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*Research Article*

# Design and Analysis of Wideband Nonuniform Branch Line Coupler and Its Application in a Wideband Butler Matrix

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This paper presents a novel wideband nonuniform branch line coupler. An exponential impedance taper is inserted, at the series arms of the branch line coupler, to enhance the bandwidth. The behavior of the nonuniform coupler was mathematically analyzed, and its design of scattering matrix was derived. For a return loss better than 10 dB, it achieved 61.1% bandwidth centered at 9 GHz. Measured coupling magnitudes and phase exhibit good dispersive characteristic. For the 1 dB magnitude difference and phase error within 3°, it achieved 22.2% bandwidth centered at 9 GHz. Furthermore, the novel branch line coupler was implemented for a wideband crossover. Crossover was constructed by cascading two wideband nonuniform branch line couplers. These components were employed to design a wideband Butler Matrix working at 9.4 GHz. The measurement results show that the reflection coefficient between the output ports is better than 18 dB across 8.0 GHz–9.6 GHz, and the overall phase error is less than 7°.

## 1. Introduction

Recently, a switched-beam antenna system has been widely used in numerous applications, such as in mobile communication system, satellite system, and modern multifunction radar. This is due to the ability of the switched-beam antenna to decrease the interference and to improve the quality of transmission [1, 2] and also to increase gain and diversity [3].

The switched-beam system consists of a multibeam switching network and antenna array. The principle of a switched-beam is based on feeding a signal into an array of antenna with equal power and phase difference. Different structures of multibeam switching networks have been proposed, such as the Blass Matrix, the Nolen Matrix, the Rotman Lens, and the Butler Matrix [4]. One of the most widely known multibeam switching networks with a linear antenna is the Butler Matrix. Indeed, it seems to be the most attractive option due to its design simplicity and low power loss [5–15].

In general, the Butler Matrix is an $N \times N$ passive feeding network, composed of branch line coupler, crossover, and phase shifter. The bandwidth of the Butler Matrix is greatly dependent on the performance of the components. However, the Butler Matrix has a narrow bandwidth characteristic due to branch line coupler and crossover has a limited bandwidth.

As there is an increased demand to provide high data throughput [16], it is essential that the Butler Matrix has to operate over a wide frequency band when used for angle diversity. Therefore, many papers have reported for the bandwidth enhancement of branch line coupler [17–20]. In reference [17, 18], design and realization of branch line coupler on multilayer microstrip structure was reported. These designs can achieve a wideband characteristic. However, the disadvantages of these designs are large in dimension and bulk.

Reference [19] introduces a compact coupler in an N-section tandem-connected structure. The design resulted in a wide bandwidth. Another design, two elliptically shaped

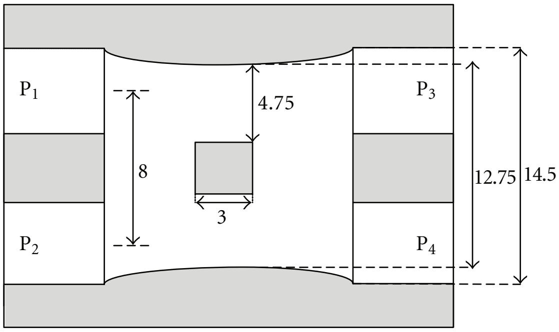


FIGURE 1: Geometry structure of a new nonuniform branch line coupler design with exponential impedance taper at the series arm.

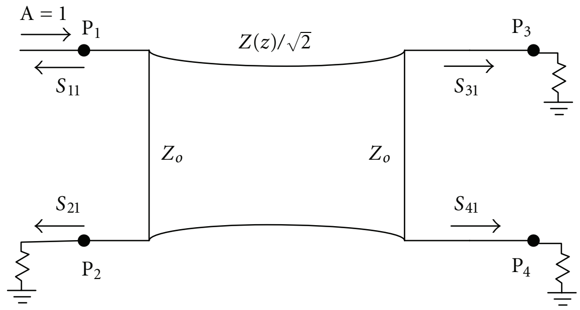


FIGURE 2: Circuit of the nonuniform branch line coupler.

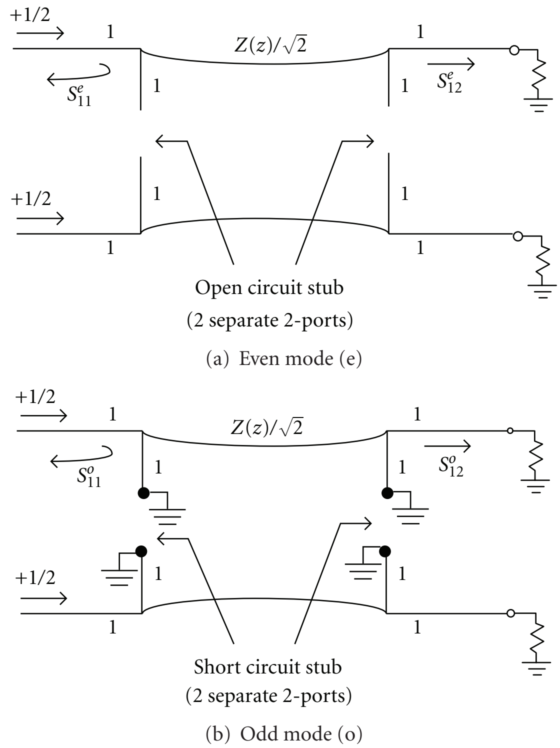


FIGURE 3: Decomposition of the nonuniform branch line coupler into even and odd modes of excitation.

microstrip lines which are broadside coupled through an elliptically shaped slot, was employed in [20]. This design was used in a UWB coupler with high return loss and isolation. However, these designs require a more complex manufacturing.

In this paper, nonuniform branch line coupler using exponential impedance taper is proposed which can enhance bandwidth and can be implemented for Butler Matrix, as shown in Figure 1. Moreover, it is a simple design without needs of using multilayer technology. This will lead in cost reduction and in design simplification.

To design the new branch line coupler, firstly, the series arm's impedance is modified. The shunt arm remains unchanged. Reduced of the width of the transmission line at this arm is desired by modifying the series arm. Next, by exponential impedance taper at the series arm, a good match over a high frequency can be achieved.

## 2. Mathematical Analysis of Nonuniform Branch Line Coupler

The proposed nonuniform branch line coupler use $\lambda/4$ branches with impedance of $50\,\Omega$ at the shunt arms and use the exponential impedance taper at the series arms, as shown in Figure 1. Since branch line coupler has a symmetric structure, the even-odd mode theory can be employed to analyze the nonuniform characteristics. The four ports can be simplified to a two-port problem in which the even and odd mode signals are fed to two collinear inputs [22]. Figure 2 shows the schematic of circuit the nonuniform branch line coupler.

The circuit of Figure 2 can be decomposed into the superposition of an even-mode excitation and an odd-mode excitation is shown in Figures 3(a) and 3(b).

The ABCD matrices of each mode can be expressed following [22]. In the case of nonuniform branch line coupler, the matrices for the even and odd modes become:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_e = \frac{Z(z)}{\sqrt{2}} \begin{pmatrix} -1 & j \\ j & -1 \end{pmatrix}, \tag{1}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_o = \frac{Z(z)}{\sqrt{2}} \begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix}. \tag{2}$$

A branch line coupler has been designed based on the theory of small reflection, by the continuously tapered line with exponential tapers [23, 24], as indicated in Figure 1, where

$$Z(z) = \begin{cases} Z_0 e^{-az}, & \text{for } 0 < z \le L, \\ Z_0 e^{az}, & \text{for } L \le z < 2L, \end{cases} \tag{3}$$

which determines the constant $a$ as:

$$a = \frac{1}{L} \ln\left(\frac{Z_L}{Z_o}\right), \tag{4}$$

$L$ = discrete steps length, $Z_o = Z\,(0)$, and $Z_L = Z\,(L)$.

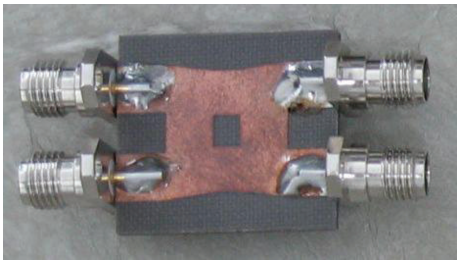

Figure 4: Photograph of a proposed nonuniform branch line coupler.

Useful conversions for two-port network parameters for the even and odd modes of $S_{11}$ and $S_{21}$ can be defined as follows [22]:

$$S_{11}^{e} = \frac{(A+B-C-D)_e}{\Delta Y^e}, \quad (5)$$

$$S_{11}^{o} = \frac{(A+B-C-D)_o}{\Delta Y^o}, \quad (6)$$

$$S_{21}^{e} = \frac{2}{\Delta Y^e}, \quad (7)$$

$$S_{21}^{o} = \frac{2}{\Delta Y^e}, \quad (8)$$

where

$$\Delta Y^e = (A+B+C+D)_e, \quad (9)$$

$$\Delta Y^o = (A+B+C+D)_o. \quad (10)$$

Since the amplitude of the incident waves for these two ports are $\pm 1/2$, the amplitudes of the emerging wave at each port of the nonuniform branch line coupler can be expressed as [22]:

$$S_{11} = \frac{1}{2}(S_{11}^{e} + S_{11}^{o}), \quad (11)$$

$$S_{21} = \frac{1}{2}(S_{11}^{e} - S_{11}^{o}), \quad (12)$$

$$S_{31} = \frac{1}{2}(S_{21}^{e} + S_{21}^{o}), \quad (13)$$

$$S_{41} = \frac{1}{2}(S_{21}^{e} - S_{21}^{o}). \quad (14)$$

Parameters even and odd modes of $S_{11}$ nonuniform branch line coupler can be expressed as (15) and (16) as follows:

$$S_{11}^{e} = \frac{Z(z)}{\sqrt{2}}\left(\frac{-1+j-j+1}{-1+j+j-1}\right) = 0, \quad (15)$$

$$S_{11}^{o} = \frac{Z(z)}{\sqrt{2}}\left(\frac{1+j-j-1}{1+j+j+1}\right) = 0. \quad (16)$$

An ideal branch line coupler is designed to have zero reflection power and splits the input power in port 1 ($P_1$) into equal powers in port 3 ($P_3$) and port 4 ($P_4$). Considering (1) to (16), a number of properties of the ideal branch line coupler maybe deduced from the symmetry and unitary properties of its scattering matrix. If the series and shunt arm are one-quarter wavelength, by using (11), resulted in $S_{11} = 0$.

As both the even and odd modes of $S_{11}$ are 0, the values of $S_{11}$ and $S_{21}$ are also 0. The magnitude of the signal at the coupled port is then the same as that of the input port.

Calculating (7) and (8) under the same $o$, the even and odd modes of $S_{21}$ nonuniform branch line coupler will be expressed as follows in(17)

$$\begin{aligned} S_{21}^{e} &= -\frac{Z(z)}{\sqrt{2}}(1+j), \\ S_{21}^{o} &= \frac{Z(z)}{\sqrt{2}}(1-j). \end{aligned} \quad (17)$$

Based on (13), $S_{31}$ can be expressed as follows

$$\begin{aligned} S_{31} &= -\frac{1}{2}\frac{Z(z)}{\sqrt{2}}((1+j)-(1-j)) \\ &= -\frac{1}{2}\frac{Z(z)}{\sqrt{2}}(1+j-1+j) \\ &= -j\frac{Z(z)}{\sqrt{2}}. \end{aligned} \quad (18)$$

Following (14), $S_{41}$ nonuniform branch line coupler can be calculating as follows

$$\begin{aligned} S_{41} &= -\frac{1}{2}\frac{Z(z)}{\sqrt{2}}((1+j)+(1-j)) \\ &= -\frac{1}{2}\frac{Z(z)}{\sqrt{2}}(1+j+1-j) \\ &= -\frac{Z(z)}{\sqrt{2}}. \end{aligned} \quad (19)$$

From this result, both $S_{31}$ and $S_{41}$ nonuniform branch line couplers have equal magnitudes of $-3$ dB. Therefore, due to symmetry property, we also have that $S_{11} = S_{22} = S_{33} = S_{44} = 0$, $S13 = S_{31}$, $S_{14} = S_{41}$, and $S_{21} = S_{34}$. Therefore, the nonuniform branch line coupler has the following scattering matrix in (20):

$$S = -\frac{Z(z)}{\sqrt{2}}\begin{bmatrix} 0 & 0 & j & 1 \\ 0 & 0 & 1 & j \\ j & 1 & 0 & 0 \\ 1 & j & 0 & 0 \end{bmatrix}. \quad (20)$$

## 3. Fabrication and Measurement Result of Wideband Nonuniform Branch Line Coupler

To verify the equation, the nonuniform branch line coupler was implemented and its $S$-parameter was measured. It was integrated on TLY substrate, which has a thickness of 1.57 mm. Figure 4 shows a photograph of a wideband nonuniform branch line coupler. Each branch at the series arm comprises an exponentially tapered microstrip line

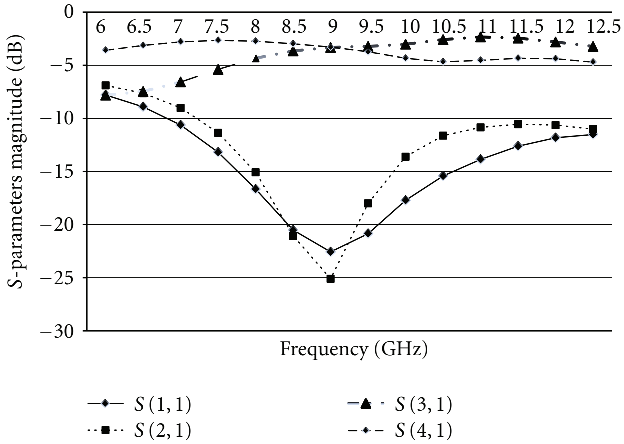


Figure 5: Measurement result for nonuniform branch line coupler.

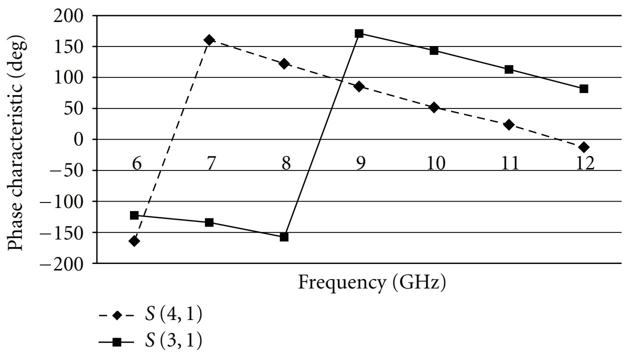


Figure 6: Phase characteristic of nonuniform branch line coupler.

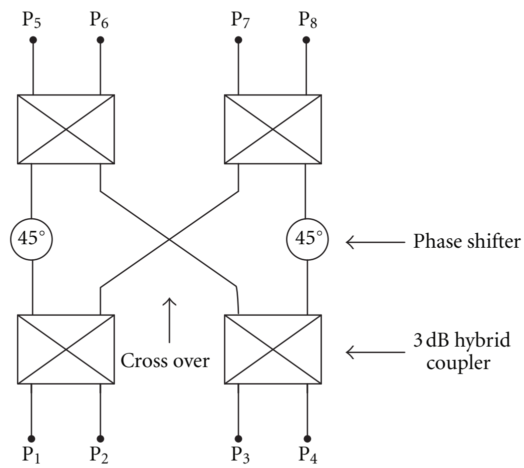


Figure 7: Basic schematic of the 4 × 4 Butler Matrix [21].

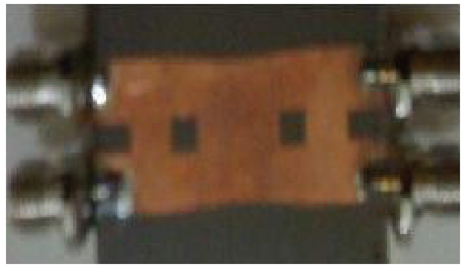

Figure 8: Photograph of microstrip nonuniform crossover.

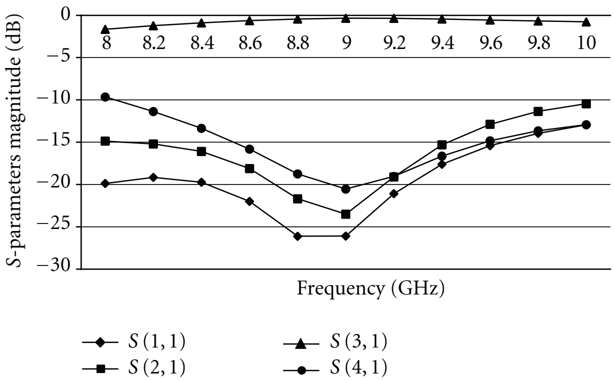


Figure 9: Measurement result for nonuniform crossover.

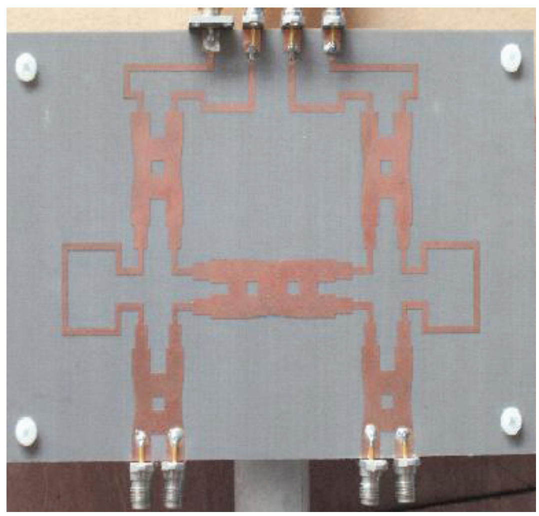

Figure 10: Final layout of the proposed wideband Butler Matrix 4 × 4.

which transforms the impedance from $Z_o = 50$ ohms to $Z_L = 50.6$ ohms. This impedance transformation has been designed across a discrete step length $L = 6.75$ mm.

Figure 5 shows the measured result frequency response of the novel nonuniform branch line coupler. For a return loss and isolation better than 10 dB, it has a bandwidth of about 61.1%; it extends from 7 to 12.5 GHz. In this bandwidth, the coupling ratio varies between 2.6 dB up to 5.1 dB. If the coupling ratio is supposed approximately 3 ± 1 dB, the bandwidth of about 22.2% centered at 9 GHz.

As expected, the phase difference between port 3 ($P_3$) and port 4 ($P_4$) is 90°. At 9 GHz, the phases of $S_{31}$ and $S_{41}$ are 85.54° and 171°, respectively. These values differ from ideal value by 4.54°. The average phase error or phase unbalance between two branch line coupler outputs is about 3°. But even the phase varies with frequency; the phase difference is almost constant and very close to ideal value of 90° as shown in Figure 6.

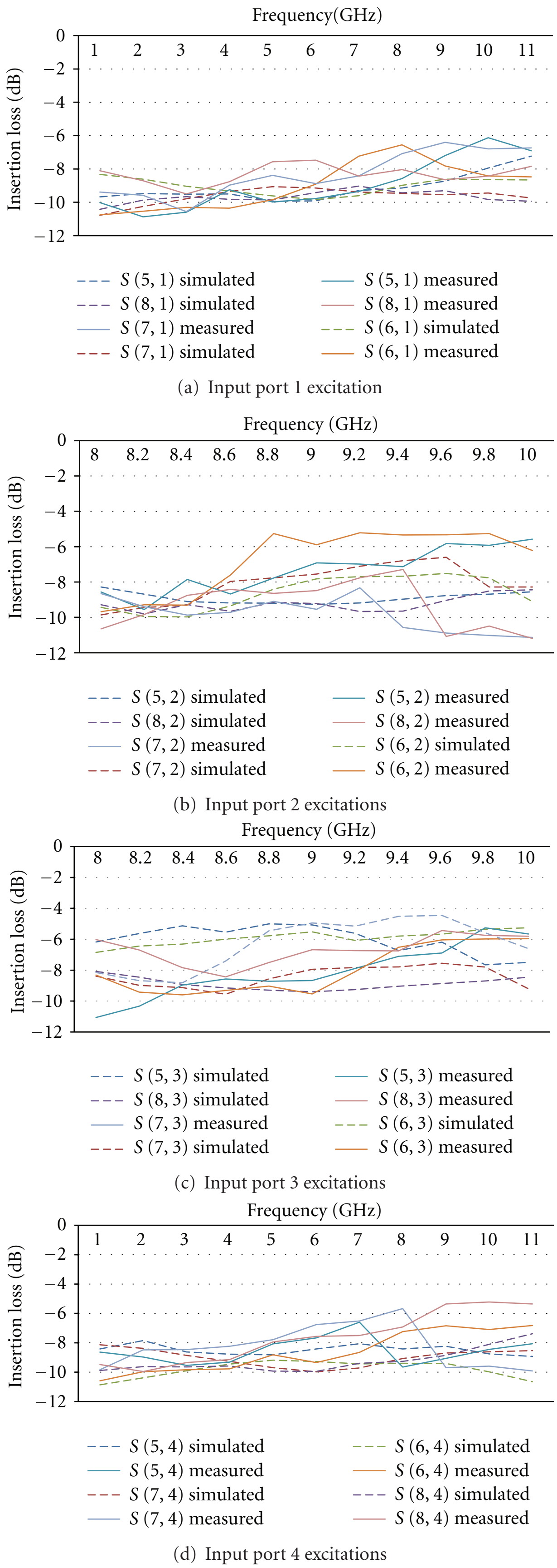


FIGURE 11: Insertion loss of the proposed Butler Matrix when different ports are fed.

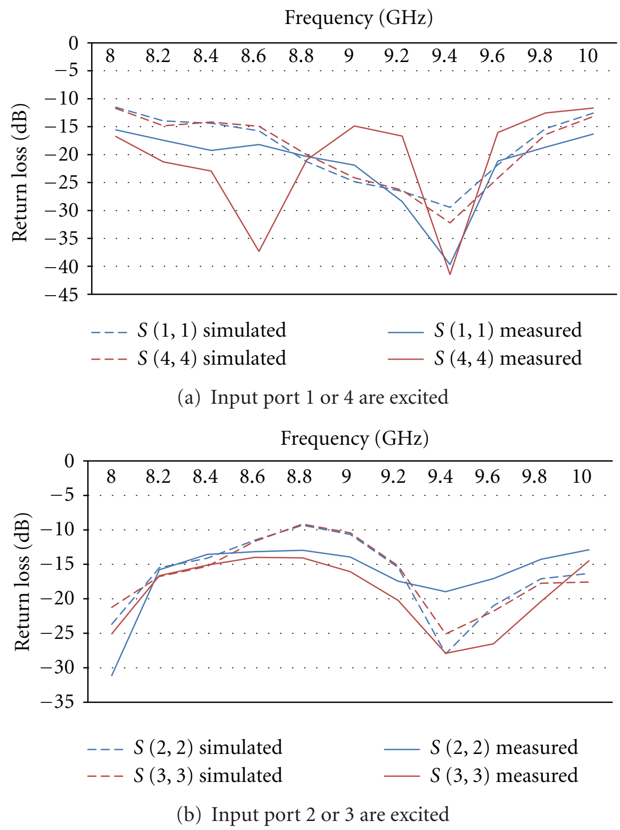


FIGURE 12: Return loss of the proposed Butler Matrix when different ports are fed.

## 4. Design and Fabrication of the Wideband Butler Matrix

Figure 7 shows the basic schematic of the $4 \times 4$ Butler Matrix [21]. Crossover also known as 0 dB couplers is a four-port device and must provide for a very good matching and isolation, while the transmitted signal should not be affected. In order to achieve wideband characteristic crossover, this paper proposes the cascade of two nonuniform branch line couplers.

Figure 8 shows the microstrip layout of the optimized crossover. The crossover has a frequency bandwidth of 1.3 GHz with VSWR = 2, which is about 22.2% of its centre frequency at 9 GHz. Thus, it is clear from these results that a nonuniform crossover fulfills most of the required specifications, as shown in Figure 9.

Figure 10 shows the layout of the proposed wideband Butler Matrix. This matrix uses wideband nonuniform branch line coupler, wideband nonuniform crossover, and phase-shift transmission lines.

The wideband Butler Matrix was measured using Network Analyzer. Figure 11 shows the simulation and measurement results of insertion loss when a signal was fed into port 1, port 2, port 3, and port 4, respectively. The insertion loss are varies between 5 dB up to 10 dB. For the ideal Butler matrix, it should be better than 6 dB. Imperfection

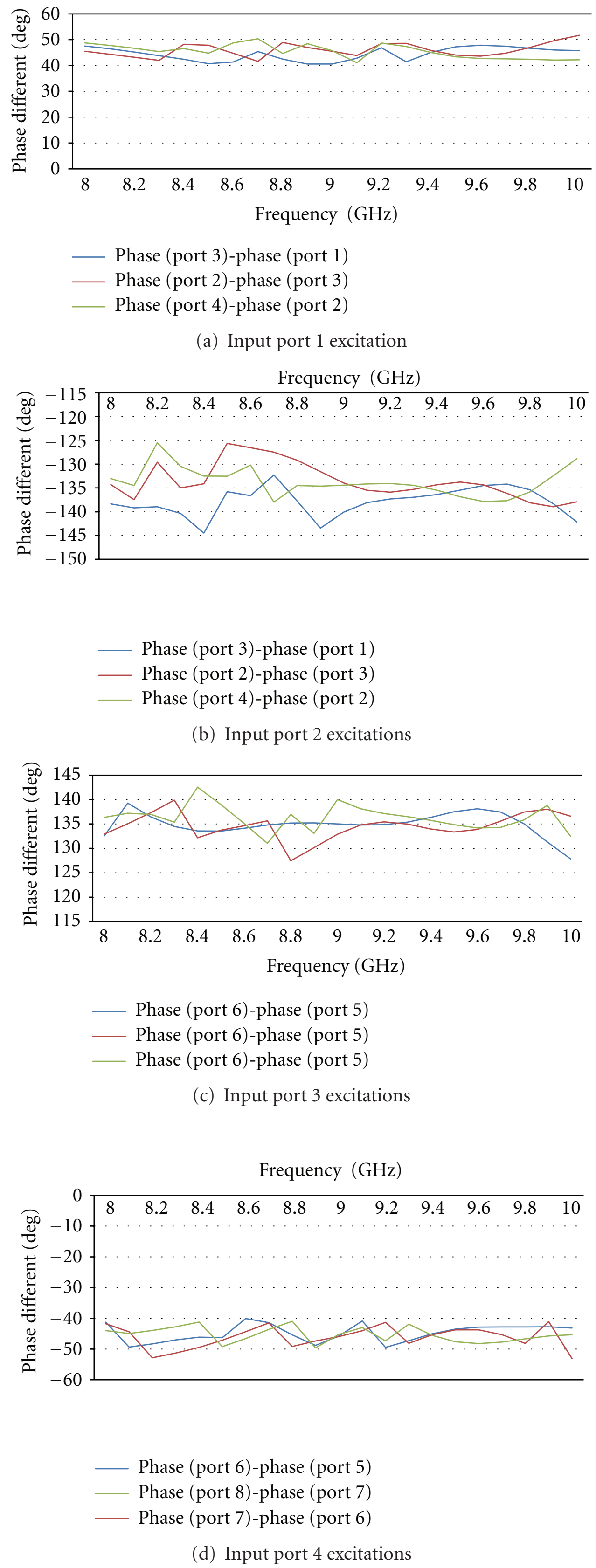


Figure 13: Phase difference of the proposed Butler Matrix when different ports are fed.

Table 1: Output phase difference and estimated direction of generated beam.

| | P5 (°) | P7 (°) | P6 (°) | P8 (°) | $\beta$ (°) | $\theta$ (°) |
|---|---|---|---|---|---|---|
| P1 | 45 | 90 | 135 | 180 | 45 | 14.4 [1L] |
| P2 | 135 | 0 | 225 | 90 | −135 | −48.6 [2R] |
| P3 | 90 | 225 | 0 | 135 | 135 | 48.6 [2L] |
| P4 | 180 | 135 | 90 | 45 | −45 | −14.4 [1R] |

of fabrication could contribute to reduction of the insertion loss.

The simulated and measured results of the return loss at each port of the wideband 4 × 4 Butler Matrix is shown in Figure 12. For a return loss better than 10 dB, it has a bandwidth about 17% centered at 9.4 GHz.

Figure 13 shows the phase difference of measured results when a signal was fed into port 1, port 2, port 3, and port 4, respectively. The overall phase error was less than 7°. There are several possible reasons for this phase error. A lot of bends in high frequency can produce phase error. Moreover, the imperfection of soldering, etching, alignment, and fastening also could contribute to deviation of the phase error.

Table 1 shows that each input port was resulted a specific linear phase at the output ports. The phase differences each between the output ports are of the same value. The phase difference can generate a different beam ($\theta$). If port 1 (P1) is excited, the phase difference was 45°, the direction of generated beam ($\theta$) will be 14.4° for 1L. It is summarized in Table 1.

## 5. Conclusion

A novel nonuniform branch line coupler has been employed to achieve a wideband characteristic by exponential impedance taper technique. It is a simple design without needs of using multilayer technology and this will lead to cost reduction and design simplification. The scattering matrix of the nonuniform branch line coupler was derived and it was proved that the nonuniform branch line coupler has equal magnitude of −3 dB. Moreover, the novel nonuniform branch line coupler has been employed to achieve a wideband 0 dB crossover. Furthermore, these components have been implemented in the Butler Matrix and that achieves wideband characteristics.

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