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A Novel Wide, Dual-and Triple-Band Frequency Reconfigurable Butler Matrix Based on Transmission Line Resonators

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ABSTRACT In this paper, a novel reconfigurable Butler matrix based on transmission line resonators is presented and implemented. This matrix is built from embedding a reconfigurable multilayer directional coupler with an open stub resonator and p-i-n diodes to operate over three different states, such as dual band, triple band, and wideband. The coupler reconfigurability allows creating bandstop filters in the UWB band by controlling the p-i-n diode states in the quarter wave ($\lambda/4$) of the open stub resonator length. To demonstrate the design approach, two prototypes of coupler and Butler matrix are fabricated and tested. Good agreement between the measured and simulated results is obtained. The proposed designs show good results in terms of compactness, low insertion loss, and high isolation with a minimal number of RF p-i-n diodes used for all states.

INDEX TERMS Butler matrix, UWB coupler, reconfigurable, PIN diodes.

I. INTRODUCTION

With the development of wireless components device, more and more applications are using the free space to send and receive data and the spectrum capacity saturation problem has become a concern [1]. In this area, the complexity as well as the cost increase with a number of switching between the frequencies bands of the radio terminals [2]–[10]. Recently, the development of reconfigurable wireless components has received many attentions for benefit of small size, reduced cost, and good flexibility for different system standards [3], [11], [12]. For high-performance, the system would require them to be reconfigurable in terms of frequency, coupling ratio and phase. In [13], a switchable phase-difference in wideband hybrid coupler is introduced. In this structure, 12 PIN diodes have been used to improve the equal power division ranging. A reconfigurable coupler with tunable coupling coefficient range is proposed in [14]. In [15], a wideband branch-line coupler with 4 to 10 dB reconfigurable has been suggested by using RF MEMS [11]. In the same area, a planar quadrature coupler [3] with continuously tunable frequency has been also proposed. However, the most reported frequency reconfigurable couplers use several active lumped components with less flexibility in terms of generated frequency bands.

Butler Matrices are referred to as a smart antenna system that forms multiple fixed beams in a specific area. They use a network composed of couplers, phase shifters and crossovers to switch from one beam to another for tracking moving users [2], [6].

A few works on reconfigurable Butler Matrices have been reported in the literature [16]–[19]. the methods for selecting one input ports of a switched beam and choosing the phase of tunable phase shift are introduced to generate more beams are presented in [17] and [18]. However, several tunable phase shifters are required, which increases the cost and the fabrication complexity. In [19], two reconfigurable phase shifters have been integrated into the Butler matrix to provide 16 beams. Recently, the unique work on designing frequency reconfigurable Butler Matrix has been reported in [16]. This circuit is based on high cost CMOS technology which adds more fabrication complexity.

In this contribution, the frequency reconfigurable capability of the Butler Matrix based on transmission line resonators is proposed. .Three state frequency reconfigurable Butler matrix using RF PIN diodes is designed and fabricated. Two PIN diodes embedded on the open stub resonator, of the directional coupler, to control the frequency reconfigurable state. Moreover, in each state, the phase difference and coupling ratio remain unchanged. The proposed concept offers several advantages including: 1) Very wide reconfigurable operating frequency. 2) Good impedance matching and isolation at all switching states and 3) low complexity due to the number of used diodes and biasing circuits. It is worth mentioning that to date, no Butler matrix reported in literature exhibits reconfigurable switchable frequency. Two experimental prototypes of reconfigurable coupler and Butler Matrix have been tested, and the measured results showed a good agreement with the simulation ones.

II. ANALYSIS OF THE PROPOSED RECONFIGURABLE COUPLER

The layout of the proposed reconfigurable multilayer directional coupler is shown in Figure 1 [1], [5]. The aim of placing PIN diodes D1 and D2 on a head to the tail structure is chosen to avoid using lumped elements (capacitor) for isolation of the positive and negative voltage. The PIN diode D1 is embedded between the microstrip line R1 and the stub resonator R2 to allow switchability of the stub resonator R2 by controlling the ON-OFF diode state. In fact, the line R1 can be connected to the stub resonator R2, when the PIN diode D1 is ON (+5 V). As a result, the length of the open stub resonator turns into quarter wave (λ/4), which creates a bandstop filter in the coupler bandwidth. On the other hand, when the biasing is reversed (−5 V). The PIN diode is turned OFF, and hence, an isolation between stub resonator R1 and resonator R2 is obtained. In this case, the stub resonator acts as an all pass wide band. Also, the PIN D2 diode was set between the resonator R2 and resonator R3. When the state of PIN diode D2 is ON, the resonator R2 would be connected to the resonator R3, and when the state of PIN diode D1 is OFF, the resonator R2 is disconnected from the resonator R3.

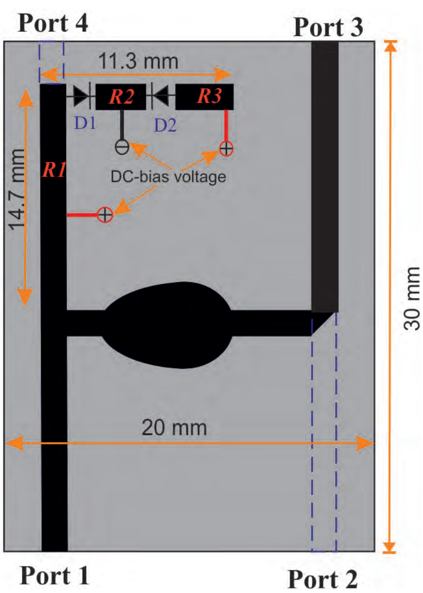

FIGURE 1. The layout of the proposed reconfigurable directional coupler.

ABCD matrix is introduced to analyze the behavior of the proposed reconfigurable coupler and can be expressed as:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos\beta l & jZ_t sin\beta l \\ jY_t sin\beta l & \cos\beta l \end{bmatrix} \tag{1}$$

where Zt and Yt are the characteristic impedance and admittance of the transmission line, respectively, and l is the length of the transmission line. In the case of a quarter-wavelength transmission line, this matrix becomes [16]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 0 & jZ_t \\ jY_t & 0 \end{bmatrix} \tag{2}$$

For the cascaded resonators, the total ABCD matrix can be formulated as:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = M_{R1}M_{D1}M_{R2}M_{D2}M_{R3} \tag{3}$$

$$M_{R1} = \begin{bmatrix} \cos\theta_1 & jZ_1\cos\theta_1 \\ \frac{j\sin\theta_1}{Z_1} & \cos\theta_1 \end{bmatrix} \tag{4}$$

$$M_{R2} = \begin{bmatrix} 1 & 0 \\ \frac{j\tan\theta_2}{Z_2} & 1 \end{bmatrix} \tag{5}$$

$$M_{R3} = \begin{bmatrix} 1 & 0 \\ \frac{j\tan\theta_3}{Z_3} & 1 \end{bmatrix} \tag{6}$$

$$M_{D1} = M_{D2} = \begin{bmatrix} 1 & Z_D \\ 0 & 1 \end{bmatrix} \tag{7}$$

where M_{R1} and M_{R1} are the ABCD matrix of the resonator R1 and R2, respectively. ZD is defined as the reference impedance of the PIN diode, where $Z_D = R_r + jX_r$ for the OFF state and $Z = R_r + j\left[\omega L_i - \frac{1}{\omega C_j}\right]$ for the ON state.

The aim of using PIN diodes is to allow controlling the coupler in three different operations, depending on the (ON-OFF) PIN diode states (Figure 2. a). When PIN diodes D1 and D2 are OFF, the ABCD matrix of the equivalent circuit, shown in Figure 2a, is given by:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = M_{R1}M_{D1} \tag{8}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos\theta_1 & jZ_1\cos\theta_1 \\ \frac{j\sin\theta_1}{Z_1} & \cos\theta_1 \end{bmatrix} \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \tag{9}$$

where $Z = R_r + jX_r$ (OFF state),

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos\theta_1 & (jZ_1\cos\theta_1 + (Rr + jXr)\cos\theta_1) \\ \frac{j\sin\theta_1}{Z_1} & (\cos\theta_1 + (Rr + jXr)\frac{j\sin\theta_1}{Z_1}) \end{bmatrix} \tag{10}$$

$$S_{12} = \frac{2}{A + {}^{B}\!/_{Z_0} + CZ_0 + D} \tag{11}$$

$$S_{12} = \frac{2}{\cos\theta_1 + \frac{(jZ_1\cos\theta_1 + Z\cos\theta_1)}{Z_0} + \frac{j\sin\theta_1}{Z_1}Z_0 + \left(\cos\theta_1 + Z\frac{j\sin\theta_1}{Z_1}\right)} = -j \tag{12}$$

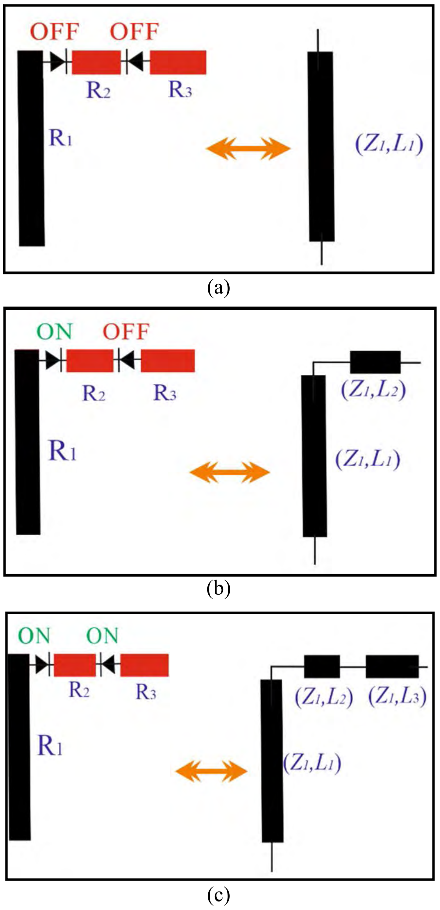

FIGURE 2. (a) The equivalent circuit of open stub when PIN diodes are OFF- OFF. (b) The equivalent circuit of open stub transmission line when PIN diodes are ON-OFF. (c) The equivalent circuit of open stub transmission line when PIN diodes are ON-ON.

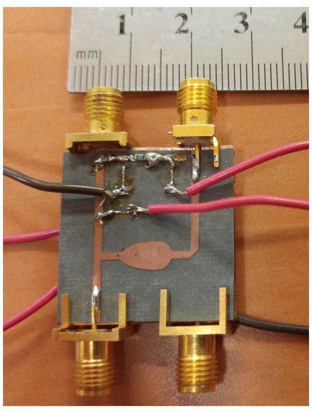

FIGURE 3. Photograph of the fabricated reconfigurable coupler.

The condition of finite isolation S21 = 0 can be achieved if Z1=Z0=Z=1 and $\theta = \pi/2$ (length of the quarter wave). As a result, an ideal finite transmission (wideband) could be produced when the electrical length of the transmission line open stub is a quarter wave (λ/4).

For the case of D1 is ON and D2 is OFF (Figure 2 b), the equivalent circuit of the resonator open stub is analyzed

TABLE 1. PIN Diode configurations for different states of a reconfigurable coupler.

Configuration	Wideband	Dual-band	Triple-band
D1	OFF	ON	ON
D2	OFF	OFF	ON

as:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = M_{D1} M_{R2} M_{D2} \tag{13}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{j \tan \theta_2}{Z_2} & 1 \end{bmatrix} \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \tag{14}$$

$$S_{12} = \frac{2}{A + {}^{B}\!/_{Z_0} + CZ_0 + D} \approx 0 \tag{15}$$

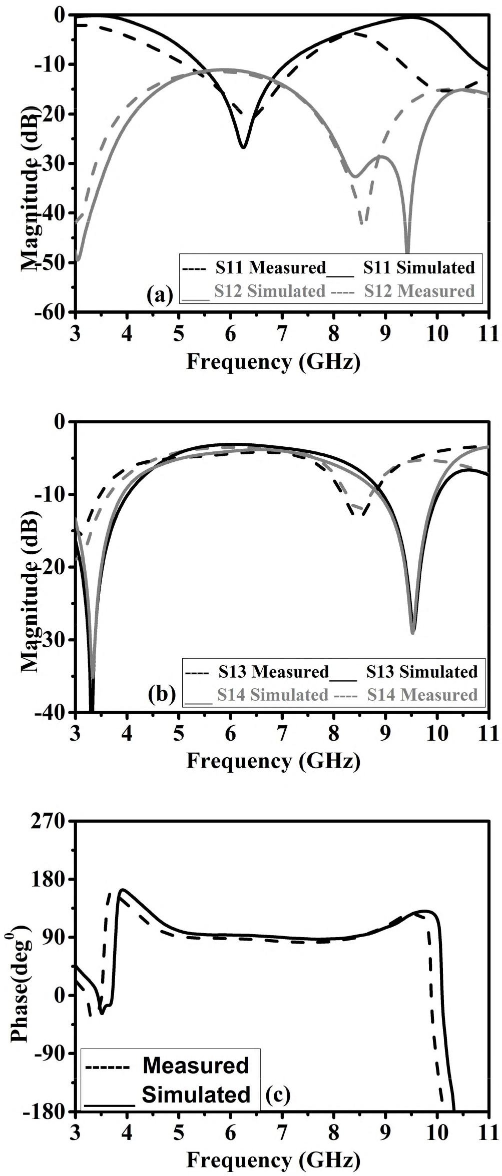

FIGURE 4. Simulated and measured results of the coupler (OFF-OFF): (a) S11 and S12. (b) S13 and S14. (c) Phase difference.

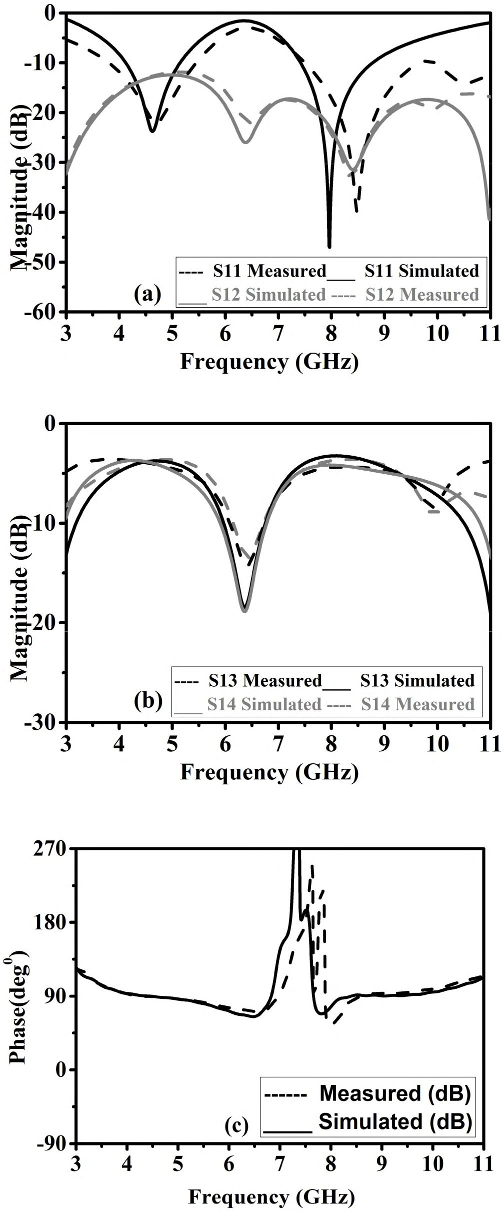

FIGURE 5. Simulated and measured results of the coupler (ON-OFF): (a) S11 and S12. (b) S13 and S14. (c) Phase difference.

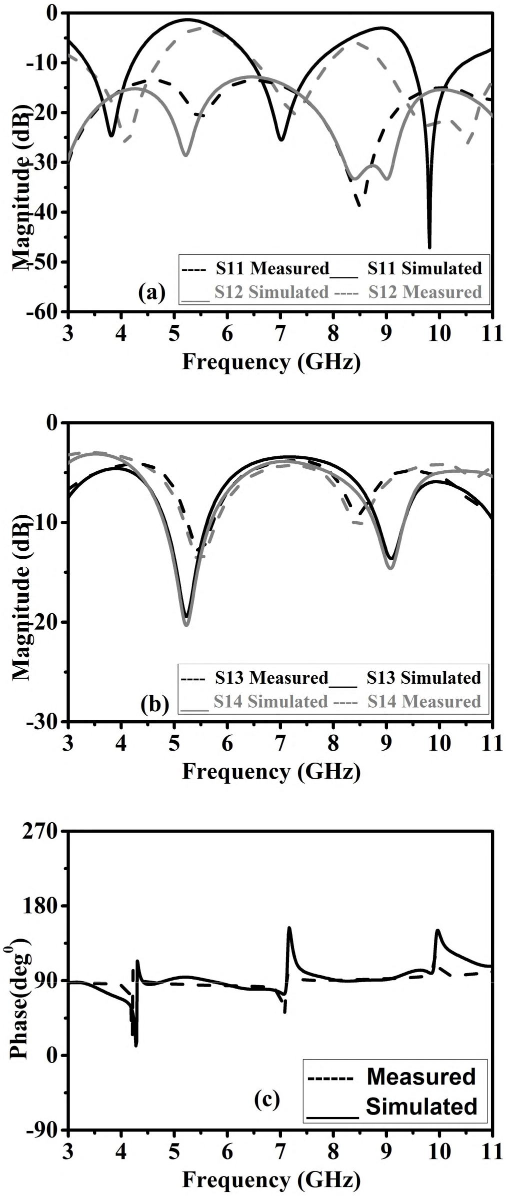

FIGURE 6. Simulated and measured results of the coupler (ON-ON): (a) S11 and S12. (b) S13 and S14. (c) Phase difference.

In this case, the length of the resonator becomes λ1/4 resulting in creating a notch (theoretically infinite attenuation).

In the case of both diodes D1 and D2 are ON, (Figure 2.c), the equivalent circuit of the resonator is:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = M_{D1} M_{R2} M_{D2} M_{R3} \tag{16}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{j\tan\theta_2}{Z_2} & 1 \end{bmatrix} \times \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{j\tan\theta_3}{Z_3} & 1 \end{bmatrix} \tag{17}$$

$$S_{12} = \frac{2}{A + {}^{B}\!/_{Z_0} + CZ_0 + D} \approx 0 \tag{18}$$

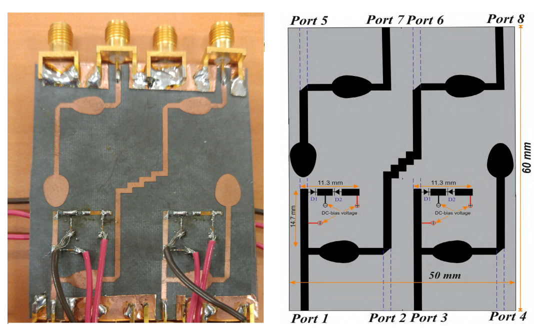

FIGURE 7. Layout and Photograph of the fabricated Butler matrix.

Therefore, a notch is created when the electrical lengths of both transmission lines are connected ($\lambda_2/4+\lambda_3/4$).

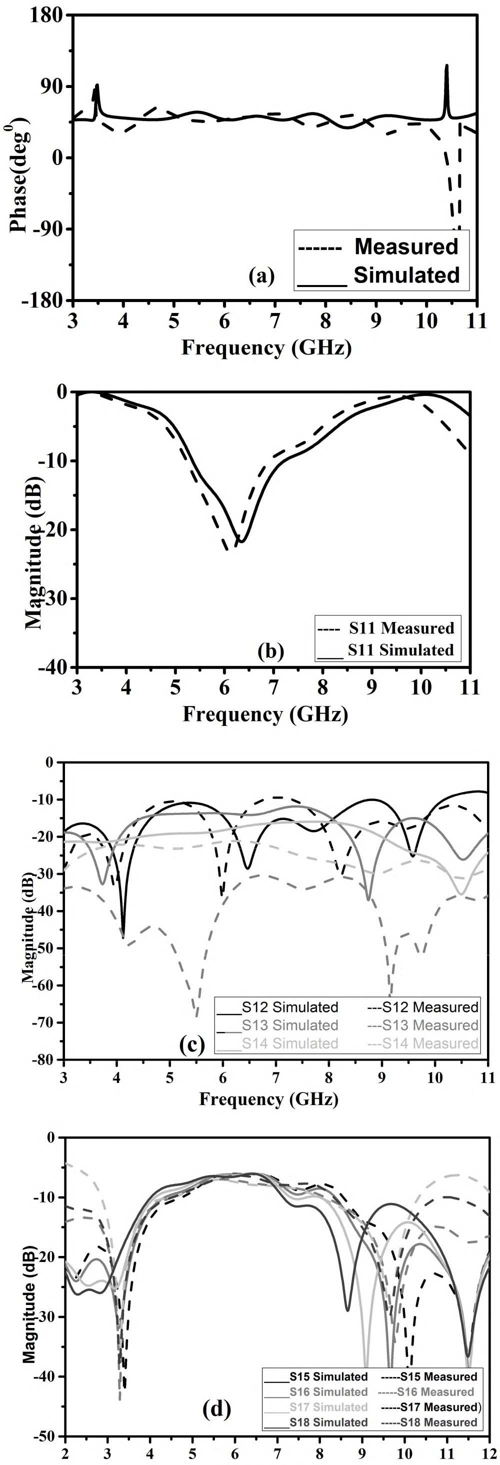

FIGURE 8. Simulated and measured results of the Butler matrix (OFF-OFF): (a) Phase difference. (b) S11. (c) S12, S13 and S14. (d) S15,S16,S17 and S18.

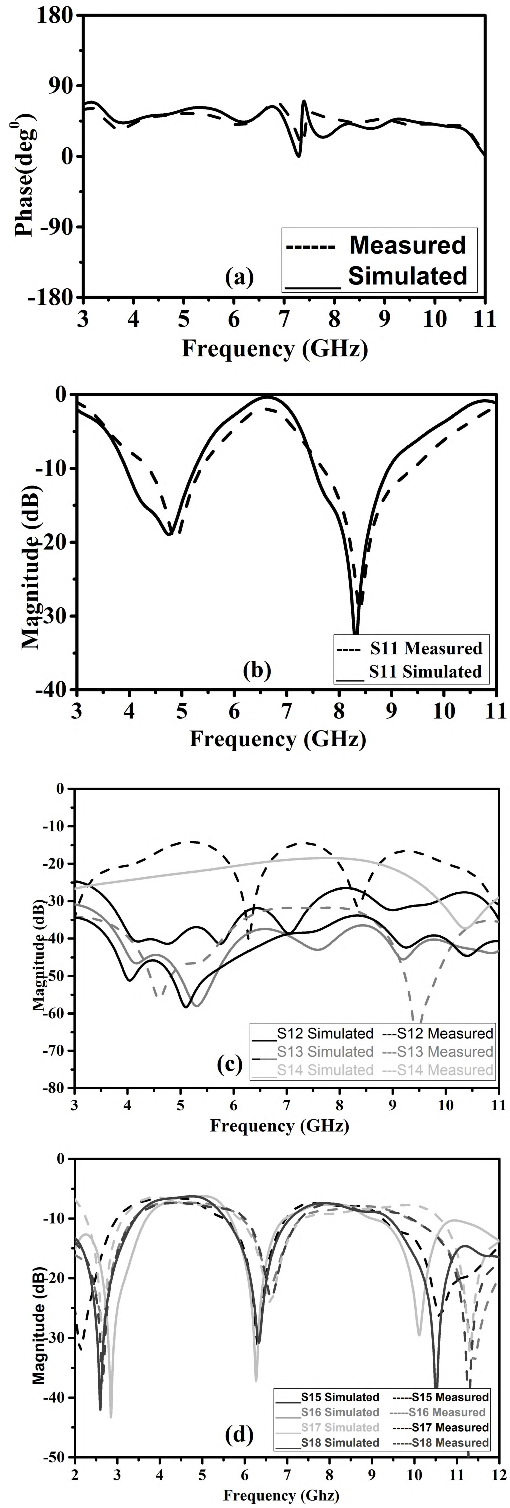

FIGURE 9. Simulated and measured results of the Butler matrix (ON-OFF): (a) Phase difference. (b) S11. (c) S12, S13 and S14 (d) S15, S16, S17 and S18.

III. RESULTS AND DISCUSSIONS

For experimental validation, a reconfigurable directional coupler was designed and fabricated using Rogers RT/Duroid 5880 with $\varepsilon r = 2.2$ and $h = 0.508$ mm. Simulated results were carried out using CST MWS Studio. The S-parameters measurements are performed by using an Agilent vector network analyzer.

TABLE 2. Performance summary of the state-of-the-art reconfigurable coupler.

Refs	*Process technology*	*Frequency band GHz*	*Power coefficient coupling dB*	*Technique used for reconfiguration*	*Element as a Butler Matrix*
[4]	microstrip	0.632-1.5	-6.4 dB –20.5	Varactor	no
[9]	microstrip	1-3	0.86-9.5	Varactor	yes
[10]	microstrip	fixed	16-35	Varactor +active capacitance	no
[11]	thin-film barium	f 1 ≈ [1.8 – 2.9] f 2 ≈ [5.6 – 6.1]	Fixed	Varactor	yes
[13]	microstrip	1.5 GHz-2.2	Fixed	RF MEMS	yes
[20]	microsrip	Fixed at 3.5	4.2 -10	Varactor	yes
[21]	CMOS and active inductor	2-6	1.3-9	Varactor	yes
[22]	GaAs MMIC	fixed	6.6-60	Schottky diode	yes
This work	Microsrip	(wide, dual and triple band)	Fixed	PIN diode	yes

A. RECONFIGURABLE COUPLER

Table. 1 summarizes the corresponding PIN diode states for coupler operation in the three different cases (Wideband, Dual-band and Triple-band).

The photograph of the fabricated reconfigurable directional coupler is shown in Figure 3.

The simulated and measured results of a wide, dual and triple band of directional coupler are presented in Figures 4, 5 and 6, respectively. From these results, it can be noted that good results in terms of return loss and isolation are obtained for all operating frequency bands. Besides, the insertion losses results (S21 and S31) are illustrated in Figures 4.b, 5.b and 6.b. It can be noted that the average value of the coupling for the direct and the coupled ports is 3.5 dB for all states (wide band [5.5-7 GHz], dual band [4.3-5.5 GHz, 7.6-8.4 GHz] and triple band [3.5-4.4 GHz, 6.8-7.9 GHz, 9.5-10.5 GHz]). It is worth mentioning that, for all state, the direct and coupled ports phase difference ((Figures 4. c, 5.c and 6.c) is almost 90° across the operating band. which confirm the proposed approach.

A comparison between the simulated and experimental results shows a good agreement. RF choke inductors are added in order to establish the proper biasing conditions of PIN diodes. In fact, these RF choke inductors present a high-impedance path to the RF signal traveling on the microstrip lines. The PIN diodes positions are chosen to have a common negative wire in order to avoid using a dc blocking capacitor, and thus reducing the cost and fabrication complexity.

From Table 2, it can be seen that the proposed reconfigurable coupler has been implemented using microstrip technology with commercially available diodes, which reduces the cost compared to the tuning elements, such as the RF MEMS [11], [13], [22], or tunable active inductors [21]. Furthermore, the proposed configuration allows for reconfigurable applications. In addition, a wider range of operating frequency bands have been achieved compared to either CMOS or PCB referenced [4], [9], [10], and [20]. The couplers reported in [4] and [10], are not suitable for Butler matrices because of the coupling coefficient, which is different from 3 dB.

B. RECONFIGURABLE BUTLER

Figure 7 shows the reconfigurable multilayer 4 × 4 Butler matrix which uses the designed coupler in section II. In this structure, the crossing lines are perfectly isolated with equally output ports (5, 7, 6 and 8) and proper phase difference.

To demonstrate the proposed Butler matrix, an experimental prototype is fabricated on Duroid substrate (RT/Duroid 5880) with $\varepsilon r = 2.2$ and a thickness of 0.254 mm as shown in Figure 9b. From Figures 8, 9 and 10, experimental and simulated results are in good agreement. In Figures (Figure 8.a), (Figure 9.a) and (Figure 10.a), the measured and simulated phase difference between output ports for all state Butler matrix are almost 450 with max of error within 80 degrees over the desired bands.

Table. 3 summarizes the corresponding PIN diode states for coupler operation in the three different cases (Wideband, Dual-band and Triple-band).

TABLE 3. PIN Diode configurations for different states of the reconfigurable butler matrix.

Configuration	Wide band	Dual-band	Triple-band
D1	OFF	ON	ON
D2	OFF	OFF	ON

Figure 8 shows the simulated and experimental results for the ports 1 and 2 with considering the matching of the other ports. It can be noted that the Butler matrix return losses for all state are better than 18 dB over the desired frequency bands. Furthermore, the isolation (S12, S13 and

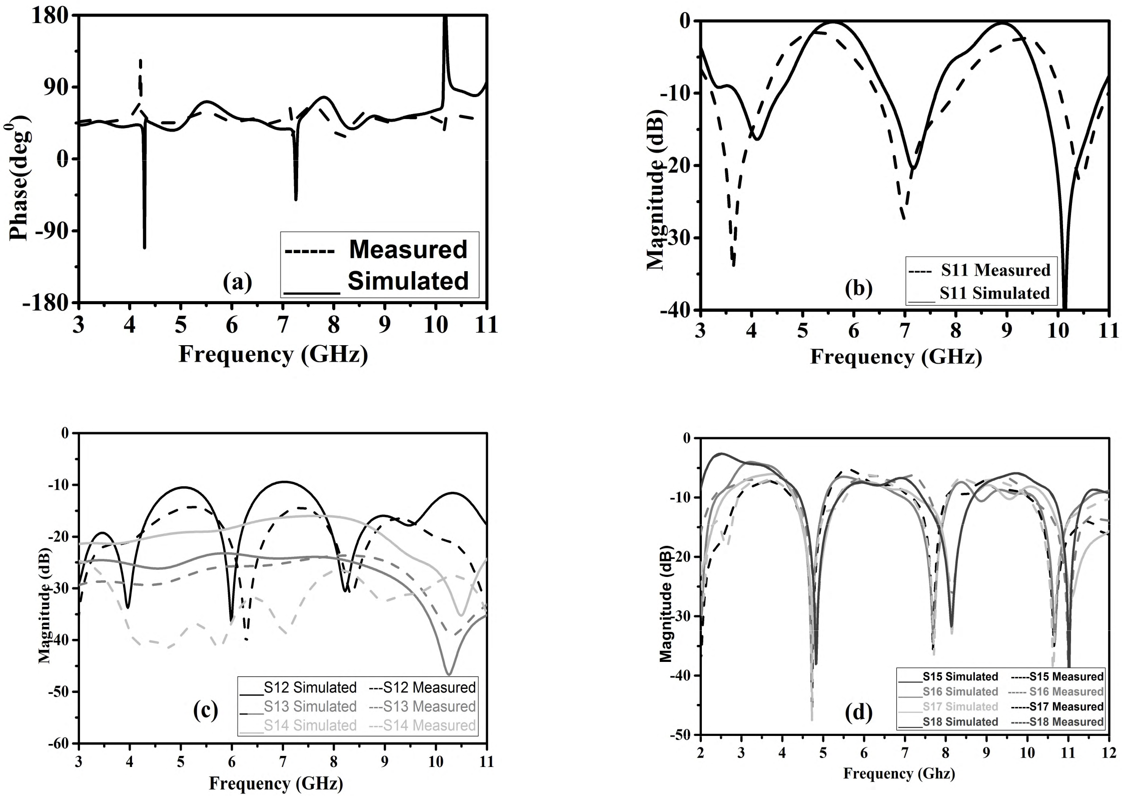

FIGURE 10. Simulated and measured results of the Butler matrix (ON-ON): (a) Phase difference. (b) S11 (c) S12, S13 and S14 (d) S15, S16, S17 and S18.

TABLE 4. Performance summary of the state-of-the-art reconfigurable coupler.

Refs	*Process technology*	*Frequency band*	*Coupling coefficient*	*Type of reconfiguration*	*Technique used for reconfiguration*	*Insertion loss dB*	*Used a crossover element*
[5]	Microstrip multilayer	UWB	≈ 6-7	_____	_____	_____	no
[7]	microstrip	2.4/5.2 GHz	≈ 6-7	_____	_____	_____	yes
[16]	CMOS	X-Band	NA	Frequency	varactor	4	yes
[17]	microstrip	3.6 GHz	≈ 6-8	reconfigurable phase-controlled	SPDT switch	3.7	yes
[18]	microstrip	5 GHz	≈ 7.7-8.7	Single-/Dual-Port Excitation	PIN diode	1.22	yes
[19]	microstrip	2.4 GHz	≈7.7	beam Controllability	varactor diodes	1.7	yes
This work	Microstrip multilayer	Wide,dual and triple	≈ 6-7	Band reconfigurable	PIN diode	1.6	no

S14) for all states are better than 12 dB, as illustrated in Figures 8.c, 9.c and 10.c, respectively. For the results shown in Figures 8. d, 9.d and 10.d, the coupling to the output ports (S15, S16 S17 and S18) are almost equalized 7 dB for all states (wide band, dual band and triple band). A small frequency shift between the measurement and simulation is noted. This is due mainly to the PIN diodes biasing components effects. Other factors may be included as the fabrication tolerance, soldering and alignment accuracy between layers.

Table 4 shows the performance comparison with recently reported Butler Matrices. In this proposed approach, a reconfigurable Butler matrix has been designed without using any crossovers as in conventional ones. In fact, crossovers add undesired effects such as increased insertion losses and mismatched junctions [6]. However, in [16]–[19], the reported reconfigurable Butler matrices have used crossovers to avoid the crossing transmission lines. Moreover, it can be seen that the Butler matrix in [16] and [17] are made with RF MEMS and CMOS tunable capacitor, which increases the complexity and cost of the circuit implementation. It can be noticed that the proposed low cost Butler Matrix has been designed without using any crossovers, which provides a widest frequency band reconfigurability from 3 to 10 GHz with good coupling coefficient.

IV. CONCLUSION

A novel design of reconfigurable Butler Matrix has been analyzed and tested. In the proposed design, a novel reconfigurable directional coupler based on tuning the length of the resonator transmission line has also been analyzed and designed to be integrated into the reconfigurable Butler matrix system. The proposed approach allows operating the system either in a wideband mode or in one of the two other states as a dual or triple band. To validate the design concept, two prototypes of coupler and Butler matrix have been constructed to validate the measured results with the simulated ones. The proposed reconfigurable devices are useful for several future wireless communications.

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