URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

4x4 Butler Compact Broadband Matrix Based on Low-Pass Filters

Denis A. Letavin
Ural Federal University
Yekaterinburg, Russian Federation
d.a.letavin@urfu.ru

Abstract

The design of the Butler 4x4 wideband matrix has been moved, whose dimensions are reduced due to the use of low-pass filters. The simulation process was carried out in a specialized program NI-AWR. The area occupied by the compact matrix is 15496.8 mm2, with a center frequency of 1 GHz (63.4% relative to the size of the regular matrix). The suggested matrix was fabricated and measured. The measured characteristics presented good similarity with the simulation results.

1 Introduction

The position of the beam in space can be controlled using multi-beam antenna arrays, representing antennas with several independent inputs, each of which has its own radiation pattern. In multipath antennas, simultaneous excitation of several inputs is also possible, which corresponds to the simultaneous existence of several beams in space and significantly expands the possibilities of using such antenna arrays. The formation of the required distribution is provided by a diagram-forming scheme. Many practical patterns of antenna arrays are known. The most common are the antenna array based on a parallel beam-forming diagram (Butler matrix) and a sequential beam-forming diagram (Blass matrix). A distinctive feature and advantage of an antenna array based on a matrix diagram-forming circuit is the possibility of compiling circuits of the same, eight-pole power dividers, and a set of fixed phase shifters. In practice, the commonly known Butler matrix is most often used. One of the promising trends for them is integrated miniaturization. The decimeter wavelength range is between 300-3000 MHz, which corresponds to electromagnetic waves from 1 to 3 m long. Microwave devices contain elements that are comparable in size to a wavelength that is closely related to the operating frequency. Therefore, with a decrease in frequency, the dimensions of the device will increase. The standard Butler 4x4 matrix consists of four directional couplers and one crossover (crossing transmission lines). The working strip will depend on the working strip of these elements. At present, one can find in the literature a description of compact Butler matrices [1] – [19]. In this paper, a compact matrix is proposed, the area of which is reduced due to the use of cells.

2 Layout

The standard matrix of 4 power dividers, 1 crossover and two phase-shifting cells is shown in Fig. 1. A typical design will have a difference of 45 degrees between the phases at the output ports. In order for the matrix to work in a wide frequency band, a three-loop directional coupler design was used as a power divider. The substrate material is FR4 (dielectric constant 4.4 and thickness 1 mm). The theoretical study of the matrices was carried out in the NI-AWR program. The matrix topology with a central frequency of 1 GHz is shown in Fig. 2.

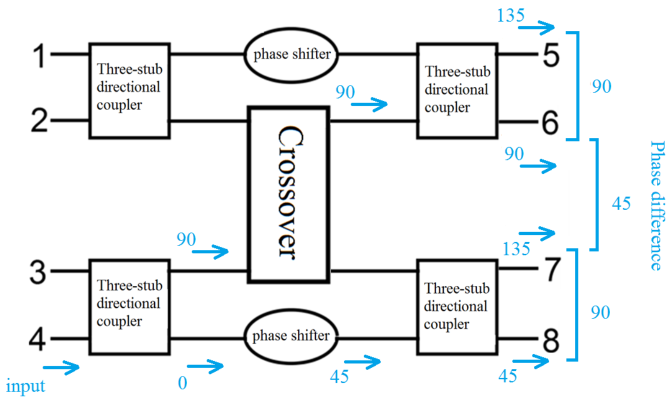

Figure 1. Butler 4x4 matrix diagram.

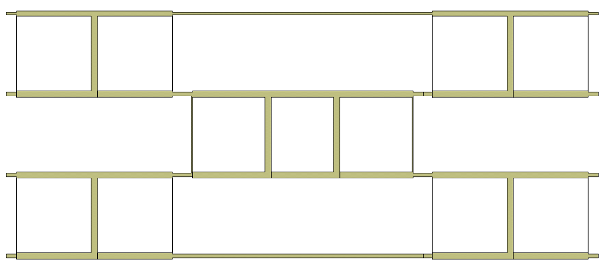

Figure 2. The layout of the Butler matrix.

The characteristics of the full-sized matrix were obtained after electrodynamic analysis of its topology in the NI-AWR program (Fig. 3, Fig. 4, Fig. 5). The area of such a matrix is 42352 mm^2. When applying a microwave signal to the first input of the matrix, we obtain that the transmission coefficients have values near - 7.5dB. The bandwidth of the matrix according to the criterion of an imbalance of transmission coefficients of +1 dB is 200 MHz. The bandwidth of the matrix at the isolation level of -10 dB is 400 MHz.

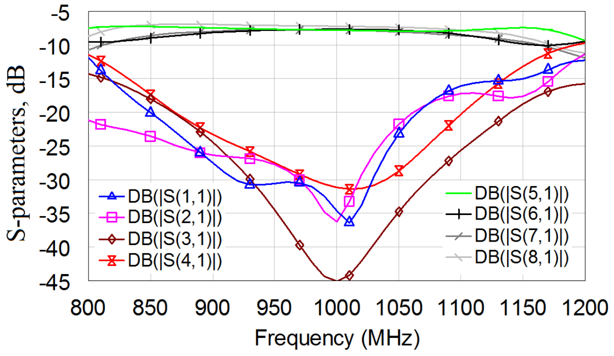

Figure 3. S-parameters from the frequency.

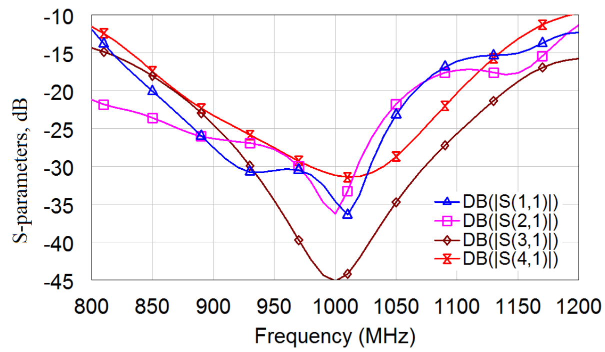

Figure 4. S-parameters from the frequency.

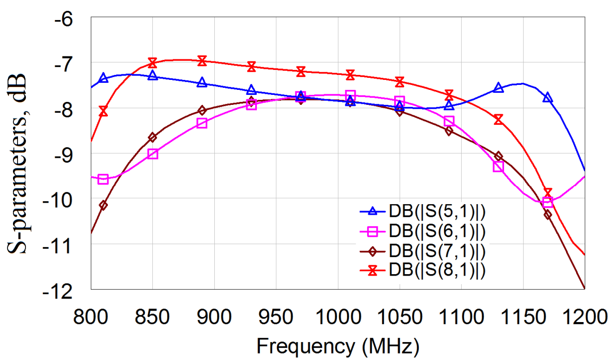

Figure 5. S-parameters from the frequency.

It can be seen that the matrix turned out to be rather cumbersome and there is an area inside the matrix that is not used in any way. In this regard, it is necessary to carry out a procedure to minimize the topology of a full-sized matrix. This procedure consists in the synthesis of cells acting as an analogue for conventional transmission lines. After replacing the segments with these cells, and having optimized the entire structure, we obtained the layout of the compact Butler matrix (Fig. 6). The frequency characteristics after electrodynamic analysis are illustrated in Figures 7-8.

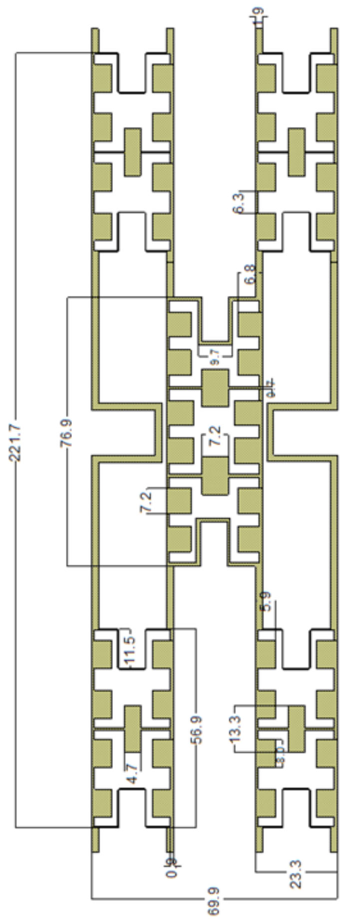

Figure 6. The layout of compact 4x4 Butler matrix for ATL.

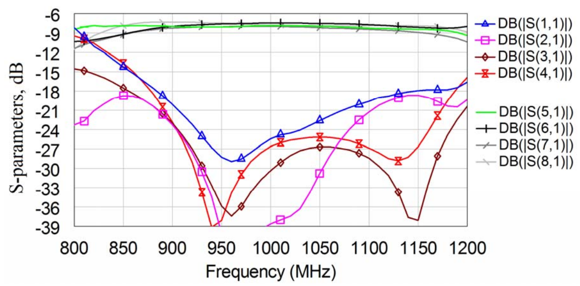

Figure 7. S-parameters from the frequency.

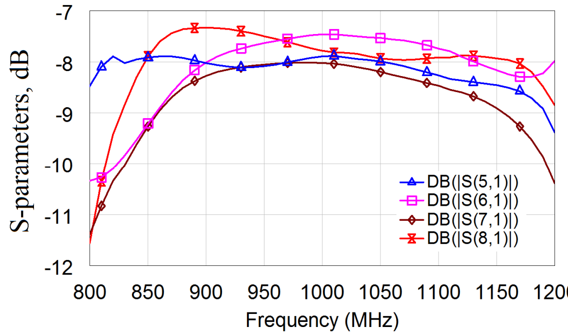

Figure 8. S-parameters from the frequency.

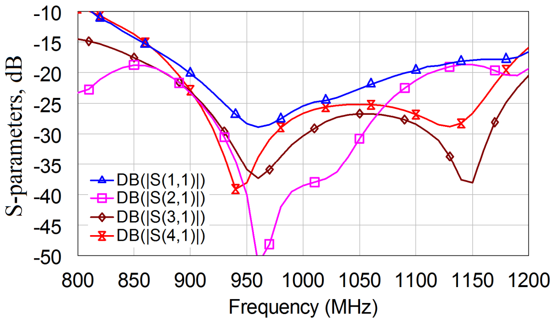

Figure 9. S-parameters from the frequency.

The area of such a matrix is 15496.8 mm^2 (which is 63.4% less than that of a full-sized one). When applying a microwave signal to the first input of the matrix, we obtain that the transmission coefficients have values near - 7.5dB. The bandwidth of the matrix according to the criterion of an imbalance of transmission coefficients of +1 dB is 180 MHz. The matrix bandwidth at the isolation level of -10 dB is 450 MHz.

3 Parameter Measurement

After we received a model of a compact 4x4 matrix, it is necessary to make a prototype of this matrix and check its characteristics in working. Figure 8 shows a photograph of the made Butler matrix. The characteristics of such a matrix were obtained using the Rohde & Schwarz ZVA24 vector network analyzer, and they showed high similarity with the theoretical ones (Fig. 9,10).

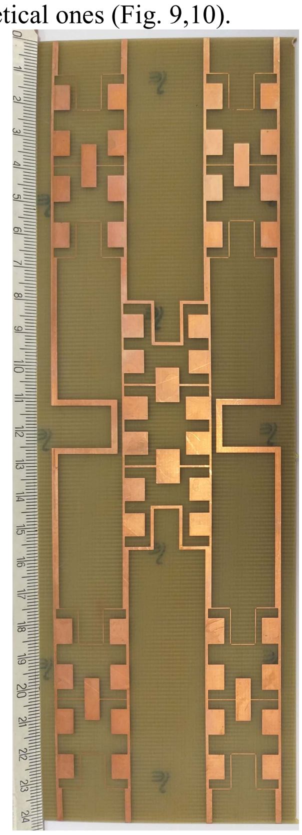

Figure 10. Photo made Matrix Butler.

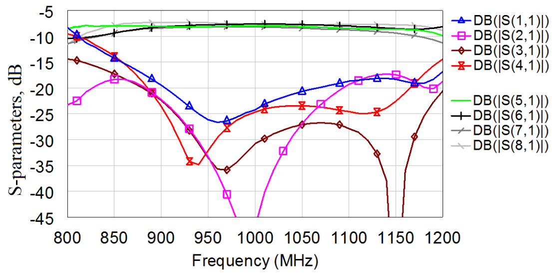

Figure 11. S-parameters from the frequency.

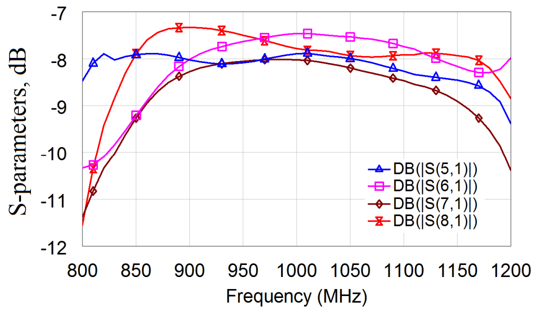

Figure 12. S-parameters from the frequency.

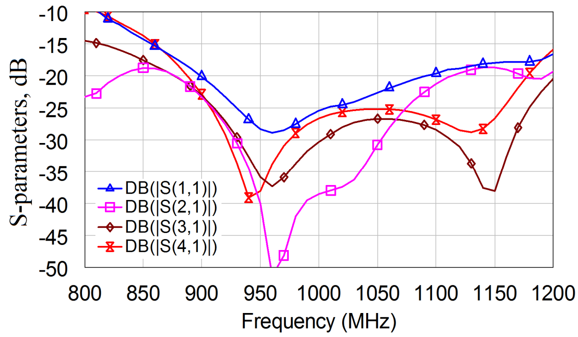

Figure 13. S-parameters from the frequency.

When applying a microwave signal to the first input of the matrix, we obtain that the transmission coefficients have values near - 8dB. The bandwidth of the matrix according to the criterion of the imbalance of transmission coefficients +1 dB is equal to 170 MHz. The matrix bandwidth at the decoupling level of -10 dB is 440 MHz. It can be seen that there are slight differences in the characteristics, but they are caused by a possible difference in the parameters of the used substrate and the accuracy of the fabrication of the matrix topology. For a more detailed comparison of full-size and compact matrices, the main characteristics are full in table 1.

Table 1 Comparison of design matrix

Design	Bandwidth, MHz	Area, mm^2	Size reduction, %
Standard	200	42352	-
Compact	170	15496.8	63.4

The area of such a matrix is 15496.8 mm^2 (which is 63.4% less than that of a full-sized one). When applying a microwave signal to the first input of the matrix, we obtain that the transmission coefficients have values near - 7.5dB. The bandwidth of the matrix according to the criterion of an imbalance of transmission coefficients of +1 dB is 180 MHz. The matrix bandwidth at the isolation level of -10 dB is 450 MHz.

4 Conclusions

A compact 4x4 matrix is proposed in the work, whose area is reduced due to the use of cells. The area of the full-size matrix is 42352 mm^2, and the size of the compact matrix is 63.4% smaller and amounts to 15496.8 mm^2. The fabricated prototype matrix showed a high convergence of practical and theoretical characteristics of the device. However, there are such negative factors, reduction of the band and an growth in losses in the transmission coefficients.

6 Acknowledgements

The authors are grateful for the NI-AWR Design Environment modeling software provided by National Instruments. The work was supported by Act 211 Government of the Russian Federation, contract № 02.A03.21.0006. The research was performed on equipment of the Urals Federal University common use center.

7 References

1. Kuek, J. J., Chandrasekaran, K. T., Karim, M. F., Nasimuddin, & Alphones, A. (2017). A compact Butler matrix for wireless power transfer to aid electromagnetic energy harvesting for sensors. 2017 IEEE Asia Pacific Microwave Conference (APMC). doi:10.1109/APMC.2017.8251447

2. Tang, C.-C., Huang, C.-Y., & Tang, C.-W. (2018). Design of the Compact Planar Butler Matrix. 2018 Asia-Pacific Microwave Conference (APMC). doi:10.23919/APMC.2018.8617162.

3. Haroun, I., Lin, T.-Y., Chang, D.-C., & Plett, C. (2012). A compact 24–26 GHz IPD-based 4×4 Butler matrix for beam forming antenna systems. 2012 Asia Pacific Microwave Conference Proceedings. doi:10.1109/APMC.2012.6421793.

4. Cerna, R. D., & Yarleque, M. A. (2018). A 3D Compact Wideband 16×16 Butler Matrix for 4G/3G Applications. 2018 IEEE/MTT-S International Microwave Symposium - IMS. doi:10.1109/MWSYM.2018.8439542.

5. Remez, J., & Carmon, R. (2006). Compact Designs of Waveguide Butler Matrices. IEEE Antennas and Wireless Propagation Letters, 5, 27–31. doi:10.1109/LAWP.2005.863615.

6. Koziel, S., & Kurgan, P. (2014). Low-cost optimization of compact branch-line couplers and its application to miniaturized Butler matrix design. 2014 44th European Microwave Conference. doi:10.1109/EuMC.2014.6986411.

7. Lian, J.-W., Ban, Y.-L., Xiao, C., & Yu, Z.-F. (2018). Compact Substrate-Integrated 4 × 8 Butler Matrix With Sidelobe Suppression for Millimeter-Wave Multibeam Application. IEEE Antennas and Wireless Propagation Letters, 17(5), 928–932. doi:10.1109/LAWP.2018.2825367.

8. Fei Wang, & Hua Wang. (2016). A broadband compact low-loss 4×4 Butler Matrix in CMOS with stacked transformer based quadrature couplers. 2016 IEEE MTT-S International Microwave Symposium (IMS). doi:10.1109/MWSYM.2016.7540284.

9. Zhou, C., Fu, J., Sun, H., & Wu, Q. (2014). A novel compact dual-band butler matrix design. Proceedings of 2014 3rd Asia-Pacific Conference on Antennas and Propagation. doi:10.1109/APCAP.2014.6992767.

10. Ding, K., He, F., Ying, X., & Guan, J. (2013). A compact 8×8 Butler matrix based on double-layer structure. 2013 5th IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications. doi:10.1109/MAPE.2013.6689925.

11. Tudosie, G., Barth, H., & Vahldieck, R. (2006). A Compact LTCC Butler Matrix Realization for Phased Array Applications. 2006 IEEE MTT-S International Microwave Symposium Digest. doi:10.1109/MWSYM.2006.249586.

12. Tian, G., Yang, J.-P., & Wu, W. (2014). A Novel Compact Butler Matrix Without Phase Shifter. IEEE Microwave and Wireless Components Letters, 24(5), 306–308. doi:10.1109/LMWC.2014.2306898.

13. Qiu Ping Chen, Shao Yong Zheng, & Yun Liang Long. (2018). Compact Butler Matrix for Wideband Beamforming. 12th European Conference on Antennas and Propagation (EuCAP 2018). doi:10.1049/cp.2018.0945.

14. Tudosie, G., Vahldieck, R., & Lu, A. (2008). A novel modularized folded highly compact LTCC Butler matrix. 2008 IEEE MTT-S International Microwave Symposium Digest. doi:10.1109/MWSYM.2008.4632926.

15. Zhang, J., & Fusco, V. (2012). A miniaturised V-band 4×4 Butler matrix SiGe MMIC. 2012 6th European Conference on Antennas and Propagation (EUCAP). doi:10.1109/EuCAP.2012.6205907.