WIDEBAND X-BAND MICROSTRIP BUTLER MATRIX

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Abstract—This paper presents the design of a wideband X-band microstrip 4×4 Butler matrix. The wideband performance of the Butler matrix means that it possesses equal coupling and difference of phases throughout the operating band. Design of the wideband components such as 3-branch branch line hybrid, crossover and Schiffman line phase shifter are presented in this paper. A final design of the Butler matrix is proposed. The Butler matrix exhibits couplings and phase errors within -6.7 ± 0.7 dB and $10°$ over a 20% bandwidth with a center frequency at 10 GHz.

1. INTRODUCTION

$N \times N$ Butler matrix is a passive microwave network consisting of 'N' input and 'N' output ports. If it is used to feed an array of 'N' antennas, the network will generate a set of 'N' orthogonal beams. It can also feed a circular array of 'N' antennas. Butler matrix is the key component of beamforming network, which is widely applied in smart antennas [1]. Butler matrix has been implemented with various techniques such as waveguide [2], microstrip [3, 4], multilayer microstrip [5], suspended stripline [6], CPW [7], etc. Microstrip technique was widely used in Butler matrix due to its numerous advantages such as low profile, easy fabrication and low cost.

Conventional Butler matrix design put emphasis upon the equal coupling of hybrid with wideband and phase shifter was designed only at the center frequency with extremely narrow bandwidth. There are several methods to widen the bandwidth of hybrid. 3-branch branch line hybrid is adopted as a substitute for 2-branch branch line hybrid. Multilayer coupled microstrip line hybrid can achieve an one-octave bandwidth [5]. Another method is that of using matching circuits which match the ports of hybrid [8].

The wideband performance of a Butler matrix means that it possesses equal coupling and difference of phases throughout the operating band. Schiffman line phase shifter is a wideband differential phase shifter, which changes the phase shift slope of one transmission line using the coupled line to match that of the other transmission line. To our knowledge, there are two literatures in which coupled line was used in the phase shifter of Butler matrix, i.e., the wideband Butler matrix in stripline [9], in which the Schiffman line phase shifter was also used to construct 180° hybrid; and the dual-band Butler matrix [10], in which a pair of coupled lines was used to fit the phase shift character of dual-band. In this paper, wideband components such as 3-branch branch line hybrid, crossover, and Schiffman line phase shifter are designed (IE3D, ZELAND) and used to construct a wideband microstrip Butler matrix with a bandwidth of 20% and with a center frequency at 10 GHz. The wideband performance of a Butler matrix proposed is important when it is used to feed a set of circular arrays where beam-scanning along the longitudinal antenna axis is complemented with an linearly frequency modulation.

2. ELEMENTS OF THE BUTLER MATRIX

The scheme of a 4×4 Butler matrix is shown in Fig. 1. The phase distribution of output ports according to input ports is shown in Table 1. As shown in Fig. 1, a Butler matrix consists of hybrids, crossover, and phase shifters. The wideband performance of the Butler matrix is due to the wideband design of its components.
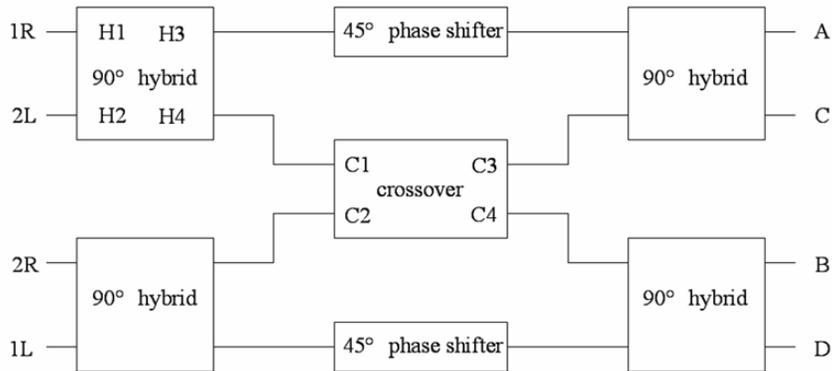
Figure 1. Schematic of the proposed Butler matrix.

Table 1. Phase distribution of output ports according to input ports.

	A	B	C	D	$\Delta\phi$
1R	-45°	-90°	-135°	-180°	-45°
2L	-135°	0°	-225°	-90°	135°
2R	-90°	-225°	0°	-135°	-135°
1L	-180°	-135°	-90°	-45°	45°

2.1. Substrate

Working at X-band requires proper selection of the substrate. Microstrip bends at high frequencies start to radiate. Butler matrix has numerous bends in its physical layout, looses much of input power if improper substrate is selected. Radiation condition is given as follows,

$$f[\text{GHz}]h[\text{mm}] > 2.14\sqrt{\varepsilon_r} \tag{1}$$

A proper substrate is selected for X-band with a substrate of $\varepsilon_r = 2.2$ and thickness of 0.254 mm (Roger5880). All ports of the following elements are designed with characteristic impedance 50 ohm (0.78 mm).

2.2. Hybrid

As is shown in Fig. 2, a 3-branch branch line hybrid is adopted as a substitute for 2-branch branch line hybrid to widen the bandwidth of the hybrid. The hybrid is designed to operate from 9 GHz to 11 GHz. The maximum of $||S(3,1)| - |S(4,1)||$ (dB) and $|\arg S(3,1) - \arg S(4,1) - 90°|$ are less than 0.4 dB and 2.5° throughout the operating band (see Fig. 3–Fig. 4).

2.3. Crossover

A planar crossover can be made by cascading two hybrids. The layout of the proposed crossover is shown in Fig. 2. Adjust the length of interconnection can reduce the return loss. The performance of the crossover is shown in Fig. 5.

2.4. Schiffman Line Phase Shifter

If the differential phase shifter is designed at the center frequency using a normal transmission line, because of the phase shift slope of crossover is bigger than that of normal transmission line, its operating band is
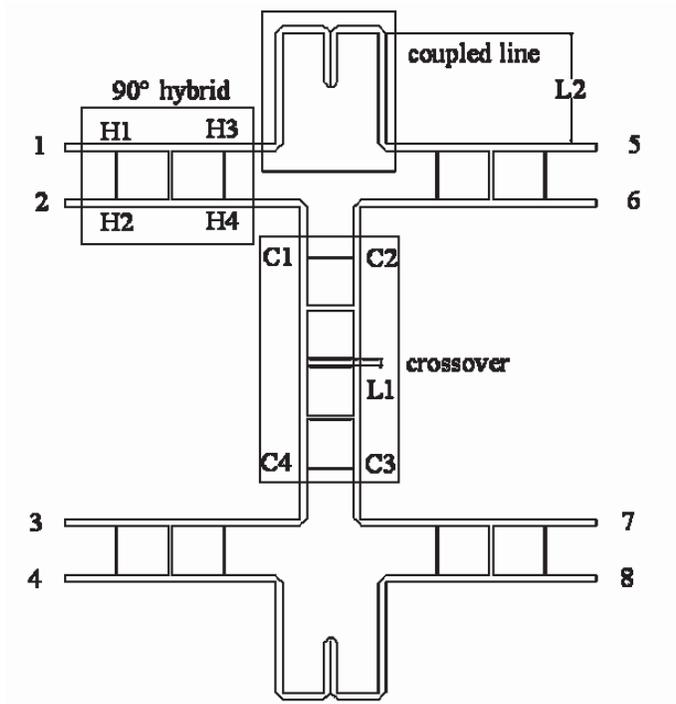
Figure 2. Layout of the wideband microstrip Butler matrix.

limited. The wideband phase shifter is designed using the principle of Schiffman line phase shifter [9]. A quarter wavelength coupled line cascades a section of normal transmission line, adjust the length L2 until the phase shift slope is match to that of the crossover and its differential phase shift is $-45°$ at the center frequency. The layout is shown in Fig. 2. The phase shift error is less than $1°$ over a 20% bandwidth (see Fig. 6).

3. WIDEBAND X-BAND MICROSTRIP 4×4 BUTLER MATRIX

In this section, simulation results for the wideband X-band microstrip 4×4 Butler matrix are presented. Fig. 2 shows the layout of the proposed Butler matrix. The return loss, isolation, and insertion loss are shown in Figs. 7–9. The simulation and measurement of phase errors are shown in Figs. 10–11. From the results, it can be concluded that the Butler matrix has a 20% bandwidth with the center frequency
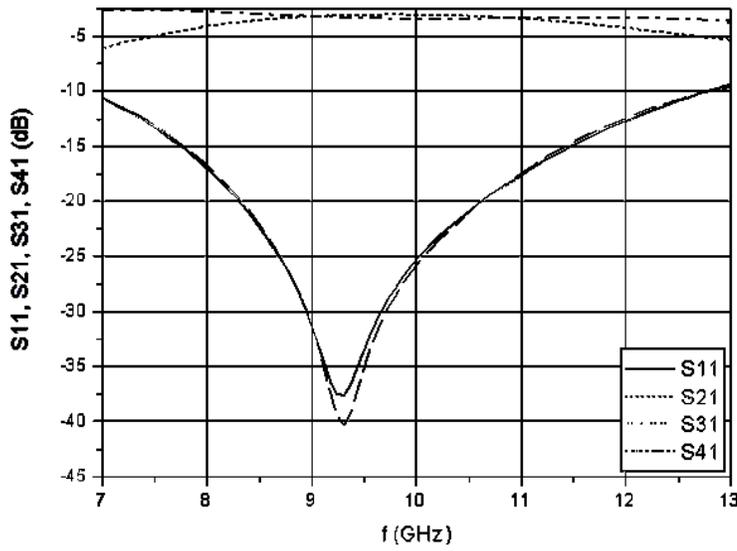
Figure 3. Simulation of the 3-branch branch line hybrid (return loss, insertion loss, and isolation).
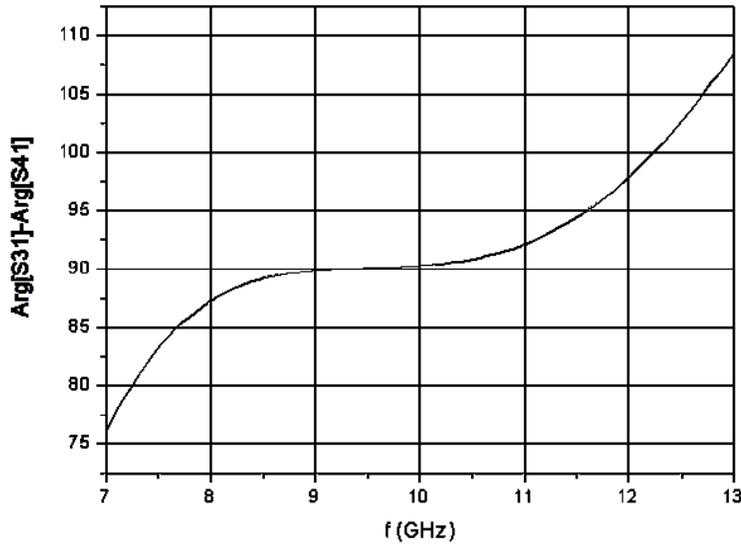
Figure 4. Simulation of the 3-branch branch line hybrid (difference of the phases between the outputs).
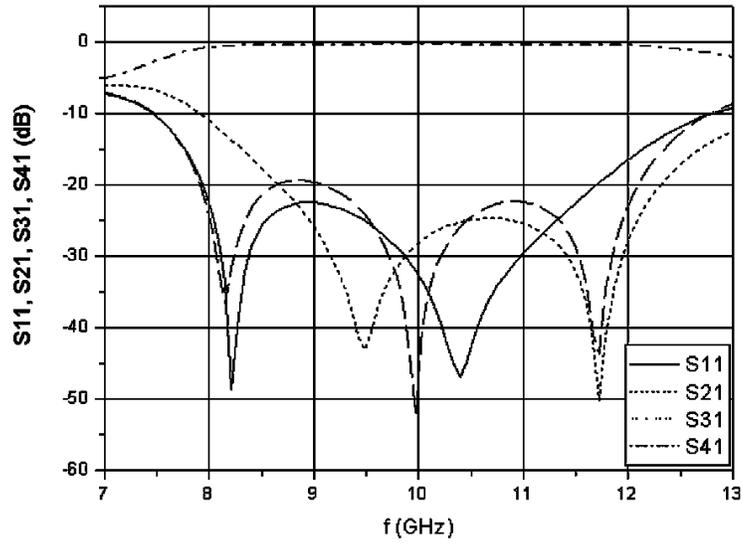
Figure 5. Simulation of the crossover.
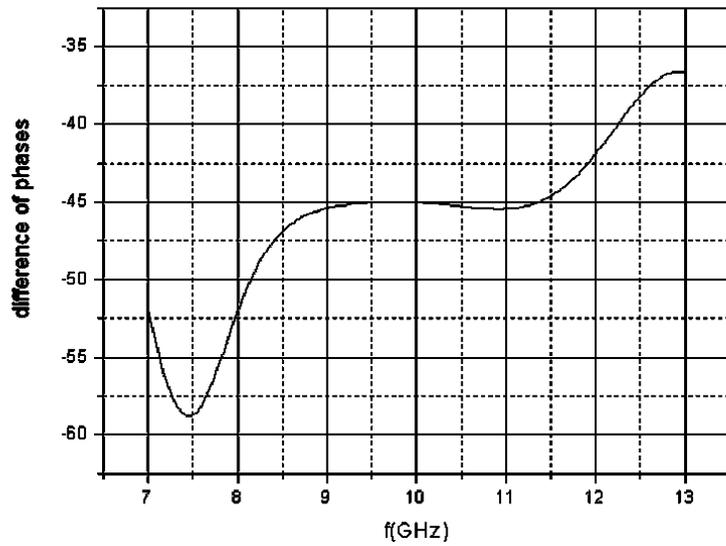
Figure 6. Simulation of the Schiffman line phase shifter.
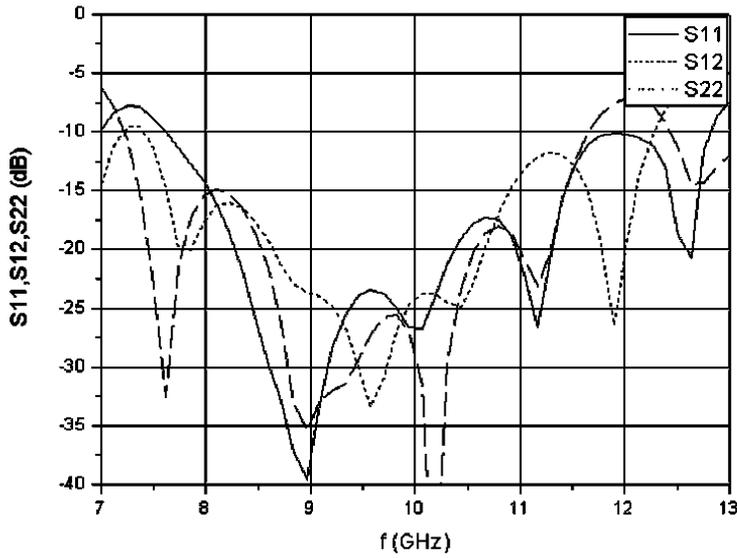
Figure 7. Simulation of the return loss and isolation.
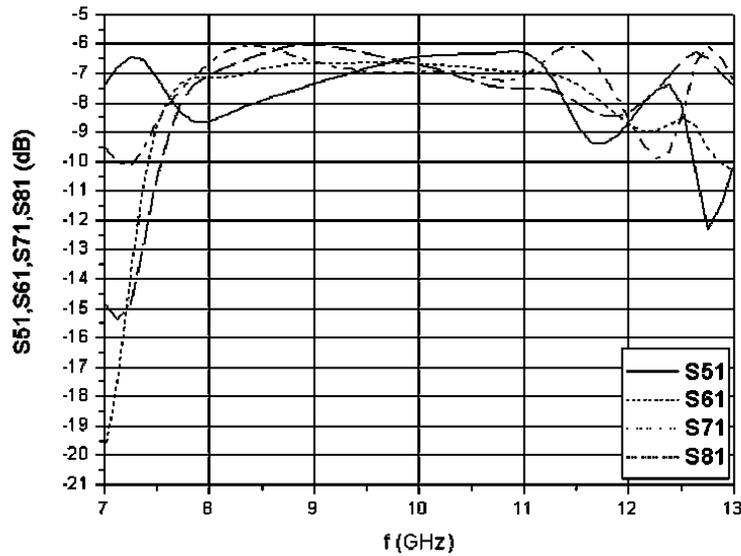
Figure 8. Simulation of the insertion loss for the 1-5, 1-6, 1-7, and 1-8 path.
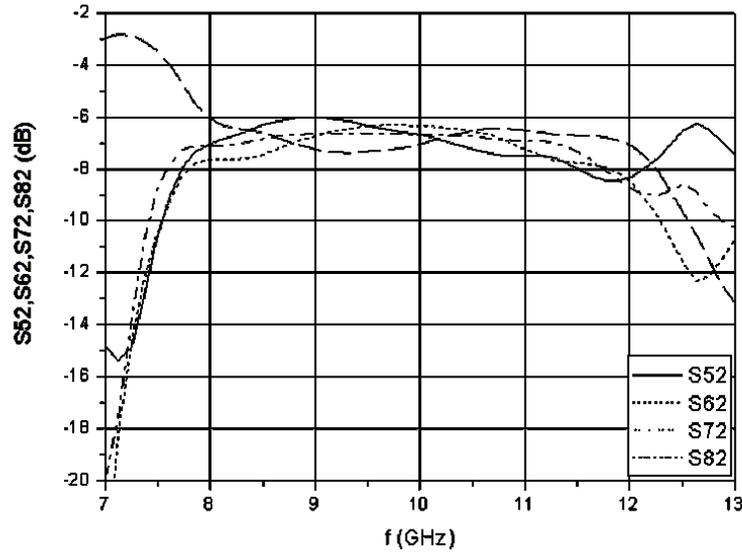
Figure 9. Simulation of the insertion loss for the 2-5, 2-6, 2-7, and 2-8 path.
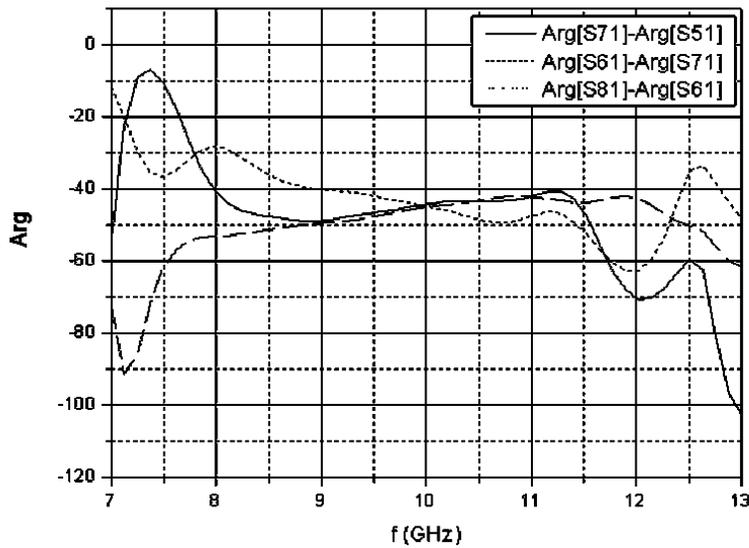
Figure 10. Simulation of the phase errors for the 1-5, 1-6, 1-7, and 1-8 path.
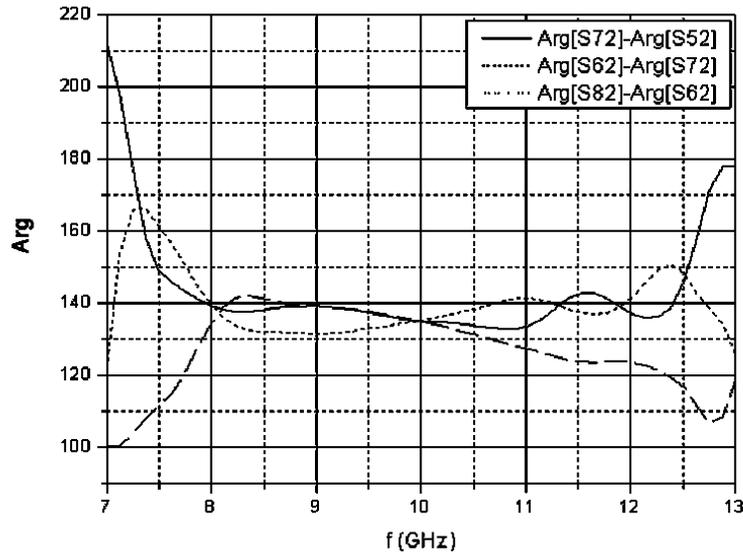
Figure 11. Simulation of the phase errors for the 2-5, 2-6, 2-7, and 2-8 path.

at 10 GHz. Throughout the operating band, the maximum error of coupling is less than 0.7 dB, the maximum phase error is less than $10°$.

4. CONCLUSIONS

A wideband X-band microstrip $4{\times}4$ Butler matrix has been designed in this paper. The wideband performance of the Butler matrix is due to the wideband design of its components. Especially, the phase shifter is designed using the principle of Schiffman line phase shifter. The Butler matrix exhibits couplings and phase errors within -6.7 ± 0.7 dB and $10°$ over a 20% bandwidth with a center frequency at 10 GHz.

REFERENCES

1. Fakoukakis, F. E., S. G. Diamantis, A. P. Orfanides, and G. A. Kyriacou, "Development of an adaptive and a switched beam smart antenna system for wireless communications," *Journal of Electromagnetic Waves and Applications*, Vol. 20, No. 3, 399–408, 2006.

2. Alessandri, F., M. Dionigi, R. Sorrentino, and L. Tarricone, "Rigorous and efficient fabrication-oriented CAD and optimization of complex waveguide networks," *IEEE Trans. Microwave Theory and Tech.*, Vol. 45, 2366–2374, 1997.

3. Fu, K. K. and A. K. Y. Lai, "FDTD optimization of beam forming network for multibeam antenna," *In Antennas and Propagation Society International Symposium*, Vol. 4, 2028–2031, 1998.

4. Denidni, T. A. and T. E. Libar, "Wide band four-port butler matrix for switched multibeam antenna arrays," *Personal, Indoor and Mobile Radio Communications, 14th IEEE Proceedings*, Vol. 3, 2461–2464, 2003.

5. Sachse, K., A. Sawichi, and G. Jaworski, "Novel multilayer coupled-line structures and their circuit applications," *Microwave, Radar and Wireless Communications, 13th International Conference*, Vol. 3, 131–155, 2000.

6. Bona, M., L. Manholm, J. P. Starski, and B. Svensson, "Low-loss compact Butler matrix for a microstrip antenna," *IEEE Trans. Microwave Theory and Tech.*, Vol. 50, 2069–2075, 2002.

7. Nedil, M., T. A. Denidni, and L. Talbi, "Novel Butler matrix using CPW multilayer technology," *IEEE Trans. Microwave Theory and Tech.*, Vol. 54, 499–507, 2006.

8. Hiranandani, M. A. and A. A. Kishk, "Widening Butler matrix bandwidth within the X-band," *Antenna and Propagation Society International Symposium, IEEE*, Vol. 4A, 321–324, 2005.

9. Foti, S. J. and T. Macnamara, "Design of wideband Butler matrices using Schiffman lines," *Multiple Beam Antennas and Beamformers, IEE Colloquium*, Vol. 5, 1–8, 1989.

10. Collado, C., A. Grau, and F. D. Flaviis, "Dual-band Butler matrix for WLAN systems," *Microwave Symposium Digest, IEEE MTT-S International*, 2247–2250, 2005.