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Research Article

A Compact Frequency- and Power-Dividing Ratio-Tunable Quadrature Coupler

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This paper presents a compact quadrature coupler with a tunable frequency and power-dividing ratio. Wide tunable frequency and power-dividing ratio are achieved by using the novel tunable unit instead of the transmission line sections in a traditional varactor-based quadrature coupler. Closed-form equations are derived for design parameters. For verification, a quadrature coupler is designed based on the given parameters, which demonstrate the tunable frequency of 2.0 GHz to 6.0 GHz and the tunable power-dividing ratio of -20 dB to 7.2 dB at 3 GHz. Finally, a microstrip tunable quadrature coupler is fabricated and measured. The measurements agree well with simulations. Under the frequency-tunable state, the measured 3-dB working frequency of this coupler can be continuously adjusted from 2.0 GHz to 4.7 GHz. And during the adjustment process, the return loss and isolation are always >15 dB. In the power-dividing ratio-tunable state, the adjustment range of the measured power-dividing ratio is from -14 to 6.0 dB at 3 GHz. Moreover, the return loss and isolation are always maintained at >20 dB.

1. Introduction

Modern communication systems, such as the global positioning system (GPS) and wireless local area network (WLAN), need high-performance components working across different communication standards. In addition, in light of today's crowded radio spectrum and the multistandard RF (radio frequency) frontends in modern telecommunication systems demanding high-performance devices, reconfigurable RF/microwave circuits have become a very important topic of research. As an essential component, various frequency-tunable [1–5] and power-dividing ratio-tunable [6–9] quadrature couplers emerged. In [6], the coupler not only has a narrow adjustment range of power-dividing ratio but also belongs to a double-layer structure. The tunable couplers in [7, 9] are designed by connecting the phase shifters between two traditional couplers. Therefore, this kind of coupler expands the adjustment range of the power-dividing ratio at the expense of circuit size.

Compared with the above single-function tunable couplers, the frequency- and power-dividing ratio tunable couplers [10–12] can integrate multiple functions into a single device or circuit, which is more in line with the development trend of modern communication systems. For the coupler in [10], the 3-dB power-dividing ratio output cannot be achieved in the frequency-tunable mode. The coupler in [11] has a wide adjustment range, but its size is large. Moreover, in [12], the coupler has a narrow adjustment range. To sum up, it is urgent to design a frequency- and power-dividing ratio-tunable quadrature coupler with a small size and wide adjustment range.

In this paper, a compact quadrature coupler, with tunable frequency and the power-dividing ratio is proposed. In Section 2 gives a method for designing the novel tunable unit which can be equivalent to the transmission line sections in a traditional varactor-based quadrature coupler across the entire frequency range. And this coupler has a high degree of symmetry and thus the canonical even- and odd-mode analysis can be simply applied. The presented tunable coupler has several advantages, such as compact design, wide tunable frequency and power-dividing ratio, and closed-form equations available for the systematic

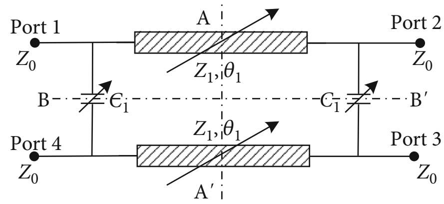

Figure 1: Schematic of the traditional varactor-based quadrature coupler with electrical length variable transmission-line section.

design with the prescribed specification. For demonstration, a quadrature coupler is presented based on the given design equations. And it demonstrates the tunable frequency of 2.0–6.0-GHz with an equal power-dividing ratio, and the power-dividing ratio is tuned from -20 dB to 7.2 dB (from 3E-2.5 to 5.3) at 3 GHz in Section 3. Then, a compact microstrip quadrature coupler with tunable frequency and power-dividing ratio is fabricated and measured in Section 4. Good isolation and return loss are obtained for all states. Finally, the conclusion is given in Section 5.

2. Tunable Quadrature Coupler Circuit and Analysis

Figure 1 shows the schematic of the frequency and power-dividing ratio tunable quadrature coupler with electrical length variable transmission-line sections. It basically consists of two transmission lines with a variable electrical length of θ_1 and a fixed characteristic impedance of Z_1. Two tunable capacitors, C_1, are placed in parallel at both ends of the transmission line to tune the operation passband.

2.1. Circuit Analysis. The structure presented in Figure 1 is bisymmetric along the symmetry lines AA′ and BB′. Thus, it can be analyzed by using the even-odd mode decomposition technique. If port 1 is specified as an input port, ports 2 and 3 are two outputs, and port 4 is the isolated port. Therefore, the corresponding *S*-parameters of this coupler should satisfy the following conditions across the entire tuning range:

$$S_{11} = S_{41} = 0, |S_{31}| = R|S_{21}|, \quad (1)$$

where R is defined as the output power-dividing ratio. According to the even-odd mode method, the intrinsic admittances Y_{ee}, Y_{eo}, Y_{oe}, and Y_{oo} under different excitation combinations can be obtained as

$$Y_{ee} = \frac{j\tan(\theta_1/2)}{Z_1}, \quad (2a)$$

$$Y_{eo} = -\frac{j\cot(\theta_1/2)}{Z_1}, \quad (2b)$$

$$Y_{oe} = j2\omega C_1 + \frac{j\tan(\theta_1/2)}{Z_1}, \quad (2c)$$

$$Y_{oo} = j2\omega C_1 - \frac{j\cot(\theta_1/2)}{Z_1}, \omega = 2\pi f_0. \quad (2d)$$

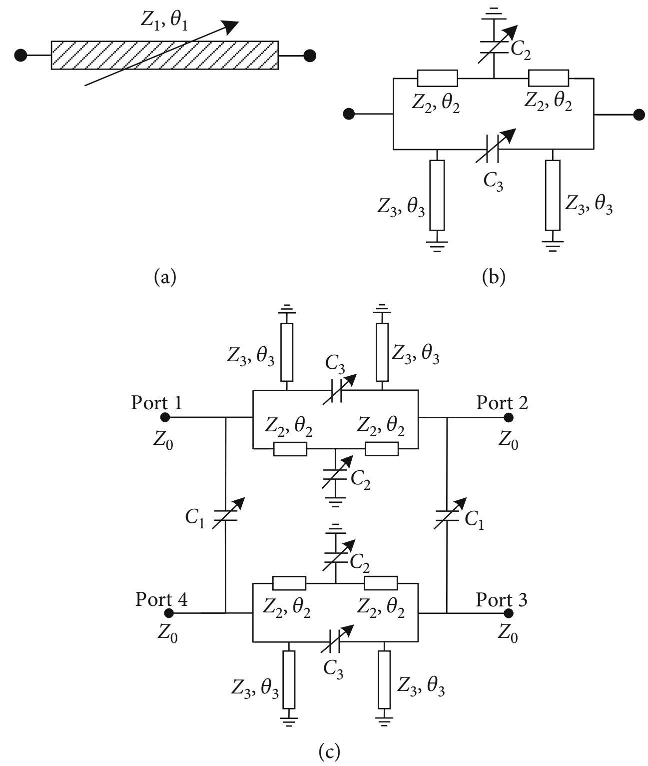

Figure 2: (a) The electrical length variable transmission-line section. (b) Configuration of the novel tunable unit. (c) Final circuit of the proposed frequency and power-dividing ratio tunable quadrature coupler.

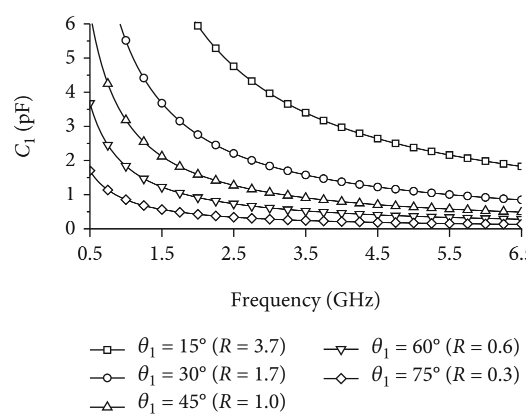

Figure 3: Calculated C_1 versus frequency for different electrical lengths θ_1 or power-dividing ratio R with $Z_0 = 50\ \Omega$.

Thus, the *S*-parameters of the coupler can be easily obtained as follows:

$$S_{11} = \frac{1}{2}\left(\frac{1}{1+Y_{ee}Z_0} + \frac{1}{1+Y_{eo}Z_0} + \frac{1}{1+Y_{oe}Z_0} + \frac{1}{1+Y_{oo}Z_0} - 2\right), \quad (3a)$$

$$S_{21} = \frac{1}{2}\left(\frac{1}{1+Y_{ee}Z_0} + \frac{1}{1+Y_{oe}Z_0} - \frac{1}{1+Y_{eo}Z_0} - \frac{1}{1+Y_{oo}Z_0}\right), \quad (3b)$$

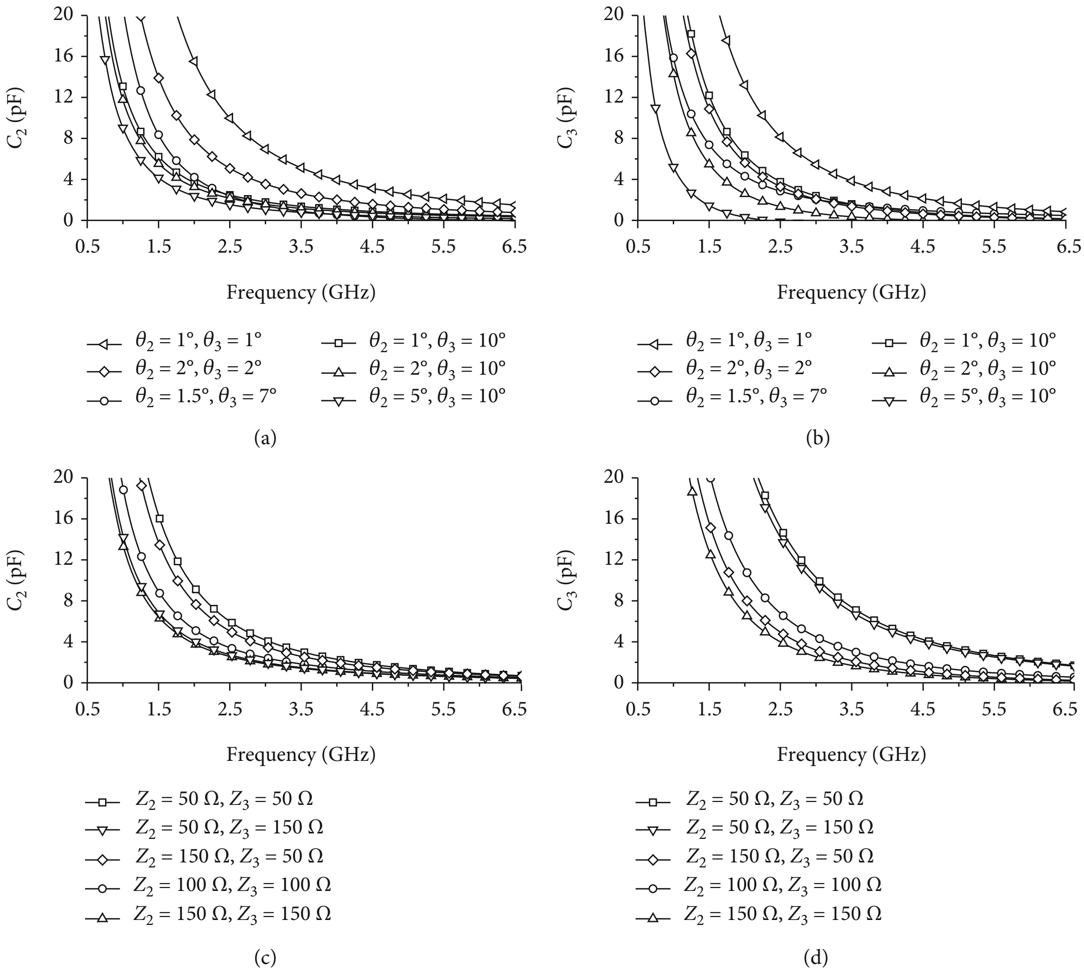

Figure 4: Calculated capacitors for different electrical lengths θ_2 and θ_3. (a) C_2 and (b) C_3 ($Z_2 = Z_3 = 150\,\Omega$). Calculated capacitors for different transmission-line impedances (Z_2, Z_3). (c) C_2 and (d) C_3 ($\theta_2 = 1°$, $\theta_3 = 5°$ at 1.0 GHz).

$$S_{31} = \frac{1}{2}\left(\frac{1}{1+Y_{ee}Z_0} + \frac{1}{1+Y_{oo}Z_0} - \frac{1}{1+Y_{eo}Z_0} - \frac{1}{1+Y_{oe}Z_0}\right), \tag{3c}$$

$$S_{41} = \frac{1}{2}\left(\frac{1}{1+Y_{ee}Z_0} + \frac{1}{1+Y_{eo}Z_0} - \frac{1}{1+Y_{oe}Z_0} - \frac{1}{1+Y_{oo}Z_0}\right), \tag{3d}$$

where Z_0 represents the port impedance. Combining (1) and ((3a)), ((3b)), ((3c)), and ((3d)), we obtain

$$Z_0{}^2 Y_{ee} Y_{eo} = 1, \tag{4}$$

$$Z_0{}^2 Y_{oe} Y_{oo} = 1, \tag{5}$$

$$R^2 = \frac{|S_{31}|^2}{|S_{21}|^2} = \frac{|(Y_{eo} - Y_{oo})Z_0|^2}{|Y_{eo} Y_{oo} Z_0{}^2 - 1|^2}. \tag{6}$$

By inserting (2a) and (2b) into (4), the following equation is obtained

Table 1: Circuit parameters for the proposed quadrature coupler ($Z_0 = 50\ \Omega$).

Parameter	Value	Parameter	Value
Z_1 (Ω)	50	R	-14~6.0 dB (3E-1.9~4)
θ_1 (°)	45	C_1 (pF)	0.3~2.5
Z_2 (Ω)	150	C_2 (pF)	0.3~2.5
θ_2 (°)	1	C_3 (pF)	0.4~2.2
Z_3 (Ω)	150	f (GHz)	2.0~4.7 ($R^2 = 1$)
θ_3 (°)	5		

$$\frac{Z_0{}^2}{Z_1{}^2} = 1. \tag{7}$$

Subsequently, the value of Z_1 can be given as

$$Z_1 = Z_0. \tag{8}$$

Then, by inserting (2c), (2d), and (8) into (5), the value of C_1 can be evaluated as

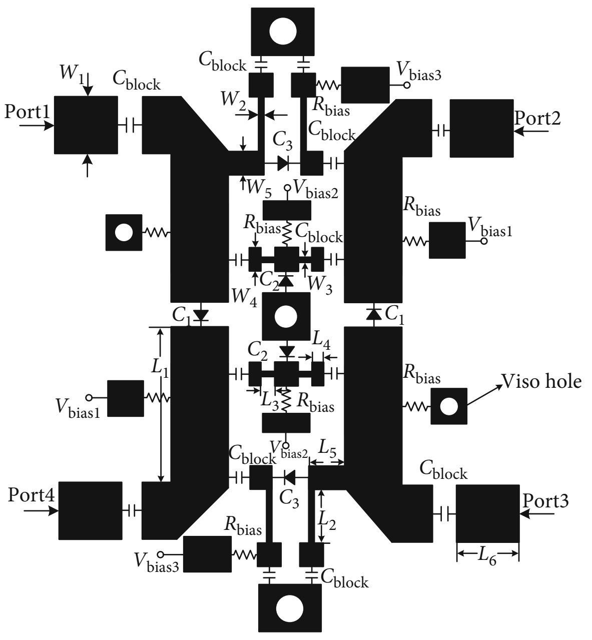

Figure 5: Layout of the proposed microstrip tunable quadrature coupler.

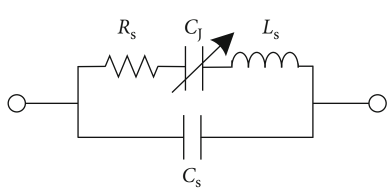

Figure 6: Equivalent circuit of the varactor.

$$C_1 = \frac{\cot(\theta_1 f/f_0)}{\omega Z_0}. \tag{9}$$

Finally, by substituting (8) and (9) into (6), the output power dividing ratio of R can be expressed as

$$R^2 = \cot^2(\theta_1 f/f_0). \tag{10}$$

2.2. Electrical Length Variable Transmission-Line Section. It can be seen from (10) that the power-dividing ratio R is only affected by the electrical length of θ_1. In other words, when the power-dividing ratio R is determined, the value of the electrical length θ_1 should remain constant over the entire adjustable range. To achieve this goal, as shown in Figure 2(b), a novel tunable unit is proposed to replace the electrical length variable transmission-line section (Z_1, θ_1), which is shown in Figure 2(a). It is basically composed of a low-pass filter and a high-pass filter connected in parallel. The low-pass filter includes two transmission lines (Z_2, θ_2) and a varactor C_2 loaded in shunt to the middle of two transmission lines. Moreover, the high-pass filter consists of the two shunt short-circuited stubs (Z_3, θ_3) and a varactor diode C_3 in a series connection between the two short-circuited stubs.

When this tunable unit is equivalent to the electrical length variable transmission-line section (Z_1, θ_1), the Y-matrix of the tunable unit $[Y]_{TU}$ should satisfy the following condition across the entire tuning range:

$$[Y]_{TU} = \begin{bmatrix} Y_{11TU} & Y_{12TU} \\ Y_{21TU} & Y_{22TU} \end{bmatrix} = \frac{j}{Z_1}\begin{bmatrix} -\cot\theta_1 & \csc\theta_1 \\ \csc\theta_1 & -\cot\theta_1 \end{bmatrix}. \tag{11}$$

To calculate the Y-matrix of a novel tunable unit ($[Y]_{TU}$), the A matrix of this unit is first found and then converted to a Y-matrix. By following Equation (11), the capacitors C_2 and C_3 can be derived as

$$C_2 = \frac{2(-Z_1Z_3 + Z_2\cot(\theta_2 f/f_0)(Z_1\cot(\theta_3 f/f_0) + Z_3\tan(\theta_1 f/f_0)))}{\omega Z_2(Z_1Z_3\cot(\theta_2 f/f_0) + Z_1Z_2\cot(\theta_3 f/f_0) + Z_2Z_3\tan(\theta_1 f/f_0))}, \tag{12a}$$

$$C_3 = \frac{1}{2\omega}\left(\frac{\cot(\theta_2 f/f_0)}{Z_2} + \frac{\cot(\theta_3 f/f_0)}{Z_3} - \frac{(\cot(\theta_1 f/f_0) + \csc(\theta_1 f/f_0))}{Z_1}\right). \tag{12b}$$

2.3. Selection of Design Parameters. According to (8), (9), and ((12a) and (12b)), one can calculate all the design parameters of the quadrature coupler. From Equation (8), it can be known that the value of Z_1 is equal to Z_0 under all conditions. When the center frequency f_0 is given, the choice of C_1, C_2, and C_3 are determined by Equations (9) and ((12a) and (12b)). In this paper, for the convenience of calculation, f_0 is set at 1 GHz. C_1 changes as the frequency for different θ_1 or power-dividing ratio R with $Z_0 = 50\ \Omega$, which is shown in Figure 3. It can be seen from Figure 3 that the value of C_1 decreases with the operating frequency. When the electrical length θ_1 or power-dividing ratio R is given, the capacitance C_1 is mainly determined by the operating frequency. And the variation value of C_1 between different power-dividing ratios is relatively small.

In the case of $Z_1 = 50\ \Omega$ and $\theta_1 = 45^\circ$ (i.e. the power-dividing ratio $R = 1$), and assuming $Z_2 = Z_3 = 150\,\Omega$, the change of C_2 and C_3 versus frequency for different θ_2 and θ_3 are shown in Figures 4(a) and 4(b). As shown in Figures 4(a) and 4(b), the capacitors C_2 and C_3 decrease with the operating frequency. Taking into account the controllable range of the varactor, and the tuning frequency, the value of θ_2 and θ_3 are chosen as 1.5° and 7°, respectively. When θ_2 and θ_3 are determined, the change of C_2 and C_3 versus frequency for different Z_2 and Z_3, are shown in Figures 4(c) and 4(d). To achieve a wide frequency tuning range as much as possible within a realizable range of the varactor, the value of Z_2 and Z_3 is chosen as 150 Ω. The final structure of the compact quadrature coupler with tunable frequency and the power-dividing ratio is shown in Figure 2(c).

3. Coupler Design and Microstrip Realization

According to the proposed method, a quadrature coupler with a tunable frequency from 2 GHz to 6 GHz for an equal

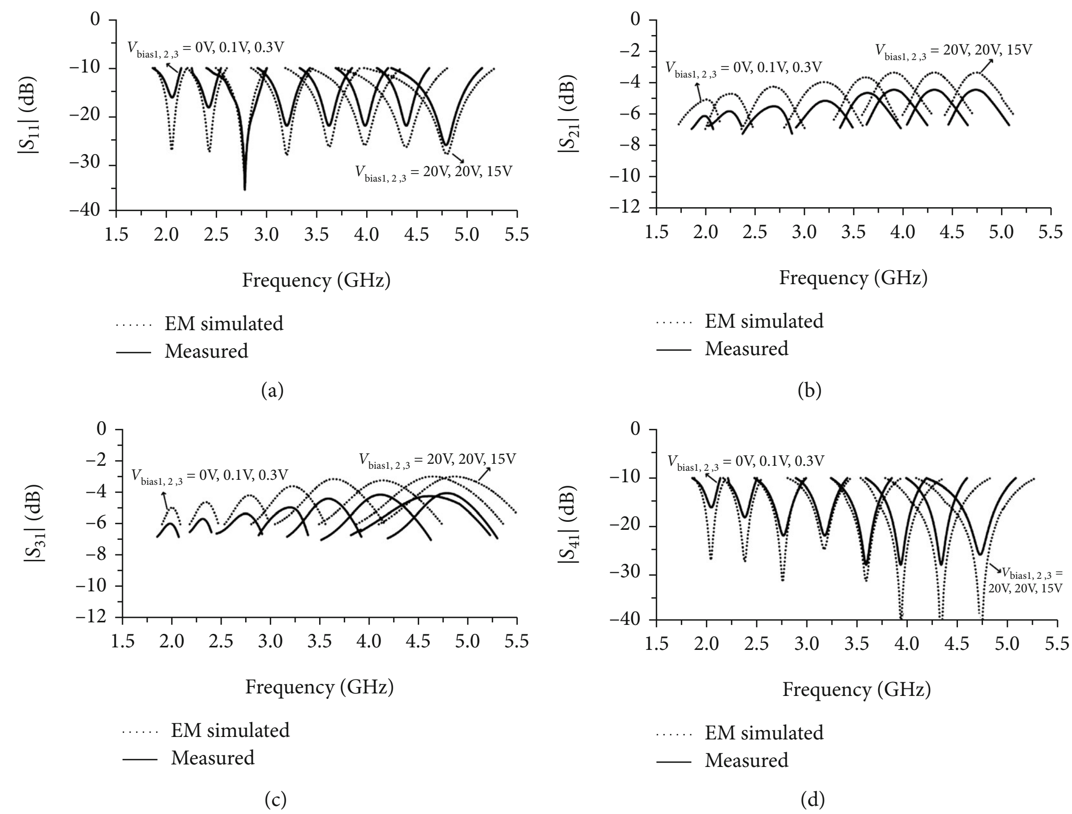

FIGURE 7: Simulated and measured results of the frequency-tunable quadrature coupler. (a) $|S_{11}|$. (b) $|S_{21}|$. (c) $|S_{31}|$. (d) $|S_{41}|$.

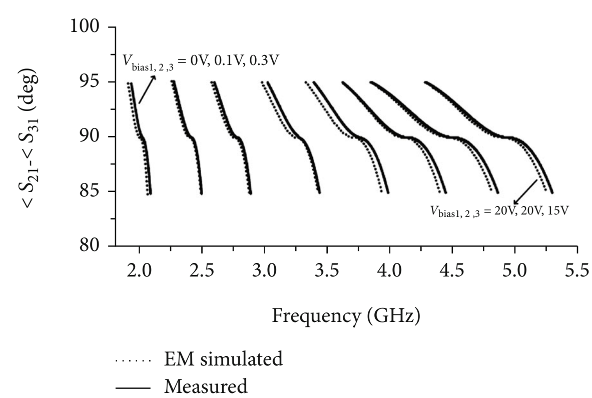

FIGURE 8: Simulated and measured phase differences of the frequency-tunable quadrature coupler.

power ratio and the power-dividing ratio tunable between -20 dB and 7.2 dB at 3 GHz is designed.

3.1. Design Procedure. The design process of this quadrature coupler is summed up as follows:

Step 1. On the basis of the discussions in Section 2.1, given R^2, frequency-tuning range and Z_0, the values of C_1 and θ_1 are determined by (9) and (10).

Step 2. When $Z_1 = 50\ \Omega$ and $\theta_1 = 45\circ$ (i.e. the power-dividing ratio $R=1$), one selects Z_2, Z_3, θ_2, and θ_3 as 150 Ω, 150 Ω, 1.5°, and 7° at 1.0 GHz, respectively, according to the discussion in Section 2.2. Using ((12a)) and ((12b)), the values of C_2 and C_3 can be obtained.

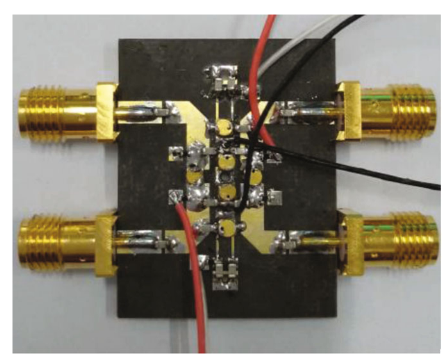

FIGURE 9: Image of the fabricated tunable quadrature coupler.

Step 3. Based on the above steps, using the commercial EM (electromagnetism) software ADS (advanced design system), the initial design parameters can be optimized.

Following the above design procedure, the calculated circuit parameters of a quadrature coupler are listed in Table 1.

3.2. Microstrip Tunable Quadrature Coupler Realization. The configuration of the proposed microstrip tunable quadrature coupler is shown in Figure 5. The tuning components C_1, C_2, and C_3 are all implemented by MA46H201 high-Q GaAs diodes from MACOM. The equivalent circuit of varactor used in ADS simulation is shown in Figure 6. The package capacitance C_s, package inductance L_s and parasitic resistance R_s of varactor are 0.15 pF, 0.45 nH, and 1 ohm, respectively. The C_{block} (100 pF) is realized by ATC 600S series capacitors. The bias resistor R_{bias} is 180 kΩ.

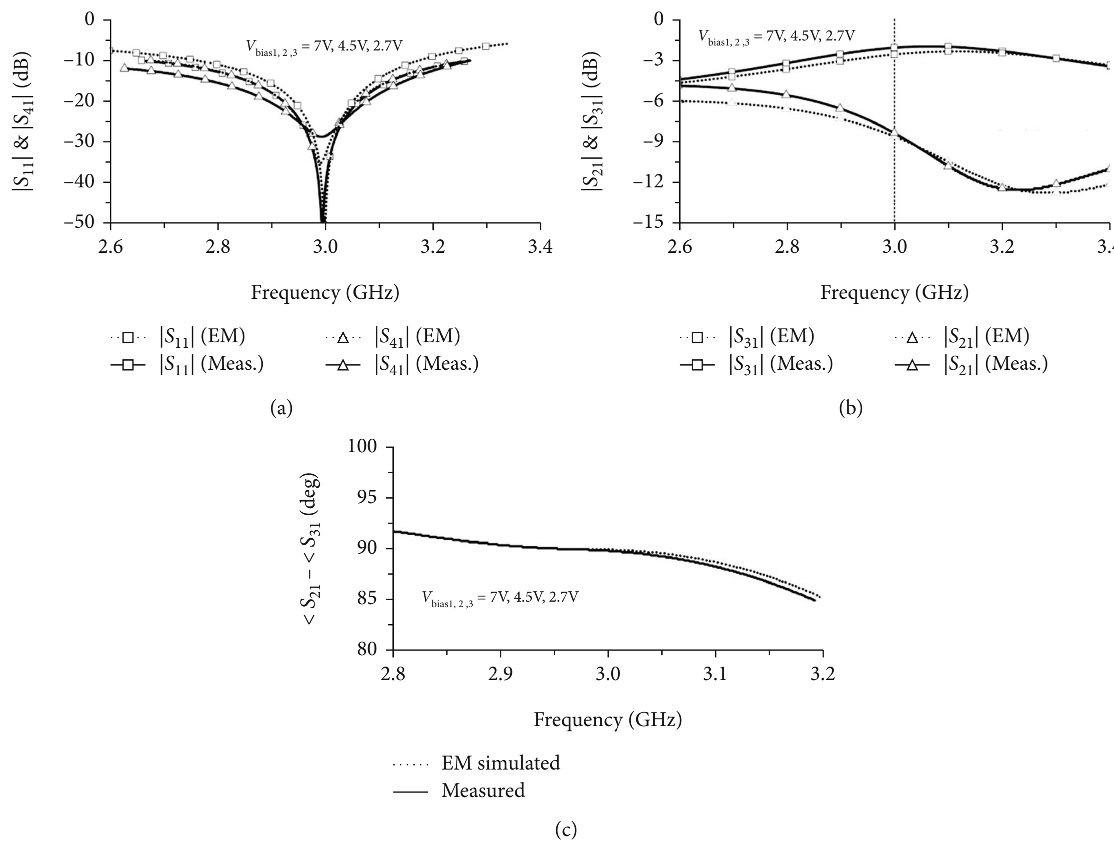

Figure 10: Simulated and measured results of the power-dividing ratio tunable quadrature coupler. The power-dividing ratio is 6.0 dB ($|S_{21}| - |S_{31}|$) at 3 GHz. (a) $|S_{11}|$ and $|S_{41}|$. (b) $|S_{21}|$ and $|S_{31}|$. (c) Phase differences.

4. Simulated and Measured Results

To verify the effectiveness of the above design, a quadrature coupler with tunable frequency and power-dividing ratio was manufactured and measured. This tunable quadrature coupler was fabricated on a Rogers RT/Duroid 5880 with $\varepsilon_r = 2.2$ and $h = 0.787$ mm. According to Table 1, the parameters for the design and manufacturing of the circuit in this coupler are set. And the final configuration of this microstrip tunable quadrature coupler is shown in Figure 5. The dimensions marked in Figure 5 are as $W_1 = 2.42$ mm, $W_2 = W_3 = 0.23$ mm, $W_4 = W_5 = 1.0$ mm, $L_1 = 5.05$ mm, $L_2 = 2.8$ mm, $L_3 = 0.2$ mm, $L_4 = 0.5$ mm, $L_5 = 0.95$ mm, and $L_6 = 5.0$ mm. ADS performs all of the simulation parameters. The vector network analyzer used for measuring is Rohde & Schwarz ZNB-8, which covers the frequency range of 1.0 GHz to 6.0 GHz.

4.1. Performance of the Tunable Frequency with $R^2 = 1$. Figure 7 shows the simulated and measured S-parameters of the proposed quadrature coupler with $R^2 = 1$. The simulations are in good agreement with the measurements. When the biasing voltages (i.e., $V_{bias1,2,3}$) of varactors change in the range of 0–20 V, the center frequency of the proposed tunable coupler can be continuously adjusted from 2.0 to 4.7 GHz. Moreover, the center frequency is limited by the range of varactors. For all states, the measured return loss and isolation are better than 15 dB. Correspondingly, the return-loss bandwidth is greater than 50 MHz at this center frequency. The measured insertion loss varies from 4.3 to 5.9 dB. The difference between the simulated and measured insertion loss is within 1.0 dB, which is mainly attributed to the limited welding process and the resistive loss from the transmission lines. Moreover, the phase difference between the simulated and measured coupler is shown in Figure 8. For all states, the measured phase imbalances at the center frequency are less than 5°.

Figure 9 shows an image of the manufactured tunable quadrature coupler. The circuit size is $0.22\,\lambda g \times 0.07\,\lambda g$, where λg is the guided wavelength at the lowest center frequency.

4.2. Performance of the Tunable Power-Dividing Ratio. As discussed in Section 2.2, the power-dividing ratio R is only affected by the electrical length of θ_1. By changing the value of θ_1, tunable R can be achieved at each state. For demonstration, this tunable coupler is simulated and measured at 3 GHz.

Figures 10 and 11 show simulated and measured results of this proposed quadrature coupler for different power-dividing ratios. The simulations are in good agreement with the measurements. The power-dividing ratio can be tuned from -14 to 6.0 dB at 3 GHz, which is limited by the range of varactors. The measured return loss and isolation are

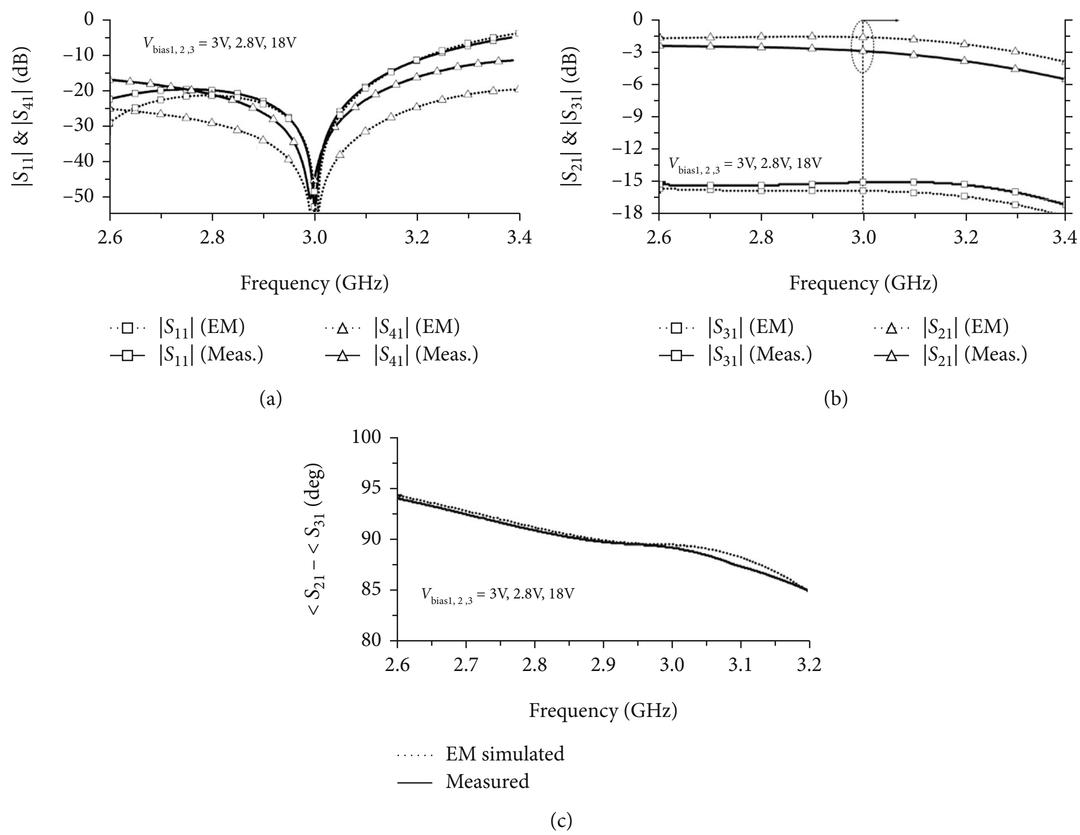

Figure 11: Simulated and measured results of the power-dividing ratio tunable quadrature coupler. The power-dividing ratio is -14 dB ($|S_{21}| - |S_{31}|$) at 3 GHz. (a) $|S_{11}|$ and $|S_{41}|$. (b) $|S_{21}|$ and $|S_{31}|$. (c) Phase differences.

Table 2: Comparisons of measured results for reported quadrature couplers.

Ref.	Configuration	Tuning elements	Tuning elements number	Range (GHz)	Power-dividing ratio	Phase imbalance	Size ($\lambda g \times \lambda g$)
[2]	Single layer	RF MEMS	4	1.5-2.2 (38%) (RL >14 dB)	Fixed	< 1°	0.23 × 0.18
[8]	0.13 μm SiGe	Varactor	2	Fixed at 28 GHz (RL > 20 dB)	0 dB–6.5 dB	< 2.5°	0.18 × 0.038
[11]	Single layer	Varactor	6	1.8-4.36 (83%) (RL > 20 dB)	-16 dB–5 dB at 3 GHz	< 5°	0.2 × 0.09
[12]	Single layer	Varactor	8	1.2-2.4 (67%) (RL > 15 dB)	0 dB–12 dB at 1.5 GHz	< 5°	0.11 × 0.13
This work	Single layer	Varactor	6	2.0-4.7 (81%) (RL > 15 dB)	-14 dB–6 dB at 3 GHz	< 5°	0.22 × 0.07

λg is the guided wavelength at the lowest tuning frequency. RL represents the return loss. MEMS represents the micro-electro-mechanical system.

better than 20 dB. Correspondingly, the return-loss bandwidth is greater than 100 MHz at this center frequency. Moreover, the phase difference between the simulated and measured coupler is shown in Figures 10(c) and 11(c). The measured phase imbalances at each state are less than 5°.

4.3. Comparison. A performance comparison between this fabricated tunable quadrature coupler and the quadrature couplers reported in the literature, is given in Table 2. It should be noted that the tunable frequency and power ratio of the coupler in [12] are realized by more than 8 tunable elements. And compared with a coupler in [11], the performance of the proposed quadrature coupler is basically the same, but the proposed coupler is smaller in size and easier to analyze. As shown in Table 2, this tunable quadrature coupler offers a tunable frequency, a tunable power-dividing ratio, and a compact size.

5. Conclusion

A compact quadrature coupler with wide tunable frequency and a power-dividing ratio is achieved by using the novel tunable unit to replace the transmission line sections in traditional varactor-based quadrature couplers. Closed-form equations are derived for design parameters. In order to verify the quadrature coupler that has a tunable frequency and tunable power-dividing ratio, the coupler with only three types of varactor is designed and fabricated. Good isolation and return loss are obtained for all states.

Data Availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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