Beamforming Networks using a Broadband 4x4 Butler Matrix with Wideband Crossovers and Couplers

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Abstract: In this work, a novel and miniaturized 4*4 Butler matrix will be presented. This proposed butler matrix comes with four 3 dB quadrature forward wave coupled line coupler, two 45 Schiffman phase shifter and one crossover. This BM has been created a centre frequency of 5.8 GHz using FR4 substrate. The crossover of this BM has substituted with a 0 dB. The proposed BM occupies a total area of (84.74 mm)*(76.56 mm). It exhibits high isolation and wideband 4x4 Butler matrix designed and simulated by employing a single-layer FR4 substrate. The return losses are better than 28 dB with its good performance.

1 INTRODUCTION

The number of wireless communication system users, combined with the restricted number of radio-frequency channels, represents a source of interference in certain areas. This lowers the efficiency of wireless transmissions and restricts their capabilities, such as cellular bandwidth and frequency efficiency. Several methods, including innovative antenna arrays, have recently been used to improve communication efficiency even in unfavourable environments. There are two categories of intelligent antenna systems: adaptive arrays and switched beam systems (Lehne, 1999).

The first is a system that effectively rejects interference by adjusting to the environment in real-time and using adaptive algorithms. It is, though, more complex and requires more signal processing than the above group. Since the second form does not employ controllers, it is less powerful and less expensive than the first. To ensure mobile tracking in a dynamic environment, a switched beam system generates several beams and selects the appropriate beam that produces the strongest signal powerful from among them. As the mobile travels, this mechanism shifts from one shaft to another. In switched-beam antenna systems, the Butler matrix is a well-known beamforming network. N input ports and N output ports feed N antennas in an NxN Butler matrix.

Planar or waveguide technology that could be used to build the Butler matrix. The Butler matrix comprises three main components: 3-dB/90 quadrature couplers, crossovers, and phase shifters. Wideband 3-dB couplers and crossovers are necessary to achieve wideband features. Microstrip multi-section branch-line structures were used to perform these characteristics (Deb et al. 2020). Several wideband Butler matrix configurations using Conductor Backed Coplanar Waveguide (CB-CPW) technology (Abdelghani et al. 2012), Substrate Integrated Waveguide (SIW) technology (Djerafi and Wu, 2012), and single layer r planar technology (Denidni and Libar, 2003) have recently been published in the literature. The authors of (Denidni, and Libar, 2003) proposed a Butler matrix for obtaining a wideband of 250 MHz and return losses less than 22.05 dB, using regular 3-dB quadrature couplers and four-section branch-line crossovers.

According to the findings in (Denidni and Libar, 2003), the bandwidth can reach 1.92 and 2.17 GHz and return losses and isolation are greater than 23 and 26 dB, respectively. Identically, the simulation

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results of the 4x4 Butler matrix are to be presented in this paper. The matrix operates over a frequency range of 5.4GHz to 5.95 GHz and provides good return losses and separation of better than -28.26 dB at the operating frequency.

2 DESIGN CONFIGURATION

As shown in the layout below, the 4x4 Butler matrix comes up with four couplers (Hock and Chakrabarty, 2005), one wideband crossover (Deb et al. 2020), and two-phase shifters (Zhai, 2014).

The first order microstrip line calculations were performed manually (Pozar, 2011), and then using the ADS calculator to optimize them. The components are based on a 1.6 mm thick FR-4 substrate with a dielectric constant of 4.4.

The output of BM is highly dependent on the coupler and crossover features; they are each simulated and configured separately before combining them to form the Butler matrix's entire architect using Advanced Design System Simulator.

2.1 Coupler

In the BM, the coupler is the most critical component. It's a -3 dB directional coupler operating a frequency of 5.8 GHz that splits the input signal into two equal-amplitude output signals. Input port 1, output port 2 (direct route), port 3 (coupled channel), and isolated port 4 (Hock and Chakrabarty, 2005) are the four ports.

Figure 1 depicts the proposed coupler's configuration, while Figure 2 depicts the simulated S-parameters.

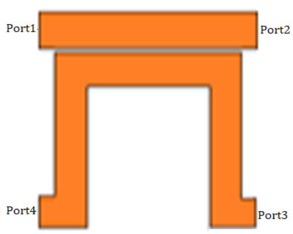

Figure 1: Layout of S-parameters of the coupler

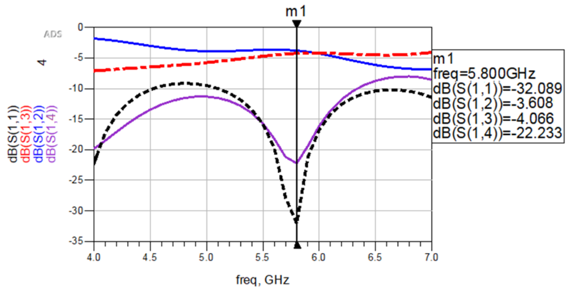

Figure 2: Simulation S11, S12, S13 and S14 of the coupler.

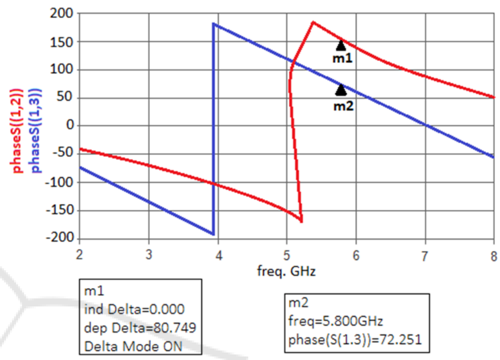

Figure 3: Simulated S12 and S13 phase difference between the output ports.

The S14 return loss and S11 isolation, respectively, are roughly -22,23 dB and -32,08 dB. It's also apparent that we've got a good match and excellent operating frequency isolation. At 5.8 GHz, the coupling is about -3, which means that power on both output ports is halved. The phase difference between the output ports is around 72.25°, as anticipated.

2.2 Phase Shifter

Phase shifters are one of the essential commonly used methods in RF.

Beamforming nets, Phase discriminators, optical beam-scanning phased arrays, and other applications use it. It shifts the signal into a Predetermined step (Zhai, 2014). Figure 4 depicts this.

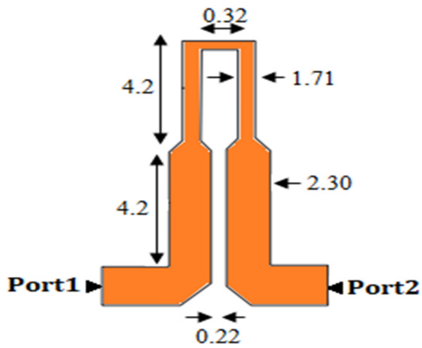

Figure 4: The structure of the Schiffman differential phase shifter

The phase shifter used is a Schiffman phase shifter, consisting of two coupled transmission lines with one folded side. Two 45 phase shifters make up the BM. The following formulation (Srivastava and Gupta, 2006) defines the line length corresponding to the step shift of 45:

$$\Delta L = \frac{\theta\lambda}{360} \tag{1}$$

In a microstrip line, the wavelength is defined as: where the phase θ change is located.

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \tag{2}$$

The wavelength is λ0, and εeff is the microstrip line's effective dielectric constant. Figure 5 depicts the phase shifter configuration as well as the simulation performance. The phase difference between ports 1 and 2 is about 45 at the operating frequency.

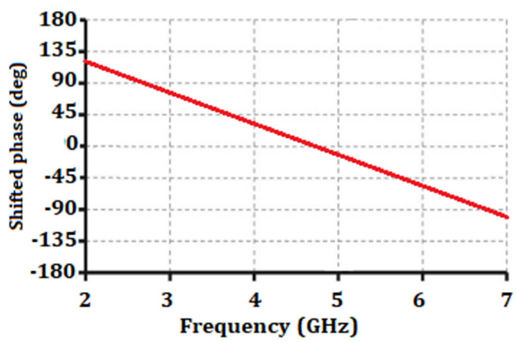

Figure 5: Simulated phase difference between the ports 1 and 2 of -45° phase shifter

2.3 Crossover

Crossover is the most complicated aspect of realizing the Butler matrix. In order to avoid overlapping signals at crossings, the crossover should be used in a fair degree of separation between the input ports. As they have four symmetrical ports, with two inputs and two outputs (Deb et al., 2020). If every neighbouring port is isolated, then we get the best crossover configuration.

The geometry and momentum S-parameters of a potential crossover are shown in Figures 6 and 7, respectively. It shows that the suggested crossover has ideal characteristics in terms of isolation and parameter lack of return. The S11 return loss is -43.38 dB, indicating that the 5.8 GHz resonant frequency is a perfect match. -1.18 is the entry failure from coupling port S13. The coupling ratio is approximately 0 dB, implying that the power at Port 1's input fully transfers to Port 3. At 5.8 GHz, S12 and S14 are separated by -40.15 dB and -37.20 dB, respectively.

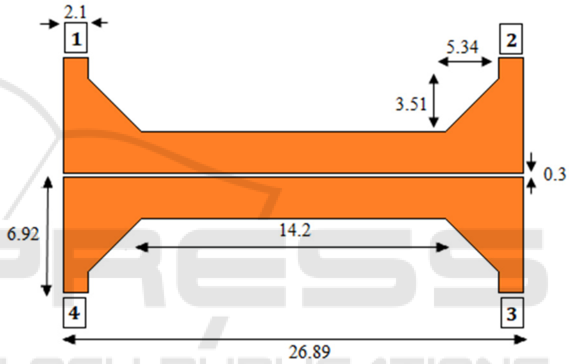

Figure 6: The structure of the proposed crossover

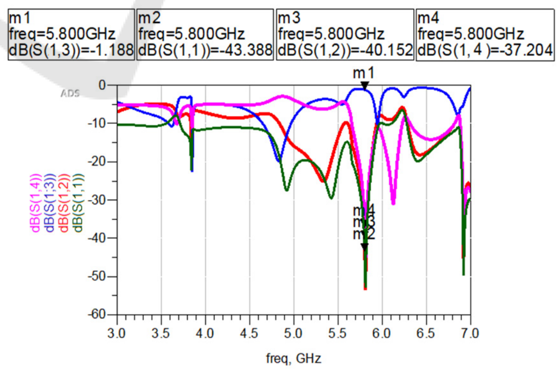

Figure 7: Simulated return loss S11, insertion loss S13, isolations S12 and S14 of the crossover.

The suggested BM is shown in Figure 9. It comes with a miniaturized shifter, coupler, and 0 dB crossover built-in.

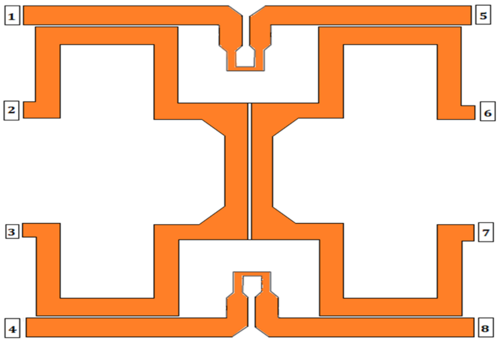

Figure 9: Proposed 4*4 BM

A N*N BM has N input lines and N output lines (where N is an even number and must be greater than or equal to 4). Between the output lines of N unit BM, there is a phase difference.

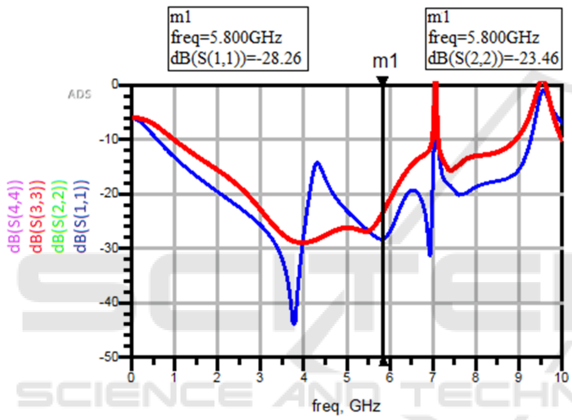

Figure 10: Simulated S11 and S22 of the four input ports

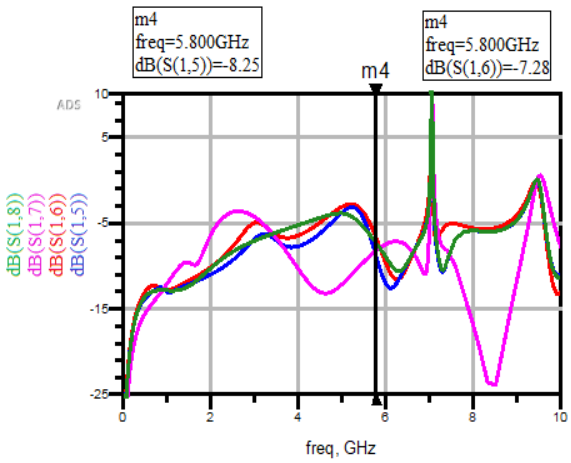

Figure 11: Simulated insertion losses of the port 1

The virtual coefficients S17, S15, and S18, S16 are approximately -8 dB and -7 dB, respectively, which is substantially different from the ideal value of -6 dB. Because of this, the control of port one is also split between the output ports. We believe the results obtained are promising.

Table 1: Performance comparison of proposed work with exciting work.

Ref	freq (GHz)	Substrate material	Total size mm^2	Return Loss S11(dB)
(Rifi et al. 2018)	5.8	FR4	90.61×96.54	-24.69
(Nachouane et al. 2014)	2.4	FR4	173.7×173	-35
(Abdelghani et al. 2012)	5.8	RO4003	90*70	<-11
(Bhowmikand Moyra, 2017)	2.5	FR4	115.18*64.4	-20
This work	5.8	FR4	44.25 * 39.92	-28.26

The comparison shows that the BM has good characteristics in terms of return loss and total size, as shown in Table 1.

3 CONCLUSIONS

As a conclusion, a new wideband 4x4 Butler matrix has been analysed, developed, and simulated. The high bandwidth is reached by using broadband systems such as crossovers and couplers. Its good performance makes it ideal for wireless communication systems as beamforming for multi-beam antenna arrays for angle diversity to minimize interference.

Experimentation is needed to validate the design.

As compared to other structures in the literature, the proposed matrix has robust characteristics in terms of substrate material, return loss and total size, as shown in Table 1.

REFERENCES

Lehne, P. H. (1999). An overview of smart antenna technology for mobile communications systems. *IEEE Comm. Surveys, fourth Quarter*, *2*(4).

Deb, P. K., Moyra, T., & Bhattacharyya, B. K. (2020). Designing of Miniaturized 4× 4 Butler Matrix Using Coupled Line Coupler and Schiffman Phase Shifter. *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, 1-10.

Abdelghani, L. M., Denidni, T. A., & Nedil, M. (2012, June). Ultra-broadband 4× 4 compact Butler matrix using multilayer directional couplers and phase shifters. In *2012 IEEE/MTT-S International Microwave Symposium Digest* (pp. 1-3). IEEE.

Djerafi, T., & Wu, K. (2012). A low-cost wideband 77 GHz planar Butler matrix in SIW technology. *IEEE Transactions on Antennas and Propagation*, *60*(10), 4949-4954.

Denidni, T. A., & Libar, T. E. (2003, September). Wideband four-port Butler matrix for switched multi-beam antenna arrays. In *14th IEEE Proceedings on Personal, Indoor and Mobile Radio Communications, 2003. PIMRC 2003.* (Vol. 3, pp. 2461-2464). IEEE.

Hock, G. C., & Chakrabarty, C. K. (2005, December). Design of a 5.8 GHz directional coupler using an electronic design automation tool. In *2005 Asia-Pacific Conference on Applied Electromagnetics* (pp. 4-pp). IEEE.

Zhai, Y., Fang, X., Ding, K., & He, F. (2014). Miniaturization design for 8× 8 Butler matrix based on back-to-back bilayer microstrip. *International Journal of Antennas and Propagation*, *2014*.

Pozar, D. M. (2011). *Microwave engineering*. John Wiley & sons.

Srivastava, G. P., & Gupta, V. L. (2006). *Microwave devices and circuit design*. PHI Learning Pvt. Ltd.

Rifi, M., Tizyi, H., Terchoune, H., & Elmarini, S. (2018). Switched beam smart antenna based on a planar 4x4 butler matrix for wireless power transfer at 5.8 GHz. *Revue Méditerranéenne des Télécommunications*, *8*(2).

Nachouane, H., Najid, A., Tribak, A., & Riouch, F. (2014, April). Broadband 4× 4 Butler matrix using wideband 90° hybrid couplers and crossovers for beamforming networks. In *2014 International Conference on Multimedia Computing and Systems (ICMCS)* (pp. 1444-1448). IEEE.

Bhowmik, P., & Moyra, T. (2017). Modelling and validation of a compact planar butler matrix by removing crossover. *Wireless Personal Communications*, *95*(4), 5121-5132.