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Miniaturized Coplanar Waveguide to Rectangular Waveguide Transition Using Integrated Resonators and Variable Housing

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ABSTRACT: In this paper, a miniaturized coplanar waveguide (CPW) to rectangular waveguide (RGW) transition using integrated resonators and variable housing is proposed. By properly designing the dimensions of the integrated resonators and variable housing, a compact and broadband transition can be accomplished. The −15-dB fractional bandwidth of the transition is as broad as 45.2%, which ranges from 8.21 GHz to 13 GHz, covering the whole X-band (8.2–12.4 GHz). Besides, the transition size is as small as 3.94 mm. To reduce the mechanical complexity, the housing height is from 24.5 mm to 22.86 mm, which is equal to the height of the rectangular waveguide. The −15-dB fractional bandwidth of the transition is as broad as 45.5%, which ranges from 8.18 GHz to 13 GHz, encompassing the whole X-band. Besides, the transition size is still as small as 3.94 mm. To verify the simulations, a back-to-back CPW-to-RWG transition is fabricated and measured. The simulation and measurement results are in good agreement.

1. INTRODUCTION

In communication engineering, planar transmission lines and waveguides are both important transmission structures. Waveguides have the characteristics of low loss and high-power capability, so they prevail in military, weather monitoring, and satellite communications that require high power and high frequency. Since they are larger and weightier than planar transmission lines, their application is limited. On the contrary, planar transmission lines are cost-effective and easy to produce. To take advantage of planar transmission lines and waveguides, integrating both of them becomes an indispensable issue.

In the past, many scholars have discussed a variety of coplanar waveguide (CPW) to rectangular waveguide (RWG) transitions [1–11]. In 1990, Ponchak and Simons utilized a ridge waveguide to implement a broadband coplanar waveguide to rectangular waveguide transition [1]. The ridge waveguide was used to progressively convert coplanar waveguide mode into rectangular waveguide TE_{10} mode. The disadvantage is that it is difficult in machining, and the transition is bulky.

Alternatively, some scholars proposed coplanar waveguide to rectangular waveguide transitions with planar circuits that are portable and easy to manufacture [2–11]. Quasi-Yagi antenna was recommended as one candidate for the transition [2]. Other scholars proposed tapered slotline probe as another choice for the transition [3, 4]. This transition uses a taper to progressively convert the CPW mode into TE_{10} mode of the rectangular waveguide. Besides, some scholars proposed finline taper as an alternative for the transition [5]. However, these structures have a large size. To reduce the size, some scholars used an inductance-compensated slotline to miniaturize the coplanar waveguide to rectangular waveguide transition [6, 7]. However, these transitions require a relay circuit.

To eliminate the need of relay circuits, some scholars proposed coplanar waveguide to rectangular waveguide transitions that do not require a relay circuit. Therefore, a transition with a probe structure was proposed [8], and others proposed a transition with a stub resonator [9]. The advantage is that it can directly convert the CPW mode into the TE_{10} mode of the rectangular waveguide. Besides, some scholars have proposed a transition with E-plane probes at U-band [10]. This transition can be used in microwave integrated circuits, but its disadvantage is that the bandwidth is narrow. Some scholars have also proposed a transition with a patch antenna at D-band [11]. However, the bandwidth is still limited.

In modern communication systems, a compact and broadband CPW-to-RWG transition is demanded as a compact transition can save the cost, and a broadband transition can enhance the performance. To achieve a compact and broadband transition, this paper proposes a coplanar waveguide to rectangular waveguide transition using integrated resonators and variable housing. Compared with the coplanar waveguide to rectangular waveguide transition using the resonator with impedance matching element [7], the impedance matching element is now placed underneath the resonator, and the inductance-compensated phase shifter is replaced with a short-circuited stub to reduce the circuit size. Consequently, the transition size can have a significant reduction of 35%. To compensate the size reduction, the housing of the coplanar waveguide should be properly designed to provide the reduced electrical length of the transition size.

The paper is outlined as follows. Section 1 introduces the literature surveys of the coplanar waveguide to rectangular waveguide transitions. Section 2 describes the details of the

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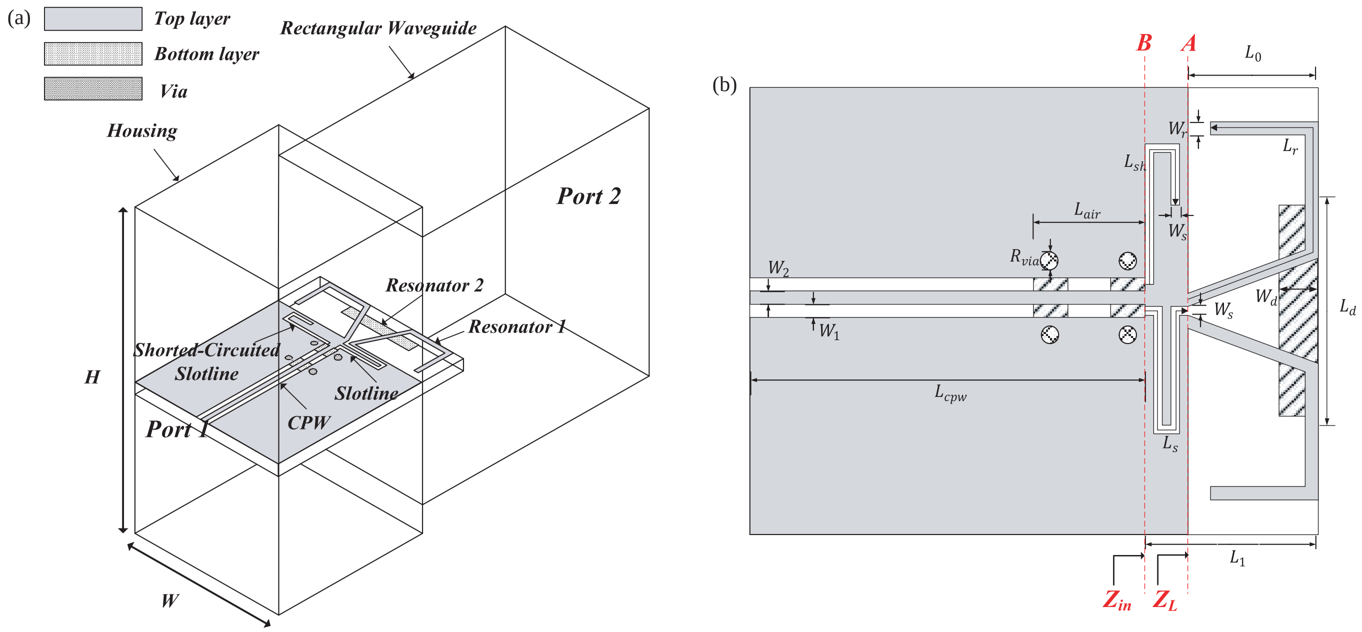

FIGURE 1. The schematic view of the CPW-toRWG transition using the integrated resonators and variable housing. (a) 3D view. (b) Planar view.

coplanar waveguide to rectangular waveguide transition using the integrated resonators and variable housing. Section 3 concludes the paper.

2. COPLANAR WAVEGUIDE TO RECTANGULAR WAVEGUIDE TRANSITION USING RESONATORS AND VARIABLE HOUSING

2.1. Topology

The schematic view of the coplanar waveguide to rectangular waveguide transition using integrated resonators and variable housing is shown in Fig. 1. As can be seen from Fig. 1(a), the transition is fed through a coplanar waveguide (CPW), which is packaged in a metal housing with a housing height of L and housing width of W. The housing width W is chosen to be 10.16 mm, equal to the width of the rectangular waveguide. The housing height H is a design variable, which will be determined later. The two ground planes of the coplanar waveguide are connected with vias to eliminate the coupled slotline mode of the coplanar waveguide. One slotline of the coplanar waveguide is terminated with a short-circuited slotline, and the other slotline transfers the energy of the coplanar waveguide into the integrated resonators 1 and 2. Then, the integrated resonators 1 and 2 couple their energy into the rectangular waveguide. The rectangular waveguide is WR-90 (22.86 mm × 10.16 mm), which ensures that only TE_{10} mode propagates in the X-band (8.2–12.4 GHz).

The planar circuit, which consists of the coplanar waveguide, short-circuited slotline, and integrated resonators, is placed in the E-plane of the rectangular waveguide. Fig. 1(b) displays the top view of the planar circuit, which is implemented by a Rogers® RO5880 substrate, having a relative dielectric constant of 2.2, loss tangent of 0.0009, and thickness of 0.79 mm. The coplanar waveguide has a characteristic impedance value of 107 Ω. The dimensions of the 107-Ω CPW can be obtained by using ADS LineCalc where the width of the center line is $W_2 = 0.3$ mm, and the width of the slot is $W_1 = 0.3$ mm at the center frequency 10.3 GHz. The length of the CPW is $L_{cpw} = 9.16$ mm. The dimensions of the vias are $L_{air} = 2.6$ mm and $R_{via} = 0.4$ mm

2.2. Planar Circuit Determination

Considering Fig. 1, to cover the bandwidth of the X-band (8.2–12.4 GHz), the length of resonator 1 is determined to be $L_r = 9.1$ mm, which corresponds to a quarter-wavelength resonance of 8.6 GHz, and the length of resonator 2 is determined to be $L_d = 4.8$ mm, which corresponds to a half-wavelength resonance of 11.6 GHz [7]. The width of resonator 1 is determined to be $W_r = 0.3$ mm and the width of resonator 2 determined to be $W_d = 0.9$ mm. The input impedance Z_L looking into the integrated resonators can be calculated as $Z_L = 127.94 - j76.41\,\Omega$ at the center frequency 10.3 GHz by using Ansoft HFSS.

To facilitate the design process, the equivalent circuit of the coplanar waveguide to rectangular waveguide transition using the integrated resonators and variable housing shown in Fig. 1 is depicted in Fig. 2. The coplanar waveguide is represented by an ideal transmission line having a characteristic impedance Z. The short-circuited slotline is represented by a short-circuited transmission line having a characteristic impedance of Z_s and an electrical length of θ_{sh}. The other slotline is replaced by an ideal transmission line having a characteristic impedance of Z_s and an electrical length of θ_s. The input impedance looking into the integrated resonators (plane A) is denoted by Z_L while the input impedance looking into the slotline (plane B) is denoted by Z_{in}.

Reconsidering the equivalent circuit shown in Fig. 2, the dimensions of the short-circuited slotline and the other slotline

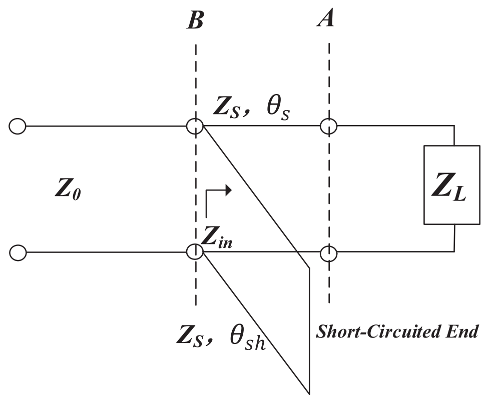

FIGURE 2. The equivalent circuit of the CPW-to-RWG transition using the integrated resonators and variable housing.

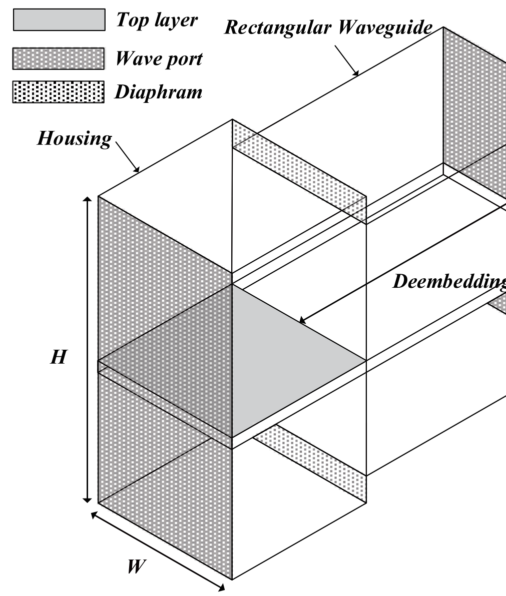

FIGURE 3. Schematic view of the variable housing.

can be determined through the following process. According to the reference book [12], the input impedance Z_{in} can be written as

$$Z_{in} = Z_s \frac{(R_L + jX_L) + jZ_s \tan\theta_s}{Z_s + j(R_L + jX_L)\tan\theta_s} \tag{1}$$

where $Z_L = R_L + jX_L$. The input impedance Z_{in} can be converted into the input admittance $Y_{in} = 1/Z_{in} = G + jB$ where the real part G and imaginary part B of the input admittance Y_{in} are described by (2) and (3).

$$G = \frac{R_L(1 + \tan\theta_s^2)}{R_L^2 + (X_L + Z_s \tan\theta_s)^2} \tag{2}$$

$$B = \frac{R_L^2 \tan\theta_s - (Z_S - X_L \tan\theta_s)(X_L + Z_s \tan\theta_s)}{Z_s \left[R_L^2 + (X_L + Z_s \tan\theta_s)^2\right]} \tag{3}$$

Since the admittance must be matched at plane B, the real part G of the input admittance Y_{in} should be equal to $1/Z$, and the imaginary part B of the input admittance Y_{in} should be equal to the negative value of the input admittance of the short-circuited slotline $\cot\theta_{sh}/Z_s$. By letting $G = 1/Z_0$ in (2), the electrical length of the slotline θ_s can be solved as described by (4). By substituting the solved electrical length of the slotline θ_s into (3), the imaginary part B can be obtained. By letting $B = \cot\theta_{sh}/Z_s$, the electrical length θ_{sh} of the short-circuited slotline can be solved as described by (5).

$$\theta_s = \tan^{-1}\left(\frac{2X_L Z_s \pm \sqrt{(-2X_L Z_s)^2 - 4(R_L Z_0 - Z_s^2)(R_L Z_0 - R_L^2 - X_L^2)}}{2(R_L Z_0 - Z_s^2)}\right) \tag{4}$$

$$\theta_{sh} = \tan^{-1}\left(\frac{1}{BZ_s}\right) \tag{5}$$

Given the input impedance looking into the integrated resonators $Z_L = 127.94 - j76.41\,\Omega$, the characteristic impedance of coplanar waveguide $Z = 107\,\Omega$, and the characteristic impedance of slotline or short-circuited slotline $Z_s = 108\,\Omega$ ($W_s = 0.2$ mm), the electrical lengths of the slotline and the short-circuited slotline can be solved for ($\theta_s = 134.8°$, $\theta_{sh} = 124.6°$) or ($\theta_s = 152.1°$, $\theta_{sh} = 88°$) through (3)–(5). The electrical lengths ($\theta_s = 134.8°$, $\theta_{sh} = 124.6°$) are implemented as they will result in a broader bandwidth than the electrical lengths ($\theta_s = 152.1°$, $\theta_{sh} = 88°$). Considering the discontinuity and coupling effects, the electrical length $\theta_s = 134.8°$ of the slotline is implemented with a slotline of length $L_s = 6.8$ mm, and the electrical length $\theta_{sh} = 124.6°$ of the short-circuited slotline is implemented with a slotline of length $L_{sh} = 5.2$ mm.

2.3. Housing Height Determination

Reconsidering the coplanar waveguide to rectangular waveguide transition using the integrated resonators and variable housing shown in Fig. 1, since resonator 2 should be placed a quarter-wavelength away from the junction between the coplanar waveguide housing and the rectangular waveguide for maximum power transfer [13], the rectangular waveguide of length

TABLE 1. Dimensions of the CPW-to-RWG transition using the integrated resonators and variable housing (unit: mm).

L_s	L_{sh}	W_s	L_r	W_r	L_d	W_d	L	L_1
6.8	5.2	0.2	9.1	0.3	4.8	0.9	2.94	3.94

TABLE 2. Dimensions of the adjusted CPW-to-RWG transition using the integrated resonators and variable housing (unit: mm).

L_s	L_{sh}	W_s	L_r	W_r	L_d	W_d	L	L_1
6.8	5.2	0.2	8.55	0.3	5.2	0.7	2.94	3.94

L should provide an electrical length of $90°$. However, the rectangular waveguide of length $L = 29.4$ mm could only provide an electrical length of $40°$ at the resonance frequency 116 GHz of resonator 2. Therefore, an additional electrical length of $50°$ is required. It is discovered that the housing of the microstrip line will have a significant influence on the performance of the microstrip line to rectangular waveguide transition [13]. Therefore, the housing of the coplanar waveguide shown in Fig. 3 can be used to provide the required electrical length of $50°$ without increasing the physical length L of the rectangular waveguide. By determining the housing height as $H = 24.5$ mm, the housing of the coplanar waveguide shown in Fig. 3 is simulated and deembedded by Ansoft HFSS. The simulated electrical length looking into the junction between the housing and the rectangular waveguide is $47.5°$, which is close to $50°$ as required. Table 1 summarizes the dimensions of the coplanar waveguide to rectangular waveguide transition using the integrated resonators and variable housing. It is worth mentioning that if the housing height $H = 10.16$ mm was chosen as the conventional transitions [3, 4, 6, 7, 9, 13], the performance of the transition would significantly deteriorate.

2.4. Frequency Response

To capture the frequency responses of the reflection and transmission coefficients for the coplanar waveguide to rectangular waveguide transition using the integrated resonators and variable housing, the coplanar waveguide to rectangular waveguide transition using the integrated resonators and variable housing shown in Fig. 1 along with the dimensions listed in Table 1 is simulated by Ansoft HFSS. The frequency responses of the reflection and transmission coefficients are shown in Fig. 4. As can be seen from Fig. 4, the reflection coefficient is smaller than -15 dB from 8.21 GHz to 13 GHz, amounting to a fractional bandwidth of 45.2%, and the transmission coefficient is larger than -0.16 dB in this frequency range. The overall length L_1 of the transition is as compact as 394 mm, which has a 2 mm reduction compared to the transition using the resonator with an impedance-matching element [7].

To reduce the mechanical complexity, the housing height is reduced from 24.5 mm to 22.86 mm, which is equal to the height of the rectangular waveguide. Therefore, the housing and rectangular waveguide are now of the same dimensions as shown in Fig. 5. To compensate the reduction of housing height H, the dimensions of resonators 1 and 2 are slightly adjusted. The dimensions are summarized in Table 2. To capture the frequency responses of the reflection and transmission coefficients for the coplanar waveguide to rectangular waveguide transition using the integrated resonators and variable housing, the coplanar waveguide to rectangular waveguide transition using the integrated resonators and variable housing shown in Fig. 5 along with the dimensions listed in Table 2 is simulated by Ansoft HFSS. The frequency responses of the reflection and transmission coefficients are shown in Fig. 6. As can be seen from Fig. 6, the reflection coefficient is smaller than -15 dB from 8.18 GHz to 13 GHz, amounting to a fractional bandwidth of 45.5%, and the transmission coefficient is larger than -0.16 dB

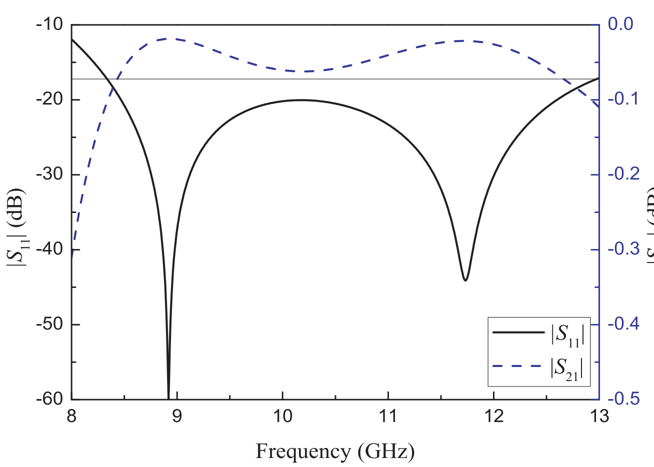

FIGURE 4. The frequency responses of the reflection and transmission coefficients for the CPW-to-RWG transition using the integrated resonators and variable housing.

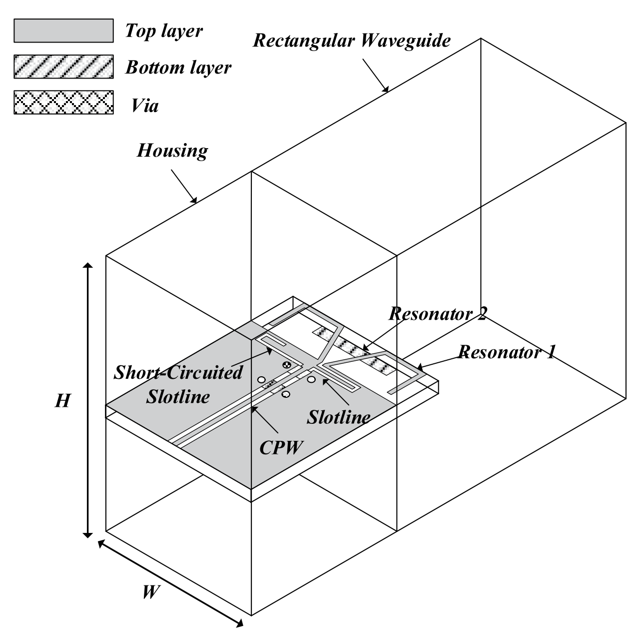

FIGURE 5. The adjusted CPW-to-RWG transition using the integrated resonators and variable housing.

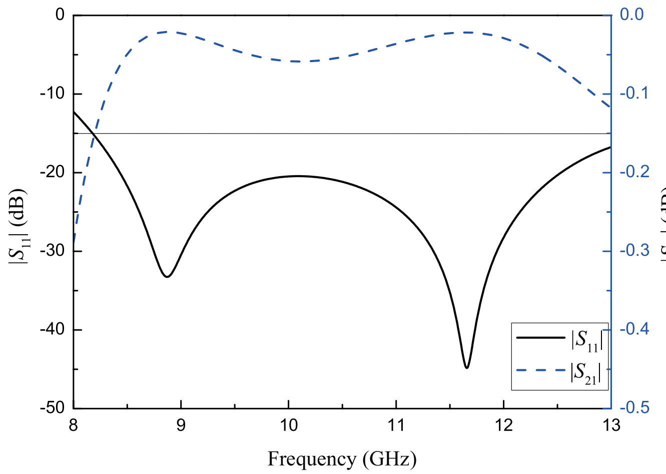

FIGURE 6. The frequency responses of the reflection and transmission coefficients for the adjusted CPW-to-RWG transition using the integrated resonators and variable housing.

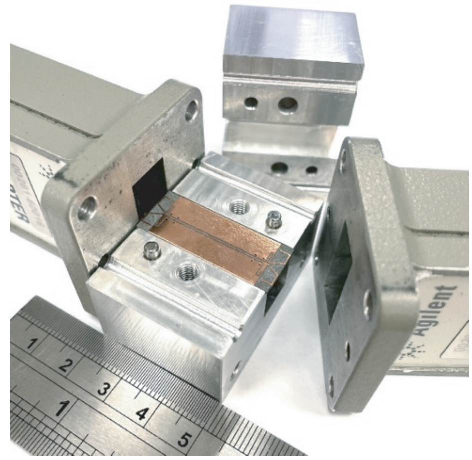

FIGURE 7. The photograph of the back-to-back CPW-to-RWG transition using the integrated resonators and variable housing.

TABLE 3. Performances of the State-of-the-Art CPW-to-RWG transitions.

Transition Type	Operational Band	Circuit Length	15 dB FBW (%)
Tapered slotline probe [3]	X-band	0.45λ	43.06
Fin-line taper [5]	X-band	0.48λ	40.78
Inductance-compensated slotline [6]	X-band	0.28λ	40.78
Resonator with impedance-matching element [7]	X-band	0.20λ	42.38
Electric probe [8]	X-band	0.53λ	40.80
Stub resonators [9]	X-band	0.28λ	42.20
E-plane probe [10]	U-band	0.30λ	40.00
This Work	X-band	$\mathbf{0.13\lambda}$	**45.50**

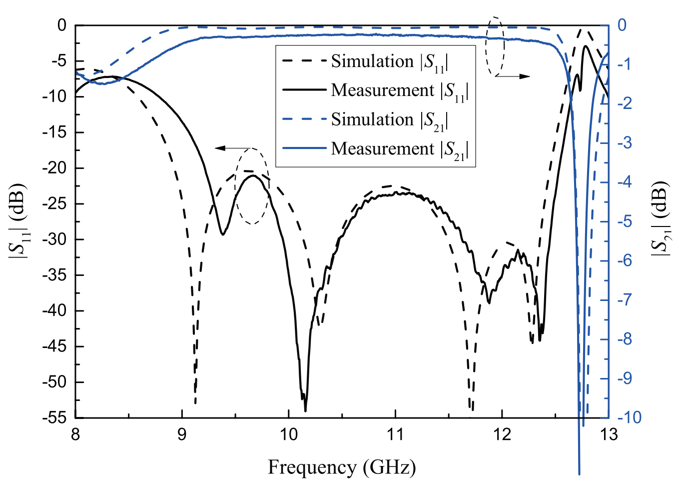

FIGURE 8. The comparison between the simulation and measurement results for the back-to-back CPW-to-RWG transition using the integrated resonators and variable housing.

in this frequency range. The overall length L_1 of the transition is as compact as 3.94 mm.

2.5. Verification

To verify the simulation results, two coplanar waveguide to rectangular waveguide transitions using integrated resonators and variable housing are connected back-to-back and fabricated as shown in Fig. 7. The planar circuit is placed on the E-plane of the rectangular waveguide WR-90. The length of the coplanar waveguide is 23 mm. The back-to-back transition shown in Fig. 7 is then measured with the Agilent N5242A PNA after calibrating the equipment with the Aglient X11644A calibration kit. The measured reflection and transmission coefficients are shown in Fig. 8. Also shown in Fig. 8 are the simulated reflection and transmission coefficients for the back-to-back transition. As can be seen from Fig. 8, the simulation and measurement results are in good agreement.

3. CONCLUSION

In modern communication systems, a coplanar waveguide (CPW)-to-rectangular waveguide (RWG) transition is required to integrate the CPW and RWG microwave components. However, the substrate used in the transition is expensive, and the housing adopted in the transition adds to the cost. To save the cost, the substrate used in the transition should be as compact as possible. To achieve this goal, a coplanar waveguide to rectangular waveguide transition using the integrated resonators and variable housing is proposed. By utilizing the integrated resonators and short-circuited slotline, the transition size can be as compact as 3.94 mm, equal to 0.13λ, which is much smaller than the size 0.20λ of the up-to-date CPW-to-RWG transition [7]. By properly designing the height of the housing, an additional electrical length can be provided without increasing the physical length of the substrate. The -15 dB reflection coefficient of the transition covers 8.21 GHz to 13 GHz, amounting to a fractional bandwidth of 45.2% and exceeding the whole X-band (8.2–12.4 GHz). The transmission coefficient is larger than -0.16 dB in this frequency range. To further save the cost, the housing is adjusted to the same dimensions as the rectangular waveguide. As a result, no additional cost is required for fabricating the specific housing of the conventional transitions [3, 4, 6, 7, 9, 13]. The adjusted coplanar waveguide to rectangular waveguide transition using the integrated resonators and variable housing is still as compact as 3.94 mm. The -15 dB reflection coefficient of the transition covers 8.18 GHz to 13 GHz, amounting to a fractional bandwidth of 45.5% and exceeding the whole X-band (8.2–12.4 GHz). The transmission coefficient is larger than -0.16 dB in this frequency range. To verify the simulation results, a back-to-back coplanar waveguide to rectangular waveguide transition using integrated resonators and variable housing is fabricated and measured. The measurement result is in good agreement with the simulation one. Table 3 summarizes the performance of the state-of-the-art CPW-to-RWG transitions. As can be seen from Table 3, the transition of this work has the smallest size of 0.13λ and the broadest -15-dB bandwidth of 45.5% Furthermore, as the housing is of the same dimension as the rectangular waveguide, no additional cost is required to fabricate a specific housing for the transition.

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