A Variable Power Combiner for 7 Tesla MRI system with 16-channel coil array

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Introduction

A Variable Power Combiner (VPC) for a 7 Tesla MRI system equipped with eight parallel transmit channels and 16-channel whole-body RF coil array for using with RF mode shimming is introduced in this work. This VPC enables the power-efficient, flexible as well as computer controlled superposition of circularly-polarized modes of a multi-channel transmit RF coil array.

The main component of a VPC [1], Fig.1, is a matrix-type, fixed power combiner network connected to the N output ports of the amplifiers. The power combiner is an N×N network of 3-dB quadrature couplers using the matrix topology of a Butler matrix [2]. Power combining takes place in this network, given that the phase and amplitude of the input signals from the power amplifiers are adjusted using a vector modulator, designed and fabricated for 7T MRI sysem [3] (Am/Ph in Fig. 1).

Proof of concept

First, a proof of concept experiment was realized on the bench without power amplifiers and using the vector modulator [3]. Fig. 2 shows the test setup according to the concept in Fig. 1 (N=8 in Fig 1). The 1:8 power splitter has been replaced by an 8×8 Butler matrix which equally distributes the power to the attenuators and phase shifters introducing phase increments of 45°. Attenuators and phase shifter are realized by a vector modulator [3] in each channel. Both Butler matrices were low-power versions of the microstrip network design described in [4] produced on substrate RO3010 with 1.3 mm thickness. The related attenuations and phase shifts of all cable connections have been considered in the calculation procedure for the vector modulator settings to achieve a specified target output signal phase/amplitude distribution.

After proofing the concept, the average amplitude error of 0.3 dB and the average phase error of 2° was found over the eight output ports.

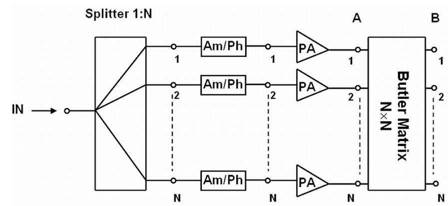

Fig. 1 Concept of the VPC [1]

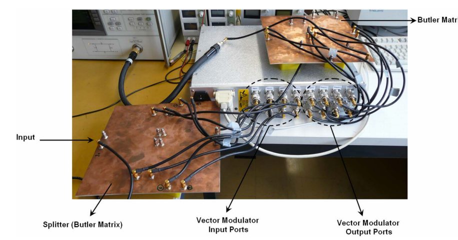

Fig. 2 Implemented VPC using vector modulator [3], input splitter (Butler matrix [4]) and combiner Butler matrix [4]

System Integration

For realistic mode-shimming experiments, VPC is integrated into a 7T whole-body MR scanner, Fig. 3, which has been extended with a custom RF shimming add-on system. Therefore, between the vendor-provided low-power splitter and the 8-channel transmitter (providing eight power amplifiers of 1 kW installed output power each) aforementioned vector modulators act as amplitude and phase actuators. A low-loss (insertion loss ≤ 0.7 dB), high-power version of an 8×8 Butler matrix [2] allows in connection with the vector modulators for variable power combination at its eight output ports. Finally, the output ports were connected to the eight CP^+ mode ports of a low-loss (insertion loss ≤ 1.1 dB) 16×16 Butler matrix[2] feeding a 16-channel coil array for whole-body MRI via T/R switches in each channel.

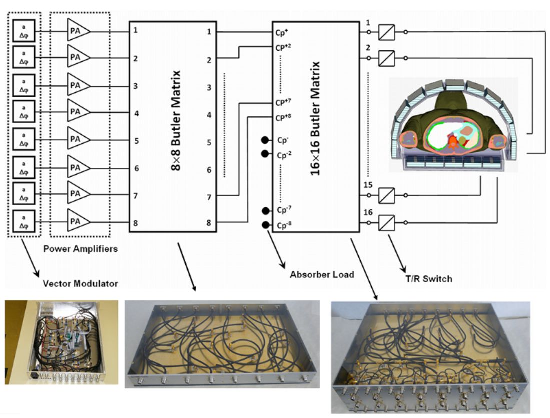

Fig. 3 Integration of the VPC into the 7 Tesla MRI system

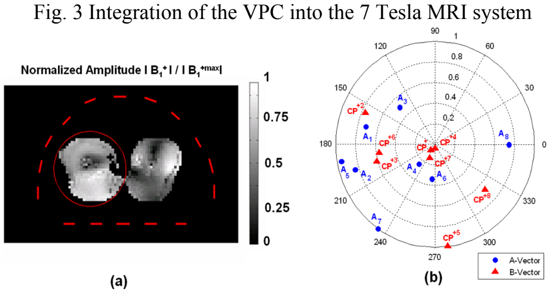

Fig. 4 (a): $|B_1^+|/|B_1^{+,max}|$ maps of upper legs after mode shimming for right upper leg. (b): Vector modulator weights **A** and relative amplitudes of the excited CP phase modes **B** at the 16×16 Butler matrix for B_1 optimization in the right upper leg

Results

The B_1^+ distribution is optimized for improved homogeneity in the right upper leg of a male volunteer. Note, that the given configuration is extremely asymmetric, because the legs are considerably closer to the five coil elements which are positioned on the patient table than to the upper elements of the 16-element coil array which is arranged on a constant radius around the volunteer. The improvement in B_1^+ homogeneity by an optimized superposition of CP^+ modes may be demonstrated by comparison of the standard deviation of amplitude distributions in the left and right leg, seen in Fig. 4(a): right leg SD = 23%, left leg SD= 42%.

The vector modulator settings **A** (see Fig. 1, calculated for this example are given in Fig. 4(b) in a polar diagram together with the relative excitation vector **B** (see Fig. 1) of the CP modes. The vector modulator weights **A** are quite evenly distributed with a power utilization of 52%. The resulting distribution of phase mode amplitudes **B** shows only few modes excited with high amplitudes. In case that these modes would be excited without VPC the power utilization would degrade to 41% which is 1 dB less efficient compared to the case with VPC (insertion loss of 8×8 Butler matrix neglected).

Discussion

Mode shimming in the right upper leg is an example for a target excitation with several strong CP modes and widely varying output phases. Consequently, the achieved power utilization in this case is found to be only slightly higher than without VPC. In the course of the RF mode shimming experiments, it turned out that the VPC improved the workflow for the acquisition of $B_1^{+\text{ maps}}$ of the individual CP modes: Consecutive mechanical cable reconnections of the 16×16 Butler matrix mode ports to the transmitter was avoided and replaced by alternating the settings of the vector modulators to consecutively combine the full transmit power to each mode port.

References

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