Design of a 9 GHz Four-Beam Antenna Array Fed by a Butler Matrix

Mohammed BENBAGHDAD (1), Mohammed ZAIDI (1), Sami HEBIB (2), and Smail TEDJINI (3)
(1) High Signal School (HSS), Tipaza, Algeria
(2) DIC Laboratory, Faculty of Technology, University of Blida 1, Algeria
(3) University of Grenoble Alpes, LCIS Valence, France

Abstract

A 9 GHz four beam antenna array fed by a Butler matrix is designed, fabricated and measured. Two 4x4 Butler matrices are addressed and compared in this work : (1) with and (2) without crossovers. It has been shown that this latter presents the best performances in terms of losses and complexity. The fabricated prototype (without crossovers) connected to four patch antennas exhibits good performance and allows the forming of four orthogonal uniform beams (at - 46°, +16°, -18° and +45°) with an effective coverage of 91°.

1 Introduction

Nowadays Beamforming systems are a subject of current research because of their various applications[1]. Usually, these systems use multiple antennas to control the direction of a main beam by appropriately weighting the magnitude and phase of individual antenna signals in an antenna array [2]. Therefore, it allows minimizing channel interference and supervising multiple beams with high gain and narrow half-power aperture [3]. Beamforming systems are composed of three elements [4] : antenna array, beamforming network (BFN) and a control circuit. The BFN, which is the main element of the system, has been widely studied by researchers. The Butler matrix is the most widely known of these BFN. It draws much attention due to its simple design and orthogonal beam features [5]. Butler matrix has two topologies [6] : with crossovers (Fig. 1(a)) and without crossovers (Fig. 1(b)). By feeding any of the input ports, the user can select the direction of the radiation main beam as desired. The pointing directions for 4×4 Butler Beamforming system can be calculated as follows[7] :

$$\theta = cos^{-1}\left[\frac{\mp(2n-1)\lambda}{8d}\right] \quad (1)$$

Where n $(=1,2,\ldots)$ is port number, λ is free space wavelength, and d the physical distance between the centers of antenna elements.

In this paper, we design and fabricate a 9GHz beamforming system based on 4x4 Butler Matrix without crossovers. The radiation pattern measurement results validate the good behavior of the designed system.

2 Butler matrix BFN description and design

2.1 Butler matrix BFN Components design

The overall performances of the BFN depend mainly on the performances of its components. In this section, we design, at 9 GHz, the two key components of the Butler matrix BFN namely the quadrature hybrid coupler and the crossover. The 45° phase shifter is simply implemented using delay lines. The electromagnetic simulation is carried out using CST Microwave Studio. All the components of the BFN are designed in microstrip technology using FR4 substrate (thickness (h) = 0.8 mm, dielectric constant = 4.4 and tanδ= 0.013).

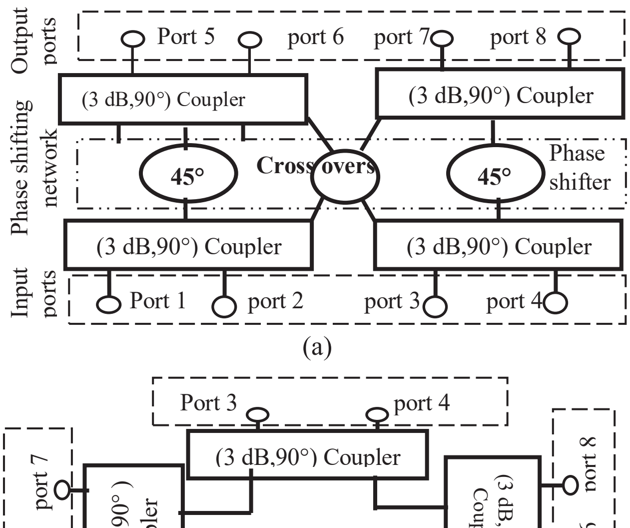


Figure 1. A 4x4 Butler matrix: (a) with crossovers and (b) without crossovers

A Quadrature hybrid coupler

Geometry of the designed quadrature hybrid coupler is shown in Figure 2. The simulated S parameter magnitudes (S_{11}, S_{21}, S_{31}, and S_{41}) are given in Figure 3. At 9 GHz, the designed coupler exhibits good performance in terms of impedance matching ($|S_{11}|$ =-22.47 dB) and isolation ($|S_{41}|$ = -22.52 dB). The insertion losses are quite negligible with $|S_{21}|$ = -3.001 dB and $|S_{31}|$ = - 3.176 dB instead of -3dB for an ideal hybrid coupler. The phase difference between ports 2 and 3 ($\angle S_{21}$- $\angle S_{31}$) is 89.33°.

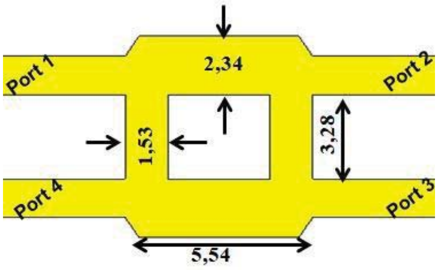


Figure 2. Geometry and dimensions (in mm) of the designed quadrature hybrid coupler

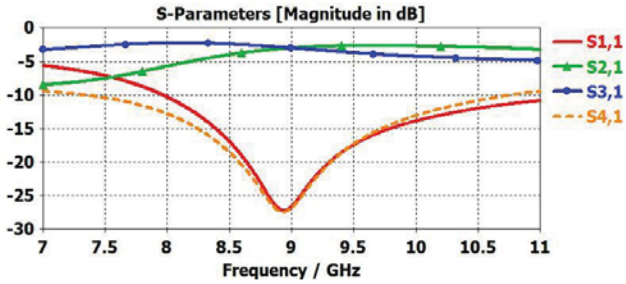


Figure 3. Simulated S parameters of the designed quadrature hybrid coupler

B Crossover

Figure 4 shows the geometry and dimensions (in mm) of the designed 9 GHz crossover. It is a symmetric circuit with two input ports (ports 1 and 4) and two output ports (ports 2 and 3). It allows two lines to cross each other. Ideally, if the port 1 is fed by an RF signal, the output port 2 and the input port 4 have no signal and only the port 3 has an RF signal identical to that of the port 1.

The simulated S parameter magnitudes of the designed crossover are given in Figure 5. At 9 GHz, the crossover presents good performance in terms of impedance matching ($|S_{11}|$ = -13.84 dB) and isolation ($|S_{21}|$= -21.81dB and $|S_{41}|$= -30.8 dB). The insertion losses are quite negligible: $[S_{31}|$= -0.78 dB instead of 0 dB for an ideal crossover.

2.2 4 x 4 Butler matrix with crossovers

In this section, the previously designed hybrid coupler and crossover are assembled in order to form a 4x4 Butler matrix BFN as shown in Figure 6. The input ports are 1, 2, 3 and 4 while the output ports are 5, 6, 7 and 8. The simulated S parameters of the final optimized BFN at 9 GHz are summarized in Table 1.

In order to validate the four beam concept, the previous designed Butler matrix BFN is used to feed a linear antenna array. This latter is composed of four rectangular patch antennas operating at 9 GHz. Figure 7.(a) shows the geometry and the dimensions of the designed patch antenna. At 9 GHz, this antenna presents a reflection coefficient ($|S_{11}|$) of -27.27dB and a maximum gain of 6.8 dBi. The Butler Matrix BFN (with crossovers) with the four patch antenna is depicted in Figure 7 (b).

The radiation patterns of this system are shown in Figure 9. According to the input port, the system provides, at 9 GHz, four different beams with progressive phase shifts of +13°, -48°, +48° and -13°. A good agreement between theoretical values (equation (1)) and simulated one is obtained (A phase difference less than 1.5° for the four cases).

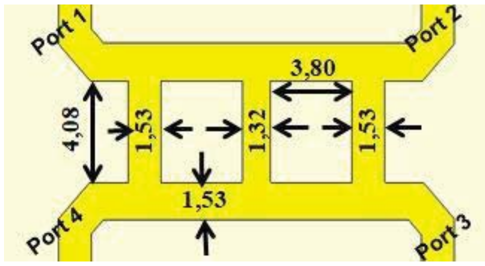


Figure 4. Geometry and dimensions (in mm) of the designed crossover

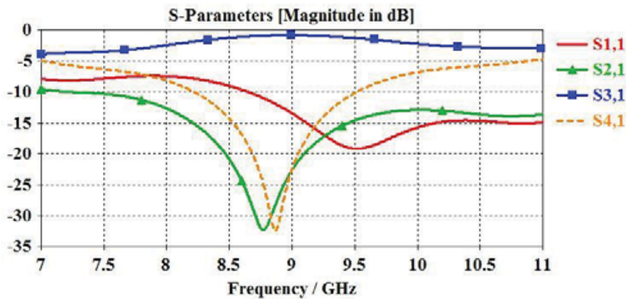


Figure 5. Simulated S parameters of the designed crossover

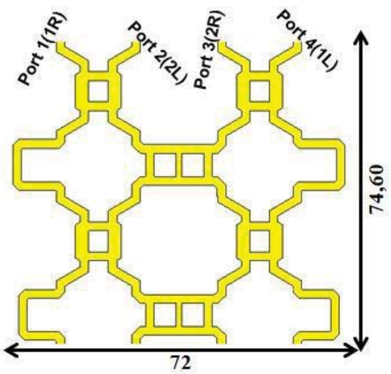
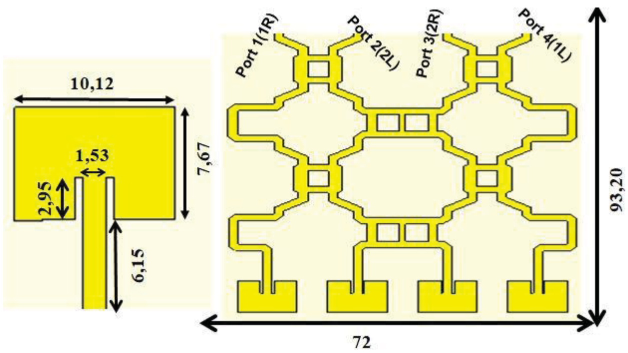


Figure 6. Geometry and dimensions (in mm) of the designed 4 x4 Butler matrix with crossovers

Table 1. S parameters (magnitudes in dB) of the designed 4 x4 Butler matrix with crossovers at 9GHz

Input Matching		Isolation (port 1 : input)		Trans. Coef. (port 1 :input)	
$\|S_{11}\|$	-22.61	/	/	$\|S_{51}\|$	-10.74
$\|S_{22}\|$	-21.39	$\|S_{21}\|$	-24.91	$\|S_{61}\|$	-11.79
$\|S_{33}\|$	-21.24	$\|S_{31}\|$	-24.30	$\|S_{71}\|$	-10.8
$\|S_{44}\|$	-22.12	$\|S_{41}\|$	-36.29	$\|S_{81}\|$	-10.55

Table 2 summarizes the performances (phase shift, secondary lobes level (SLL) and maximum gain) of the four-beam antenna array fed by the designed Butler matrix BFN for different input ports. It should be noted that the main beam phase shifts are symmetrical with respect to the boresight direction.



(a) (b)

Figure 7. Geometry and dimensions (in mm) of the designed (a) 9 GHz patch antenna and (b) Butler Matrix BFN (with crossovers) fedding four patch array

Table 2. Simulated performances of the beamforming system (with crossovers)

Input port	Phase shift (°)	SLL(dB)	Gain (dBi)
1 (1R)	+13	- 4.8	6.5
2 (2L)	-48	- 4.0	8.02
3 (2R)	+48	- 4.0	8.02
4 (1L)	-13	- 4.8	6.5

Table 3. S parameter amplitudes of Butler matrix without crossovers at 9 GHz

Input Matching		Isolation (port 1 : input)		Trans. coef. (port 1 : input)	
$\lvert S_{11}\rvert$	-14.24	$\lvert S_{21}\rvert$	-15.82	$\lvert S_{51}\rvert$	-7.02
$\lvert S_{22}\rvert$	-16.29			$\lvert S_{61}\rvert$	- 6.95
$\lvert S_{33}\rvert$	-16.71	$\lvert S_{41}\rvert$	-15.97	$\lvert S_{71}\rvert$	-7.76
$\lvert S_{44}\rvert$	-14.17			$\lvert S_{81}\rvert$	-6.83

2.3 4x4 Butler matrix without crossovers

In this section, a 4 x4 Butler matrix without crossovers is designed. Its architecture is shown in Figure 8. As previous, we summarize the values of the simulated S parameters (Amplitudes) of the designed Butler matrix without crossovers in Table 3. The radiation patterns of the system (without crossovers) are shown in Figure 10. According to the input ports, the system provides four steering directions of - 42°, +10°, -10° and +42° at the center frequency of 9 GHz. A shift (lower than 6°) from the theoretical values is obtained.

We summarize the performances of beamforming system (without crossovers) in Table 4.

According to these simulation results, the beamforming system without crossovers presents better performance than the one with crossovers in terms of transmission coefficients (amplitudes and phases). Moreover, the design of the system without crossovers is less complex than the one having crossovers. For all these reasons, the beamforming system without crossovers is chosen to be fabricated and experimentally validated in the next section.

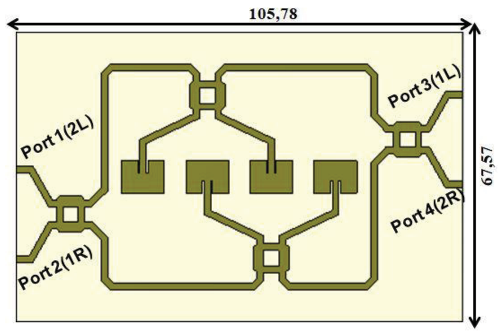


Figure 8. Butler Matrix (without crossovers)

Table 4. Simulated performance of the beamforming system (without crossovers).

Input port	Phase shift (°)	SLL (dB)	Gain (dBi)
1 (2L)	- 42	-4.6	8.84
2 (1R)	+10	-7.8	9.28
3 (1L)	-10	-7.6	9.28
4 (2R)	+42	-4.6	8.81

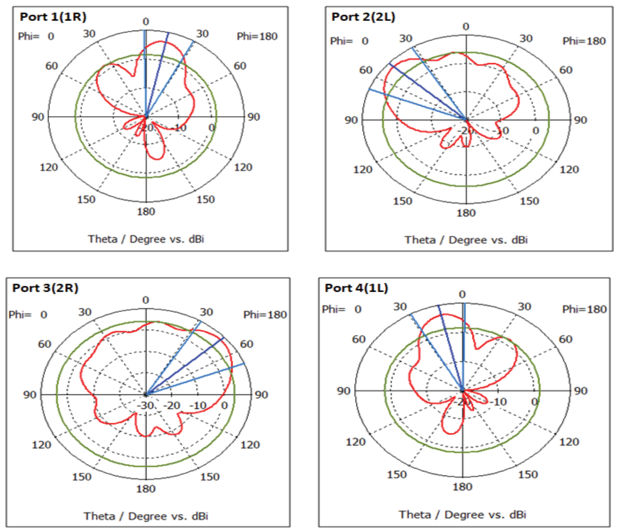


Figure 9. Radiation patterns of beamforming system (with crossovers).

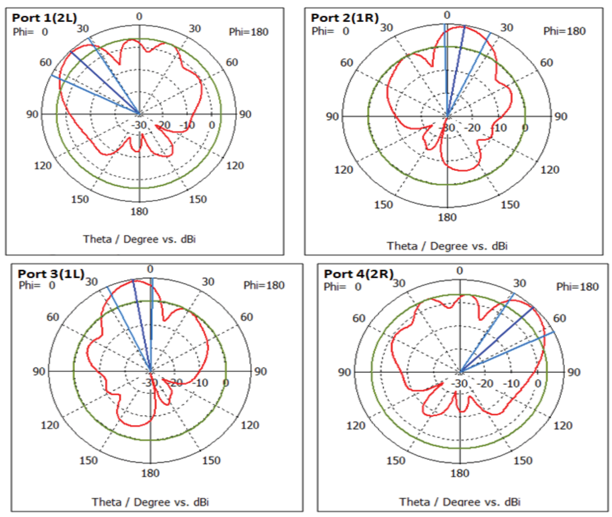


Figure 10. Radiation patterns of the beamforming system (without crossovers).

3 Experimental results and discussion

In this section, we present the experimental results of the Beamforming system without crossovers. A photograph of the fabricated prototype, printed on FR4 substrate, is illustrated in Figure 12.

The S parameter measurements have been performed using Agilent N5230C PNA-L. Figure 13 gives the reflection coefficients of the realized system as a function of frequency. For symmetry reasons only S_{11} and S_{22} parameters have been plotted on this figure. We note good matching performance of the system in a frequency band ranging from 7 to 11 GHz.

The radiation pattern measurements have been done using LucasNülle SO4204-9W measurement kit. The measurements setup is illustrated in Figure 11.The radiation patterns of the fabricated prototype are shown in Figure 14 for different inputs ports. As we can note, the system provides four beam steering angles of - 46°, +16°, -18° and +45°. A shift lower than 4° compared to theoretical values is obtained. It is noted that the obtained diagrams are quite coarse because of the reflective environment.

4 Conclusion

In this paper, we designed and fabricated a four-beam antenna array fed by a Butler matrix operating at 9 GHz. Two Butler BFN topologies (with and without crossovers) have been considered and simulated. For its good performance in terms of transmission coefficients and low design complexity, the topology without crossovers was chosen for fabrication. A realized prototype which integrates four patch antennas was experimentally validated. It produces four orthogonal uniform beams (at -46°, +16°, -18° and +45°) with effective coverage of 91°.

Figure 11. Radiation pattern measurement setup

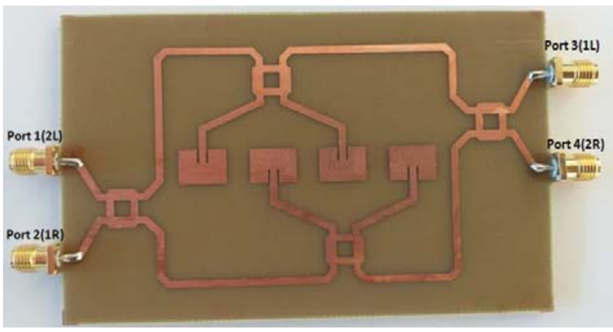


Figure 12. Realized beamforming system prototype

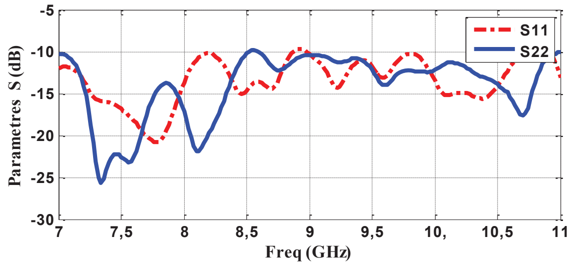
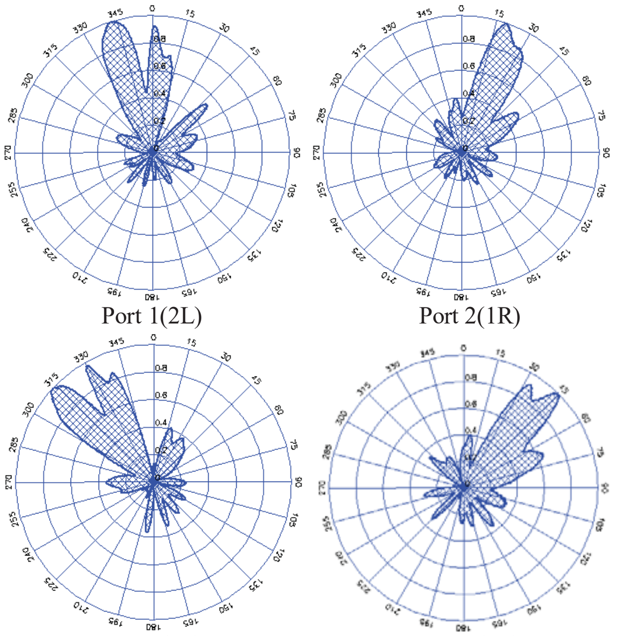


Figure 13. Measured reflection coefficients at ports1and 2



Port 1(2L) Port 2(1R)

Port 3(2L) Port 4(2R)

Figure 14. Measured radiation patterns for different input ports

5 References

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