Progress In Electromagnetics Research M, Vol. 4, 1–21, 2008

A NEW ULTRA-WIDEBAND BEAMFORMING FOR WIRELESS COMMUNICATIONS IN UNDERGROUND MINES

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Abstract—In this paper, a novel ultra-wideband switched-beam antenna system based on 4×4 two-layer Butler matrix is presented and implemented to be used in hostile environment, such as underground mines. This matrix is based on the combination of a broadband two-layer slot-coupled directional coupler and a multilayer slot-coupled microstrip transition. With this configuration, the proposed matrix was designed without using any crossovers as used in conventional Butler matrices. Moreover, this new structure is compact and offers an ultra-wide bandwidth of 6 GHz. To examine the performance of the proposed matrix, experimental prototypes of the multilayer microstrip transition and the Butler matrix were fabricated and measured. Furthermore, a three 4-antenna arrays were also designed, fabricated and then connected to the matrix to form a beamforming antenna system at 3, 5.8 and 6 GHz. As a result, four orthogonal beams are produced in the band 3–9 GHz. This matrix is suitable for ultra-wideband communication systems in confined areas.

1. INTRODUCTION

The main cause of degradation of communication quality in underground mines is multipath fading [1]. This multipath phenomenon arises when a transmitted signal undergoes reflection from various obstacles in the propagation environment which degrades the transmission quality and limits the frequency efficiency [2–4]. Smart antennas are one resolution to overcome this problem [5]. Smart antenna systems are introduced to improve wireless performance and increase system capacity by spatial filtering, which can separate spectrally and temporally overlapping signals from multiple users. Smart antennas systems can be generally categorized into two approaches based on transmit strategy: adaptive arrays and switched beams [6–8]. Adaptive arrays consist of multiple antenna elements at the transmitting and/or receiving side of the communication link, whose signals are processed adaptively in order to exploit the spatial dimension of the mobile radio channel. This technique allow to steer the main lobe in the desired signal direction and to create pattern nulls in directions of interferences, which results in a better signal-to-interference ratio. However, the physical implementation of these algorithms is more complex and leads to costly systems. On other hand, switched beams systems are referred as antenna array system that forms multiple fixed beams with enhanced sensitivity in a specific area. This antenna system detects signal strength, selects one of the several predetermined fixed beams, and switches from one beam to another as the user moves.

One of the most widely-known of switched beam networks is Butler matrix [6]. It is a passive feeding $N \times N$ network with beam steering capabilities for phased array antennas with Noutputs connected to antenna elements and N inputs or beam ports. Feeding an N-element antenna array using an $N \times N$ Butler matrix, N orthogonal beams can be generated, and each one has a gain of the whole array.

Recently, Ultra-Wideband (UWB) radio technology has been getting more and more popular for high-speed wireless connectivity [9–15]. UWB radio systems are very promising since transmission data rates greater than those on the other wireless local area network WLAN systems can be obtainable with less power dissipation [16]. It is foreseen today as a possible solution for short-range indoor wireless applications where high resolution, reduced interference, and propagation around obstacles are challenging [17]. In this area, it is strategic to have wideband and spatial filtering at the same time to combine the both advantages. However, conventional Butler matrices, which use that a network composed of microwave hybrids and crossovers, have a limited bandwidth. In addition, crossovers add undesired effects such as increased insertion losses, mismatched junctions, additional line cross couplings and poor power handling [18]. For wideband applications, few configurations of Butler matrix have been suggested [19–21]. In [19], a 4×4-microstrip single layer matrix using wideband crossover has been proposed. This matrix still narrowband because of the limited band of the hybrid couplers used in these structures. Tudosie et al. [20], have built an 8×8-matrix at 5 GHz using LTCC technology. The obtained bandwidth is 2 GHz, which is not enough to cover future high-speed systems. Moreover, the LTCC technology is very difficult for fabrication. The suspended strip lines with multilayer structure have also been studied in [21]. A modified version of [21] using a combination of two directional couplers acting as crossovers is proposed in [22]. However, the bandwidth still narrow, which is around 1 GHz. The most challenge to take up in Butler matrix is increasing the bandwidth and avoiding the line crossing.

In this contribution, a design of a new ultra-wideband multilayer beamforming network based on a multilayer 4×4 Butler matrix is described. This matrix is advantageously used to offer a very wide bandwidth and to avoid using any crossing lines. To validate the proposed design, an experimental prototype of the proposed 4×4-matrix was designed, fabricated and measured. Simulation and experimental results including return loss, insertion loss are presented and discussed. Furthermore, to examine the performance of the proposed matrix in terms of beamforming, a 4 antenna array was built and connected to this matrix to form a multiple beam antenna system. Simulation and measurements were carried out on this beamforming system and the obtained results are also presented and discussed.

2. DESIGN PROCEDURE

A standard $N \times N$ Butler matrix has N input and N output ports. Matrices with 90° hybrids are symmetrical networks, whereas those with 180° hybrids are asymmetrical [21]. For each input port, the network will produce signals with progressive phase shifts at the output ports with equal power. As a result, this matrix produces N orthogonal beams at its outputs. A conventional Butler matrix uses $Nn/2$ hybrids with $N/2(n-1)$ phase shifters. For planar structure, the crossover needed may be calculated as reported in [18].

$$C_n = 2C_{n-1} + 2^{n-2}\left(2^{n-2} - 1\right) \tag{1}$$

where n is the matrix order, which is related to the number of ports by $N = 2^n$. In (1) n should equal or greater than 2, and $C_1 = 1$.

From the relation (1), when the number of crossovers involved in the implementation of conventional Butler matrices is high, more space will be needed. For instance, a matrix with 32 ports, the number of crossover is 416, which is very huge and could introduce a lot of losses.

For this reason, configurations without crossovers are more suitable. In this perspective, a new Butler matrix design is proposed.

Figure 1 shows the Butler matrix that uses microstrip directional coupler, a two-port slot coupled transition, and phase shift transmission lines. The key components of the proposed ultra-wideband Butler matrix are the directional coupler and slot coupled transition. Using the EM simulator IE3D, which is part of Zeland software package [24], the design procedure of the directional coupler, the slot-coupled transition, and the 4×4 Butler matrix was carried out. In the following subsections, the design and the performance of each component of this matrix are presented and described in more details.

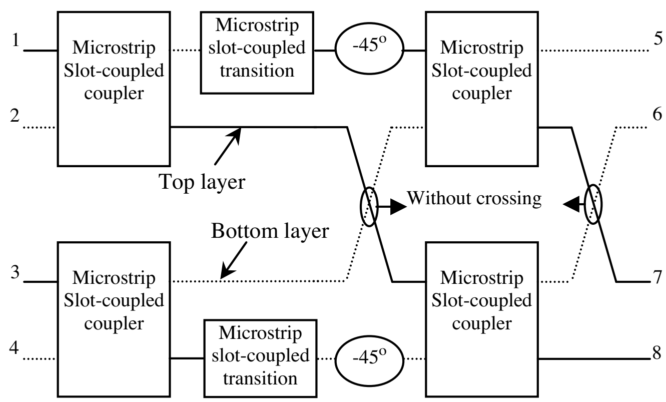


Figure 1. Block diagram of the proposed UWB Butler matrix.

2.1. Microstrip Slot-Coupled Directional Coupler

Directional couplers are the most important devices in microwave integrated circuits. Slot-coupled directional couplers between double-sided substrate microstrip lines have recently found applications in the design of many important microwave and millimeter-wave circuits [25]. To widen the bandwidth and to avoid crossovers in the proposed Butler matrix circuit, a slot-coupled directional coupler [26] is chosen (Fig. 2). The rule of this coupler is to ensure coupling between two microstrip lines through a slot etched on the common ground plane as illustrated in Fig. 2. This component is symmetrical and has the following property: if port 1 is fed, then the signal travels to port 3 (direct path) and port 2 (coupled path), while the port 4 is isolated. The input power is split equally (~ -3 dB) between the two output ports, and the two output signals present 90° of phase difference.

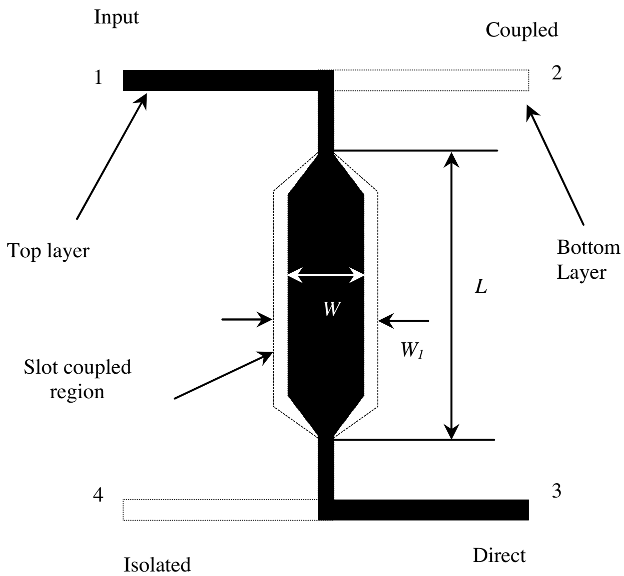


Figure 2. Layout of the microstrip slot-coupled directional coupler.

Few researchers have worked on slot-coupled couplers. Tanaka [25] has used a conformal mapping method to analyze and design the coupler. Later, Uysal et al. [26] have proposed a hexagonal slot coupled to optimize the performances of the coupler structure. In this work, we design a slot-coupled directional coupler based on the approach reported in [26]. The chosen slot-coupled geometry (hexagonal) offers a good transition and enough coupling between the microstrip feed line and the slot coupled region line.

The initial dimensions are calculated using the design procedures given in [25]. Since the slot-coupled geometry is not rectangular, it is difficult to predict the accurate values of the coupler dimensions. Thus, the exact coupler layout was simulated and optimized by full-wave simulations using IE3D [24], which is considered as a good simulator for single and multilayer microwave circuits. With this CAD tool, the coupler design was designed and optimized. The optimum design dimensions are $W = 3.5\,\text{mm}$, $W_1 = 4.8\,\text{mm}$, $L = 10.6\,\text{mm}$ and $h = 0.254\,\text{mm}$.

It was noted that the coupling mechanism is controlled by the thickness of the substrate, the dimensions of transmission lines, and the dimensions of the slot size located on the common ground plane.

Simulation results of the directional slot-coupled coupler are shown in Fig. 3. From these curves, it can be seen that the directional slot-coupled coupler offers an ultra-wide bandwidth of 5 GHz. In terms of phase shift, the coupler has roughly $\sim 90°$, which is illustrated in Fig. 4. With these features, this coupler is suitable to build UWB Butler matrix circuits.

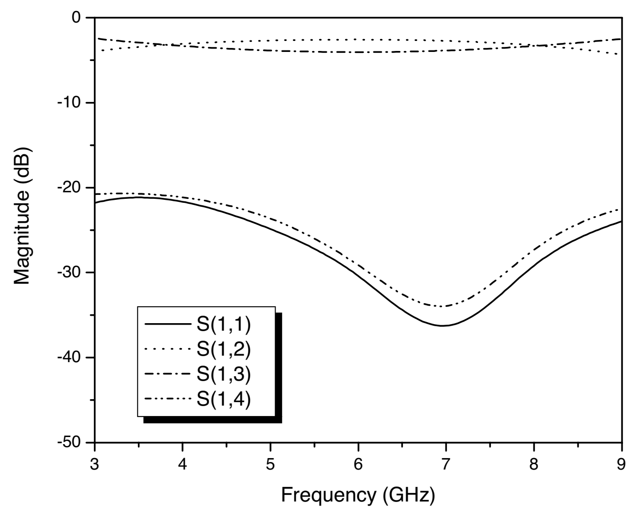


Figure 3. Simulated Scattering parameters of the directional coupler.

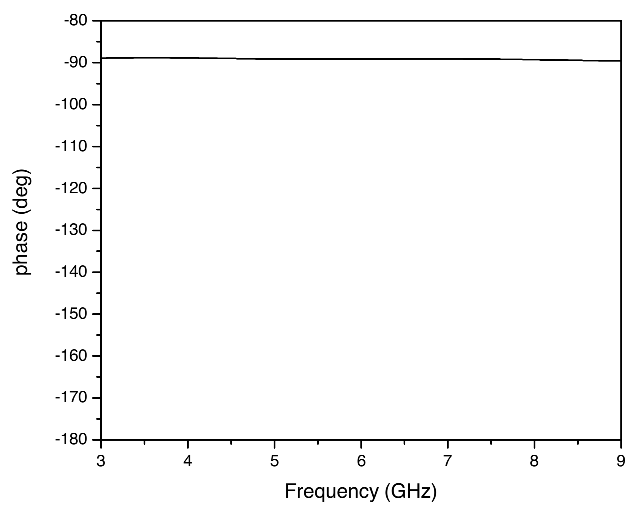


Figure 4. Simulated result of phase shift between the outputs of coupler.

2.2. Microstrip Slot-Coupled Transition

Planar multilayer transmission lines, such as microstrip lines have been applied in many microwave and millimetre-wave circuits [27]. In some multilayered structures, these transmission lines are even combined to form circuit components. One drawback of using these multiple layer structures is the fact that the necessity to pass signals between transmission lines in different layers. In this area, the use of transitions is necessary for designing circuits using multilayer technology. Therefore, the low-loss, wideband, and compact transitions are necessary to ensure the compatibility and flexibility between transmission lines located in different layers.

There are two main techniques for a transition between microstrip lines in multilayer technology. One employs an electrical contact and the other use electromagnetic coupling [28–31]. One type uses vias to connect the top layer microstrip ground planes with the lower microstrip ground plane and the other does not. The transitions using via holes are compact and broadband, but the vias can cause parasitic inductance and are difficult to be fabricated [29]. In other hand, the transitions by electromagnetic coupling require no wire bonds or via holes [29–31]. In this perspective, printed slots have been preferred to be versatile for vertical transitions. With this transition, a signal arriving on the upper transmission line eventually reaches the discontinuity in the end of this transmission line. This discontinuity created here radiates energy that is mostly coupled to the bottom line by the opening in the ground plane.

In this section, a broad-band back-to-back microstrip-to-microstrip transition is designed using the frequency-dependent behavior of surface-to-surface slot coupling [32, 33]. The choice of this type of transition is justified by the enhancement features such as ultra wide-bandwidth, low radiation loss, and deep up-band rejection [33]. Fig. 5 shows the geometrical layout of the two-port microstrip-to-microstrip transition. This transition is characterized by an aperture formed on the common ground plane of the two-layered structures to provide a fed-through coupling between the upper and lower microstrip lines. In this structure, the upper microstrip conductor is vertically coupled with the central strip conductor of the lower microstrip through a slot-coupled located in the common ground plane.

The transition was designed using the EM simulator IE3D, which is part of Zeland software package. The top and bottom 50-ohm transmission lines were computed using HP's LineCalc. The coupling-line widths and line lengths were varied in order to optimize the transition match. The slot coupled offers a good transition and enough coupling between the upper microstrip feed line to bottom

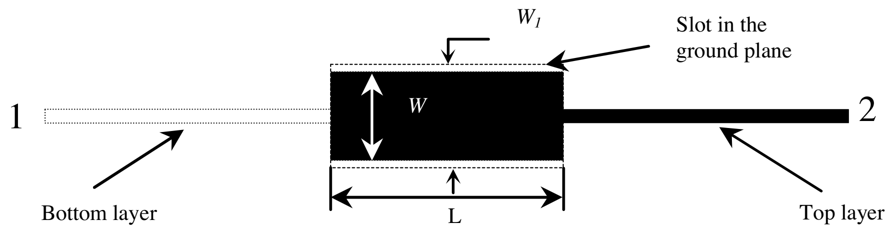


Figure 5. Layout of an improved back-to-back slot coupled transition.

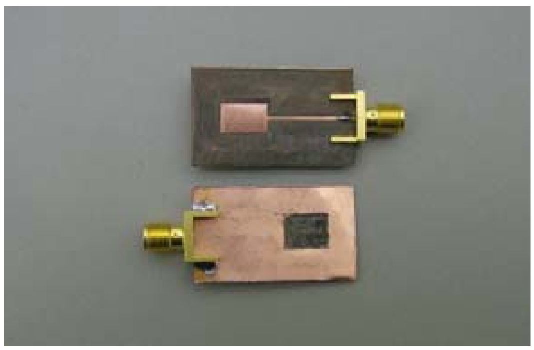
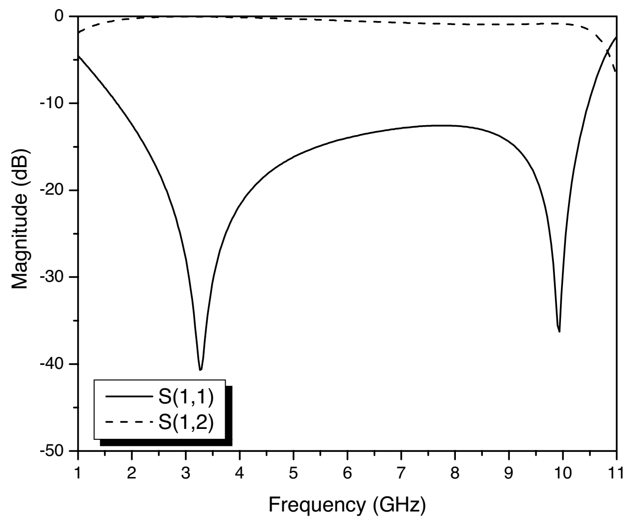


Figure 6. Photograph of the fabricated transition.

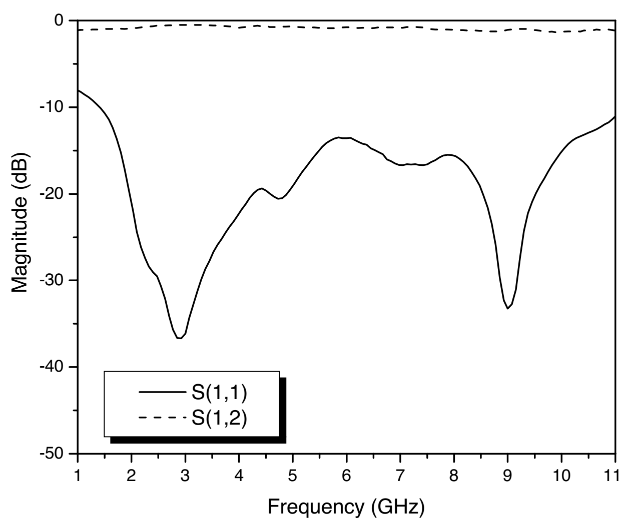
microstrip line section via the slot coupled region. The transition was designed using a Duroid substrate (RT/Duroid 5880) with $\varepsilon_r = 2.2$ and thickness of 0.254 mm. The dimensions of the transition are $L = 9.2\,\text{mm}$, $W = 5.5\,\text{mm}$ and $W_1 = 6.9$.

Based on this design, an experimental prototype was fabricated and tested. Fig. 6 shows the photograph of the fabricated transition. The simulated and measured results are shown in Fig. 7. From these, it can be seen that the comparison between simulated and experimental data shows a good agreement, and the optimized microstrip to microstrip transition offers a very wide bandwidth of $\sim 8\,\text{GHz}$ (130%). The simulated insertion loss is observed to be less than 0.5 dB and the return loss is higher than 40 dB in the whole passband of 8 GHz.

As an application of this transition, an ultra-wideband Butler matrix was introduced, where a very wide bandwidth was achieved and the details of this are given in the next section.



(a)

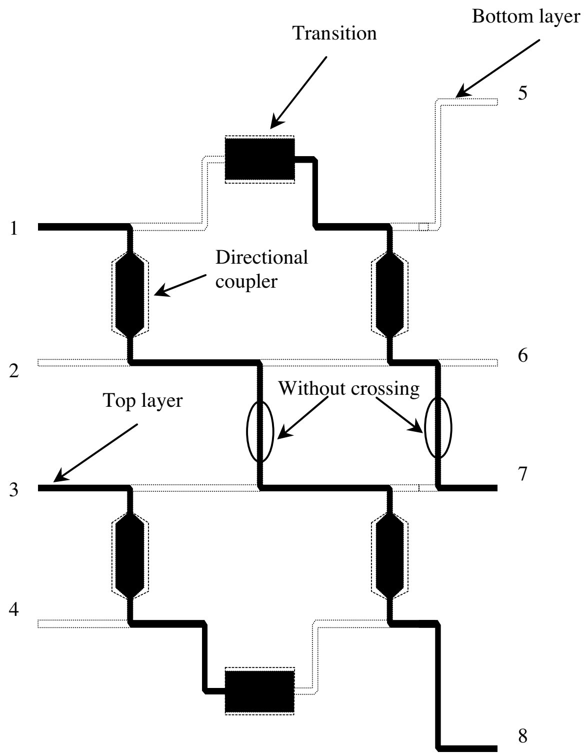


(b)

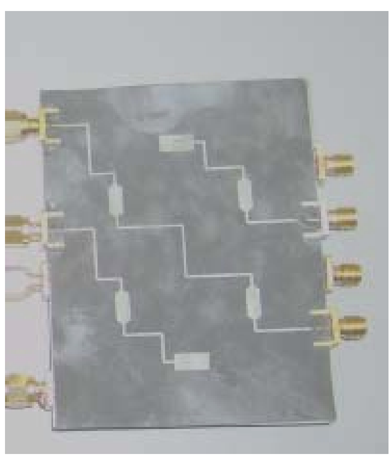
Figure 7. Scattering parameters of the transition: (a) Simulated, (b) Measured.

2.3. 4×4 Butler Matrix

The block diagram of the proposed 4×4 Butler matrix is presented in Fig. 1 and its layout is shown in Fig. 8. Combining the above



(a)



(b)

Figure 8. The proposed UWB 4 × 4 Butler matrix (a) Layout (b) Fabricated.

components presented in A) and B), the matrix circuit was designed using two-layer substrates. The top layer is coupled to the bottom layer through both the slot-coupled directional couplers and transitions. This structure allows perfect isolation between cross lines. To demonstrate our approach, an experimental prototype was fabricated on Duroid substrate (RT/Duroid 5880) with $\varepsilon_r = 2.2$ and thickness of 0.254 mm. Simulation and experimental results are presented in the following section.

To examine the performance of the fabricated prototype, experimental measurements were performed. The phase shift of $-45°$ is designed by using an appropriate transmission line section. With this matrix, signals incident at input ports (#1, #2, #3, or #4) are divided into four output ports (#5, #6, #7, and #8) with equal amplitude and specified relative-phase differences.

This Butler matrix is designed for frequency range from 3 to 9 GHz. Figs. 9 and 10 show simulation and experimental results of the insertion and the return loss for the ports 1 and 2 when the other ports are matched. These results demonstrate that the matrix has a good performance in terms of magnitude. The return loss is better than 35 dB and the coupling to the output ports are almost equalized (7.5 dB).

Figures 11 and 12 illustrate a good agreement between the simulated and experimental results of the phase shift of adjacent output ports, where

$$\text{Phase difference } 1 = \text{Phase}(\text{S }(5,1)) - \text{Phase}(\text{S }(6,1)) \tag{2}$$

$$\text{Phase difference } 2 = \text{Phase}(\text{S }(6,1)) - \text{Phase}(\text{S }(7,1)) \tag{3}$$

$$\text{Phase difference } 3 = \text{Phase}(\text{S }(7,1)) - \text{Phase}(\text{S }(8,1)) \tag{4}$$

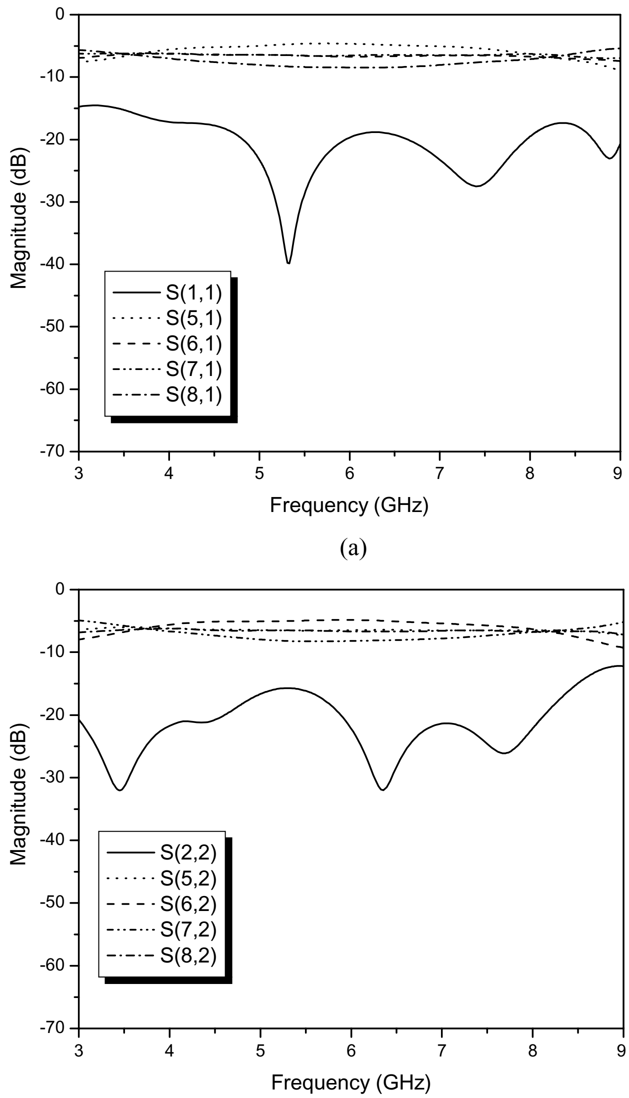
$$\text{Phase difference } 4 = \text{Phase}(\text{S }(5,2)) - \text{Phase}(\text{S }(6,2)) \tag{5}$$

$$\text{Phase difference } 5 = \text{Phase}(\text{S }(6,2)) - \text{Phase}(\text{S }(7,2)) \tag{6}$$

$$\text{Phase difference } 6 = \text{Phase}(\text{S }(7,2)) - \text{Phase}(\text{S }(8,2)) \tag{7}$$

It can be seen that the phase differences are not perfectly flat in the entire bandwidth which the theoretical values are in 45° (Fig. 11) and $-135°$ (Fig. 12) respectively. The phase errors are going from 19° (3 GHz) to 26° (9 GHz) in all the bandwidth compared to desired value of 45° and 135°. These errors are due to the use of the narrowband transmission line phase shifters and transitions phases errors.

To demonstrate the performance of this matrix in terms of beamforming in the entire bandwidth, we connect this matrix to three different antenna arrays [34, 35] designed at operating frequencies of 3, 5.8 and 9 GHz, respectively. As reported in [34], the bandwidth of



(b)

Figure 9. Simulated results of the 4×4 Butler matrix (a) Signal at port1 (b) Signal at port2.

the element antenna is about 8% for each frequency (3, 5.8 and 9 GHz) and mutual coupling is better than -20 dB. These characteristics allow testing the proposed Butler matrix in terms of beamforming. The

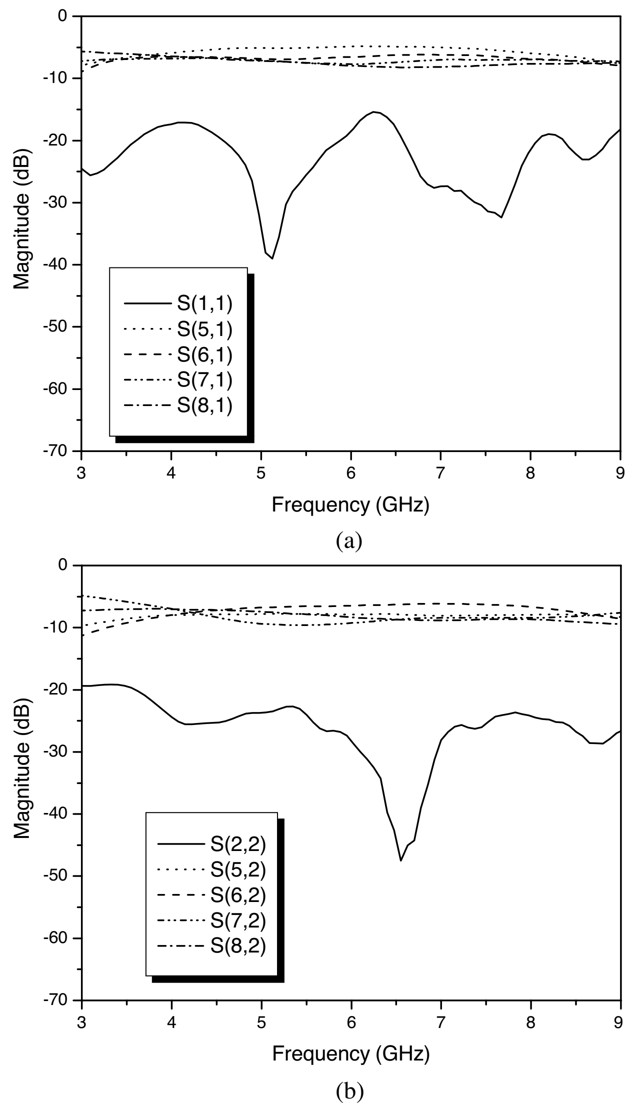


Figure 10. Measured results of the 4X4 Butler matrix (a) Signal at port1 (b) Signal at port2.

spacing between elements for each array is kept $0.5\lambda_0$, where λ_0 is the length at operating frequency of each array. This spacing is necessary to obtain the minimum level side lobes between elements at 3, 5.8 and 9 GHz.

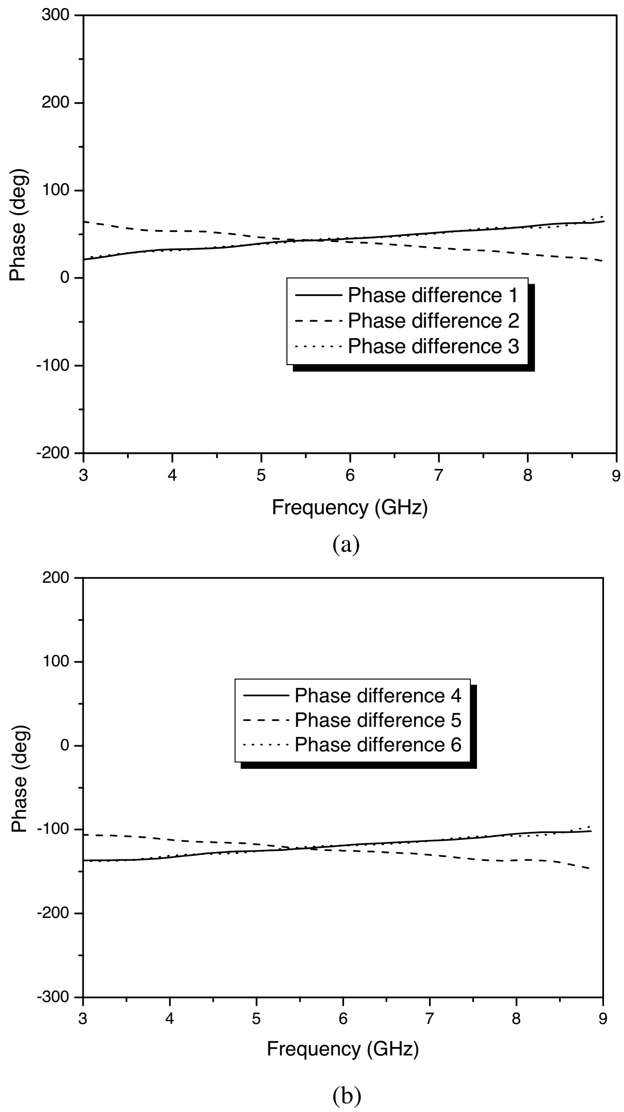
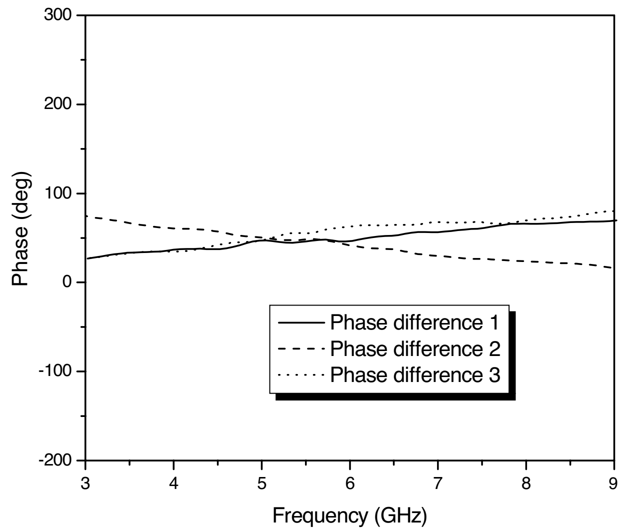
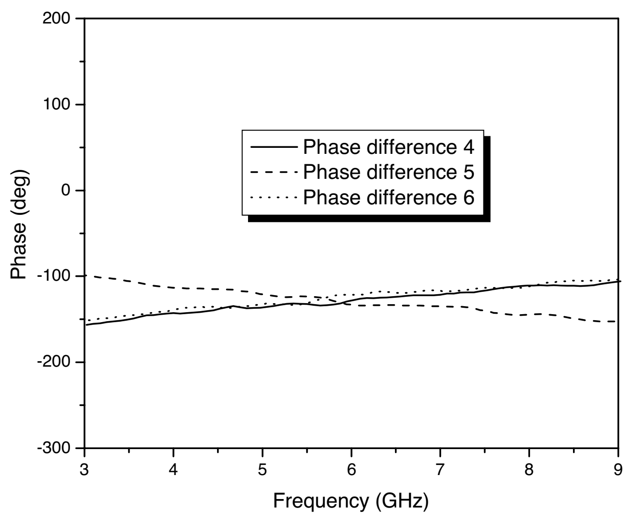


Figure 11. Simulated results of phase difference at the adjacent output port of the Butler Matrix (a) Signal at port1 (b) Signal at port2.

Figure 13 shows the simulated and measured results of radiation patterns in the H-plane of the beamforming antenna array system at 3, 5.8 and 9 GHz. With this matrix, four beams are produced



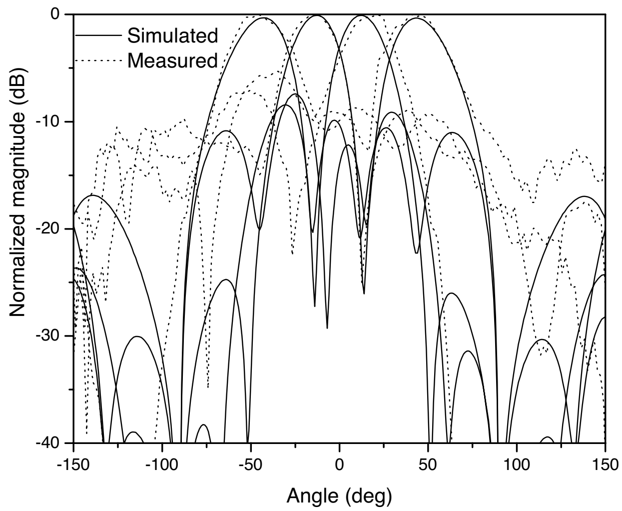
(a)



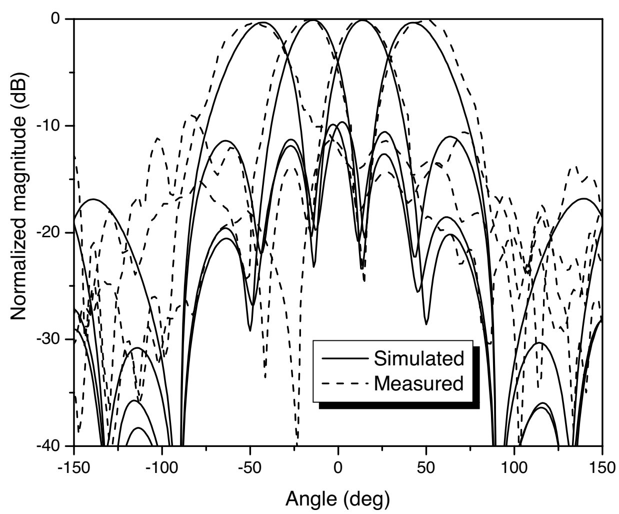
(b)

Figure 12. Measured results of phase difference at the adjacent output port of the Butler Matrix (a) Signal at port1 (b) Signal at port2.

for each array at −45°, −15°, 15° and 45°. It can be shown that the comparison between simulated and experimental results indicates a good agreement, which validate the proposed concept. As can be concluded, the phase errors and imbalanced coupling obtained have a minor effect on the side lobe levels of the produced beams. These features make the proposed matrix suitable for UWB beamforming applications in hostile environment.



(a)



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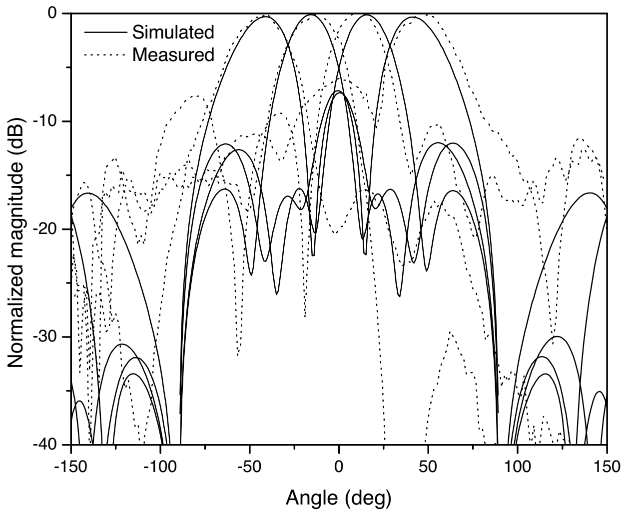

(c)

Figure 13. Simulated and measured H-plane radiation pattern (a) 3 GHz (b) 5.8 GHz (c) 9 GHz.

3. CONCLUSION

An ultra wideband 4×4 Butler matrix has been designed, fabricated and tested using a two-layer structure. The circuit is compact and has low losses. In the proposed design, a combination of a microstrip slot-coupled directional coupler and a transition were employed to widen the bandwidth and to avoid using any line crossovers as conventional ones. Simulated and experimental results show a good agreement, and they show that a bandwidth of about 6 GHz was achieved. Furthermore, the proposed matrix has been connected to an antenna array to form a beamforming system, resulting in four orthogonal beams at 3, 5.8 and 9 GHz. With these features, the proposed Butler matrix is suitable for UWB underground wireless applications.

REFERENCES

1. Nerguizian, C., C. Despins, S. Affes, and M. Djadel, "Radio-channel characterization of an underground mine at 2.4 GHz wireless communication," *IEEE Trans. on Wireless Commun.*, Vol. 4, No. 5, 2441–2453, Sept. 2005.

2. Chao, R. Y. and K. S. Chung, "A low profile antenna array for underground mine communication," *Proc. of ICCS'94*, Vol. 2, 705–709, 1994.
3. Dessouky, M. I., H. A. Sharshar, and Y. A. Albagory, "Improving the cellular coverage from a high altitude platform by novel tapered beamforming technique," *Journal of Electromagnetic Waves and Applications*, Vol. 21, No. 13, 1721–1731, 2007.
4. Jeong, Y.-S. and J.-H. Lee, "Estimation of time delay using conventional beamforming-based algorithm for UWB systems," *Journal of Electromagnetic Waves and Applications*, Vol. 21, No. 15, 2413–2420, 2007.
5. Winter, J. H., "Smart antennas for wireless systems," *IEEE Personal Communications*, Vol. 1, 23–27, Feb. 1998.
6. 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.
7. Ho, M.-J., G. L. Stuber, and M. Austin, "Performance of switched-beam smart antennas, for cellular radio systems," *IEEE Trans. Veh. Technol.*, Vol. 47, No. 1, 10–19, Feb. 1998.
8. Mitilineos, S. A., S. C. Thomopoulos, and C. Capsalis, "Genetic design of dual-band, switched-beam dipole arrays, with elements failure correction, retaining constant excitation coefficients," *Journal of Electromagnetic Waves and Applications*, Vol. 20, No. 14, 1925–1942, 2006.
9. Khani, H. and P. Azmi, "Performance analysis of a high data rate UWB-DTR system in dense multipath channels," *Progress In Electromagnetics Research B*, Vol. 5, 119–131, 2008.
10. El-Fishawy, N. A., M. Shokair, and W. Saad, "Proposed MAC protocol versus IEEE 802.15.3a for multimedia transmission over UWB networks," *Progress In Electromagnetics Research B*, Vol. 2, 189–206, 2008.
11. Xiao, S.-Q., J. Chen, X.-F. Liu, and B.-Z. Wang, "Spatial focusing characteristics of time reversal UWB pulse transmission with different antenna arrays," *Progress In Electromagnetics Research B*, Vol. 2, 223–232, 2008.
12. Naghshvarian-Jahromi, M. and M. Tayarani, "Miniature planar UWB bandpass filters with circular slots in ground," *Progress In Electromagnetics Research Letters*, Vol. 3, 87–93, 2008.
13. Yin, X.-C., C.-L. Ruan, C.-Y. Ding, and J.-H. Chu, "A planar

U type monopole antenna for UWB applications," *Progress In Electromagnetics Research Letters*, Vol. 2, 1–10, 2008.
14. Naghshvarian-Jahromi, M., "Compact UWB bandnotch antenna with transmission-line-FED," *Progress In Electromagnetics Research B*, Vol. 3, 283–293, 2008.
15. Koo, B.-W., M.-S. Baek, and H.-K. Song, "Multiple antenna transmission technique for UWB system," *Progress In Electromagnetics Research Letters*, Vol. 2, 177–185, 2008.
16. Porcino, D. and W. Hirt, "Ultra-wideband radio technology: Potential and challenges ahead," *IEEE Comm. Mag.*, Vol. 4, No. 7, 66–74, July 2003.
17. Dogandzic, A., J. Riba, G. Seco, and A. L. Swindlehurst, "Positioning and navigation with applications to communications," *IEEE Signal Proc. Magazine*, Vol. 22, 10–11, July 2005.
18. Corona, A. and M. J. Lancaster, "A high-temperature superconducting Butler matrix," *IEEE Trans. on Applied Superconductivity*, Vol. 13, No. 4, Dec. 2003.
19. He, J., B.-Z. Wang, Q.-Q. He, Y.-X. Xing, and Z.-L. Yin, "Wideband X-band microstrip Butler matrix," *Progress In Electromagnetics Research*, PIER 74, 131–140, 2007.
20. Tudosie, G., H. Barth, and R. Vahldieck, "A compact LTCC Butler matrix realization for phased array applications," *IEEE MTT-S Int. Microwave Symposium Digest*, 441–444, June 2006.
21. Bona, M., L. Manholm, J. P. Satarski, and B. Svensson, "Low-loss compact Butler matrix for a microstrip antenna," *IEEE Trans. on Microwave Theory and Tech.*, Vol. 50, No. 9, Sept. 2002.
22. Wincza, K. and S. Gruszczynski, "A broadband 4/spl times/4 Butler matrix for modern-day antennas," *European Microwave Conference*, Vol. 2, 4, Oct. 2005.
23. Macnamara, T. M., "Position and magnitudes of fixed phase shifters in Butler matrices incorporation 90° hybrids," *IEE Proceedings*, Vol. 135, No. 5, Oct. 1988.
24. IE3D 8.2, Zeland Software, Inc. Fremont, CA.
25. Tanaka, T., K. Tsunoda, and M. Aikawa, "Slot-coupled directional couplers between double-sided substrate microstrip lines and their applications," *IEEE Trans. Microwave Theory Tech.*, Vol. 36, 1752–1757, Dec. 1988.
26. Lim, C. and S. Uysal, "Design of a broadband directional coupler using microstrip-like multilayer technology," *Microwave and Optical Technol. Lett.*, Vol. 23, 273–275, Dec. 1999.
27. Warns, C., W. Menzel, and H. Schumacher, "Transmission lines

and passive elements for multilayer coplanar circuits on silicon," *IEEE Trans. Microw. Theory Tech.*, Vol. 46, No. 5, 616–622, May 1998.

28. Theodorou, A. and N. Uzunoglu, "Transition properties of a vertical conductor connecting two microstrip lines at different planes," *IEEE Trans. Microw. Theory Tech.*, Vol. 43, No. 5, 1162–1172, May 1995.
29. Chen, C., M. Tsai, and G. Alexopoulos, "Optimization of aperture transitions for multiport microstrip circuits," *IEEE Trans. Microw. Theory Tech.*, Vol. 44, No. 12, 2457–2465, Dec. 1996.
30. Tran, A. M. and T. Itoh, "Analysis of microstrip lines coupled through an arbitrarily shaped aperture in a thick common ground plane," *IEEE MTT-S Symposium Digest*, Vol. 3, 819–822, Atlanta, 1993.
31. Ivanov, T. and A. Mortazawi, "Two stage double layer microstrip spatial amplifiers," *IEEE MTT-S Symposium Digest*, Vol. 2, 589–592, Atlanta, May 1995.
32. Burke, J. J. and R. W. Jackson, "Surface-to-surface transition via electromagnetic coupling of microstrip and coplanar waveguide," *IEEE Trans. Microwave Theory Tech.*, Vol. 37, 519–525, Mar. 1989
33. Zhu, L. and K. Wu, "Ultrabroad-band vertical transition for multilayer integrated circuits," *IEEE Microw. Guided Wave Lett.*, Vol. 9, No. 11, 453–455, Nov. 1999.
34. Nedil, M., A. T. Denidni, and L. Talbi, "Novel Butler matrix using CPW multilayer technology," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 54, Issue 1, 499–507, Jan. 2006.
35. Nedil, M., A. T. Denidni, and L. Talbi, "Design of a broadband slot antenna fed by CPW for wireless application at 5.8 GHz," *IEEE Vehicular Technology Conf., VTC2004-Spring*, Vol. 1, 18–21, 2004.
36. Watanabe, K., J. Ishihara, and K. Yasumoto, "Coupled-mode analysis of a gating-assisted directional coupler using singular perturbation technique," *Journal of Electromagnetic Waves and Applications*, Vol. 13, No. 12, 1681–1682, 1999.
37. Denidni, T. A. and T. E. Libar, "Wide band four-port Butler matrix for switched multibeam antenna arrays," *IEEE Proceedings on Personal, Indoor and Mobile Radio Communications*, 2461–2463, Sept. 2003.
38. Sharma, R., T. Chakravarty, S. Bhooshan, and A. B. Bhat-

tacharyya, "Design of a novel 3 dB microstrip backward wave coupler using defected ground structure," *Progress In Electromagnetics Research*, PIER 65, 261–273, 2006.

39. Wu, J.-J., "A multimode interference coupler with exponentially tapered waveguide," *Progress In Electromagnetics Research C*, Vol. 1, 113–122, 2008.
40. Dall'Omo, C., T. Monediere, B. Jeko, F. Lamour, I. Wolk, and M. Elkael, "Design and realization of a 4×4 microstrip butler matrix without any crossing in millimeter-wave," *Microwave and Optical Tech. Lett.*, Vol. 38, No. 6. Sept. 2003.
41. Stutzman, W. L. and G. A. Thiele, *Antenna Theory and Design*, second edition, John Wiley & Sons, Inc., 1998.
42. Wong, M. F., V. F. Hanna, O. Picon, and H. Baudrand, "A novel coplanar-waveguide directional coupler with finite-extent backed conductor," *IEEE Trans. on Microwave. Theory and Tech.*, Vol. 12, 2123–2129, Dec. 1991.