Planar Butler Matrix Technology for 7 Tesla MRI

P. Yazdanbakhsh[1], A. Bitz[2], S. Orzada[2], O. Kraff[2], M. E. Ladd[2], and K. Solbach[1]

[1]High Frequency Technique, University Duisburg-Essen, Duisburg, NRW, Germany, [2]Erwin L. Hahn Institute for Magnetic Resonance Imaging, Essen, Germany

Introduction

Variation of the B_1 field distribution at high field causes variation of the flip angles inside the patient's body which leads to shading in the acquired images. Numerous methods have been proposed to mitigate B_1 inhomogeneity. More recently, it was shown that "B_1 shimming" can be performed using multiple transmitters [1,2], but utilizing these additional transmit channels effectively is extremely critical. Arrays formed from the orthogonal modes of a Degenerate Birdcage Coil (DBC) have been shown to have beneficial properties [3, 4]. In order to access these modes simultaneously, a Butler Matrix [5] is used to drive the individual rungs of the DBC in linear combinations to form the uniform birdcage mode as well as higher gradient modes. The other advantage of using the modes of a birdcage coil excited by a Butler Matrix is that they form naturally decoupled orthogonal modes that do not require decoupling strategies [6]. The Butler Matrix has also been found to provide reflection coefficients that are insensitive to the load [7]. In this work a novel reduced-size 8×8 high-power Butler Matrix has been designed and fabricated at 300 MHz to excite a coil array in 7 Tesla MRI.

Methods and Construction

The realization of an 8×8 Butler Matrix, Fig.1 (a), requires a combination of 90° 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 the matrix has been designed as shown in Fig.1 (b) which uses ports at the edges as well as at the center of the matrix. To design the 90° hybrid couplers, Branch-Line (BL) couplers were used, Fig. 2(a), because of their high power and high voltage capability. BL couplers split the RF power equally between their outputs with a relative phase of 90°. Considering the dimensions of the BL coupler, the length of the branch line and series line is generally chosen to be a quarter wavelength at the design frequency. Our realization is based on microstrip technology and has been designed on two different substrates: (1) RO4003 with $\varepsilon_r = 3.38$, $\tan\delta=0.0027$ and a thickness of h=1.524 mm, and (2) RO3010 with higher permittivity of $\varepsilon_r = 10.2$, $\tan\delta=0.0023$ and h=1.28 mm. For the RO4003 substrate, 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 ×16.2 cm^2 for the BL coupler. To realize an 8×8 Butler Matrix at 300 MHz, constructed from twelve BL couplers, the size of each coupler should be reduced. Therefore, a novel compact size BL coupler using chamfered bends to fold the branches and reduce the total size of the coupler was designed, see Fig 2(b). Using this method, the size of the BL coupler was reduced to 10.7×9 cm^2. This coupler was implemented in the layout environment of the Agilent ADS software suite and has been optimized, realized (cf. Fig. 3(a)), and tested. If the full Butler Matrix network, shown in Fig 1(b), were to be realized in just one board, the physical dimensions of the Butler Matrix would be 60×65 cm^2, which is difficult to accommodate in the bore of the MR 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 (a). The size of this Butler Matrix is 28(length) × 22(width) × 18 (height) cm^3. RO3010 substrate with the higher permittivity was considered for the next experiment. The size of individual BL couplers, shown in Fig 3(b), has been reduced to 5.8 × 4cm^2 using this board. The Butler Matrix network was designed (in ADS layout) and realized in one board, Fig 4(b), and its physical dimensions have been reduced to 27cm× 27 cm.

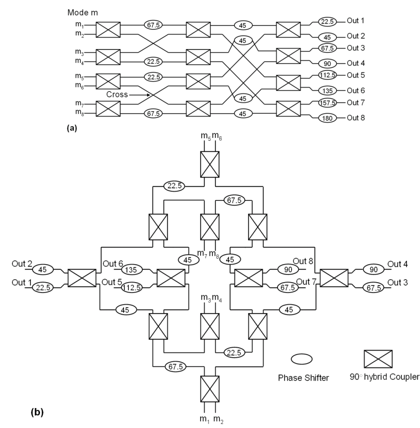
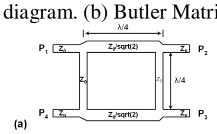


Fig. 1:(a) Planar 8×8 Butler Matrix block diagram. (b) Butler Matrix without any crossing



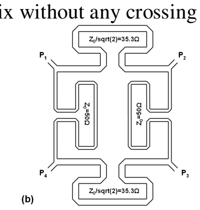
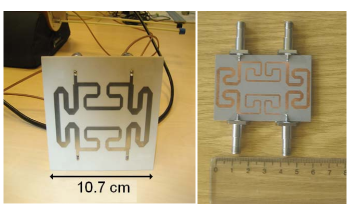
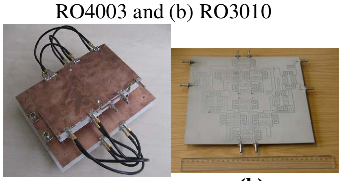


Fig. 2:(a) Schematic of a BL coupler, (b) Folded BL coupler



(a) **(b)**

Fig.3 Realized BL coupler on (a) RO4003 and (b) RO3010



(a) **(b)**

Fig.4 Realized 8×8 Butler Matrix on (a) RO4003 and (b) RO3010 (Output ports are located on the bottom side)

Results

To examine the performance of BL couplers and Butler matrices, measurements were carried out at 300 MHz using an Automatic Vector Network Analyzer (ANA). The measurement results for BL couplers are presented in Fig. 5 and match well with simulation results achieved with ADS software. The first prototype coupler, fabricated on RO4003, had an attenuation loss of 0.15 dB, while the smaller, second coupler on RO3010 showed an increase to 0.18 dB. The isolation and matching values for the first coupler (-33 dB) was a bit better than the second coupler (-27dB). The first coupler had a phase error of 0.75°, whereas this value for the second coupler was about 1.15°. Fig. 6 shows the insertion loss values of the 8×8 Butler matrices when port 1 of each 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 magnitude and phase accuracy 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 needed.

Discussion and future work

The second Butler Matrix, using the RO3010 material and realized on one board, had less attenuation (0.67 dB) because the cable connections were eliminated, but we experienced higher temperature rise due to more concentrated dissipation in the smaller circuits and higher average phase error because of unstable connections between the SMA connectors and the extremely soft substrate (RO 3010). This Butler Matrix therefore needs special mechanical support (with heat sink properties) for the substrate board in contrast to the larger and very stiff RO4003 board, and also requires stringent decoupling of the mechanical load from the connected cables. For our future work we will employ two 8×8 Butler matrices, fabricated on RO3010, to create a 16-channel high-power reduced-size Butler Matrix at 300 MHz.

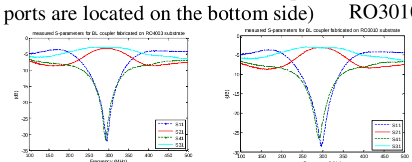


Fig. 5 Measured S-parameters for BL coupler fabricated on (left) RO4003 and (right) RO3010 substrates

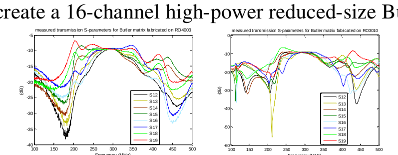


Fig. 6 Transmission measurements of the 8×8 Butler Matrix fabricated on (left)RO4003 and (right) RO3010, when port 1 is fed

References

[1] Adriany G et al, Magn Reson Med 2005; 53: 434-445.
[2] Collins CM et al, Magn Reson Med 2005; 54: 1327-1332.
[3] Vester M et al ISMRM 2006, P 2024.
[4] Alagappan V et al, MRM 2007 57(6).
[5] Butler J et al, Electron Design (9) 1961 p170.
[6] Alagappan V et al, Magn Reson Med 2007; 57:1148-1158.
[7] Nistler J et al, ISMRM 2006, Abstract 2566.