

Measurements of the variable power combiner were performed using an Automatic Vector Network Analyzer (ANA) 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. 5(a). The output signals from the matrix were measured by the ANA as  $S_{12}$  transmission coefficients. Design levels and measured levels are shown in Fig. 5(b). Some deviation from the target levels was observed, which is in part due to the insertion loss of the cables and the matrix and in part due to the phase errors in the excitation signals. Finally, Fig. 6 shows the profiles of the modes produced by this variable power combiner.

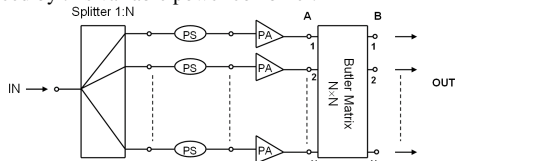


Fig. 3 Concept of variable power combining using a Butler matrix

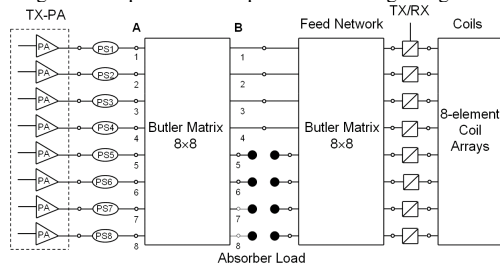


Fig. 4 MRI system using the variable power combiner with a Butler matrix driven 8-element coil array

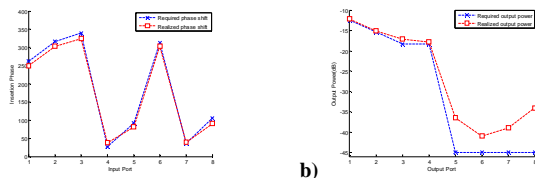


Fig. 5 (a): Required (ideal) and realized phase shift of input signals. (b): Relative output power at the ports of 8x8 Butler matrix

**References** [1] Butler J et al, Electron Design (9) 1961 p 170. [2] D.E. Goldberg, Addison-Wesley, Publishing Company, Inc., 1989. [3] German Patent Application DE 10 2006 028 690 A1, "Verstärkereinrichtung für eine Modenantenne", filed 22 June 2005.

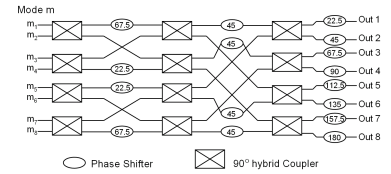


Fig. 1 Schematic of an 8x8 Butler matrix



Fig. 2 Fabricated 8x8 Butler matrix for 300 MHz

## Discussion

The variable power combiner for a 7T Butler matrix coil array was used to produce the fundamental and higher-order Circularly Polarized modes with the prescribed power ratios. Note that if we have a perfectly matched network and loads, the total power loss through the Butler matrix is only the single-pass loss that is encountered in normal matrix operation. With the Microstrip Matrix Technology used here, this can be as low as about 0.6 dB at 300 MHz. It is also possible to excite the combiner matrix in such a way that the phases of the generated output signals can be controlled arbitrarily. One problem with this variable power combiner concept is that for certain power and phase distributions at the output we have to apply some amplitude weighting in addition to the pure phase weighting at the input; this reduces the utilization of the available amplifier power. However, the optimizer algorithm can be configured such that this loss can be minimized. Any errors in adjustment of the amplitudes and phases of the input signals will lead to deviations from the targeted output signal (and power) distribution: In principle, we will see lower levels at the ports that should be high due to higher levels where we wish lower levels; e.g., in our proof of concept experiment, we targeted zero output at four of our eight ports, but we achieved a residual level of about 1% of the input power at each of the nominal "zero-level" ports, which implies that 4% of the input power was lost for the other four ports.

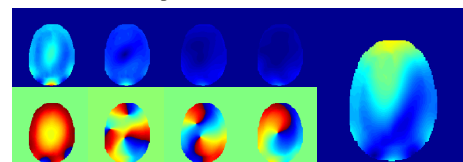


Fig. 6 Profiles of the four  $CP^+$  modes produced by the variable power combiner in combination with a Butler matrix driven 8-channel head coil with prescribed power levels (left); combination of the four  $CP^+$  modes (right)