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A W-Band Waveguide-to-Suspended Stripline In-Line Transition with Single-Side Fin-Line

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ABSTRACT: A novel full W-band in-line waveguide-to-suspended stripline transition based on reversed single-sided fin-line structure is proposed. To achieve wideband mode conversion and impedance matching, a combination of an asymmetric antipodal fin-line and a reversed single-sided fin-line structure is employed. The electromagnetic (EM) wave undergoes a mode transition from TE_{10} mode to quasi-parallel plate waveguide (Q-PPW) mode through the asymmetric antipodal fin-line. Subsequently, the mode transforms into suspended stripline mode due to the reversed single-side fin-line structure. The proposed in-line transition achieves a wide bandwidth through a simplified structural design. To assess the performance of the proposed design, a back-to-back in-line transition operating at the W-band is fabricated and measured. The measured results of the back-to-back structure demonstrate that the reflection coefficient is better than -13 dB, and the insertion loss is less than 0.54 dB across the entire W-band (75–110 GHz). The advantages of the proposed transition, such as wide bandwidth and simple structure, render it highly promising for advanced millimeter-wave circuits and systems.

1. INTRODUCTION

Rectangular waveguide is widely recognized as a high-performance transmission line suitable for millimeter-wave and terahertz systems, owing to its advantageous characteristics such as low loss and high power-handling capability. On the other hand, stripline serves as a crucial transmission line in microwave systems. However, as the operating frequency increases, stripline exhibits increased loss, posing challenges to their performance. As a solution, suspended stripline has been developed as an improved alternative to traditional stripline [1]. Smooth transitions between rectangular waveguides and suspended stripline play a vital role in achieving seamless integration between different transmission media, which is often used in millimeter-wave and terahertz system such as mixer [2, 3], multiplier [4], filter [5], and other related components. These transitions enable efficient and reliable signal transfer between the rectangular waveguide and suspended stripline, ensuring the continuity and optimal performance of the overall system.

In the past few decades, numerous waveguides-to-suspended stripline transitions have been proposed. Among them, E-plane probe-type transition has gained significant popularity [6–11]. This transition design utilizes a printed probe to facilitate the coupling of energy between the waveguide and suspended stripline. The E-plane probe-type transition is well regarded for its advantages, including low insertion loss, wide operating bandwidth, and a relatively simple structure. However, it is important to highlight that the widely used E-plane probe-type waveguide-to-suspended transition features perpendicular input and output ports. This configuration imposes limitations in applications where an in-line arrangement is desired. To overcome this limitation, an inline waveguide to suspended stripline transition is designed based on unilateral fin-line as described in [12]. This transition efficiently converts the input TE_{10} mode of the waveguide to suspended stripline TEM mode across a wide frequency range. However, the insertion loss is compromised due to the significant radiation loss of the slot line within the transition. Additionally, the design structure is complex, adding complexity to the implementation. An in-line waveguides-to-suspended stripline transition based on a fin-line structure has been developed in [13]. A microstrip line (MSL) is employed as an intermediate transition between the waveguide and suspended stripline. However, it should be noted that the proposed design exhibits a complex structure with small fractional bandwidth (24%), which can make it challenging to design and less practical in certain applications.

In this paper, we introduce a novel in-line waveguide-to-suspended stripline transition over the full W-band. An asymmetric antipodal fin-line and a reversed single-sided fin-line structure are used to achieve mode conversion and impedance match during wide frequency range. To assess the performance of the proposed design, a back-to-back in-line transition is fabricated operating at the W-band. The measured results demonstrate that the reflection coefficient is better than -13 dB, and the insertion loss is less than 0.54 dB across the entire W-band (75–110 GHz). The proposed transition offers advantages including wide bandwidth and simple structure.

2. TRANSITION BASE ON IMPROVED ANTIPODAL FIN-LINE STRUCTURE

2.1. Structure and Operating Principle of the Transition

The proposed in-line waveguide-to-suspended stripline transition is depicted in Figure 1. The structure incorporates a taper

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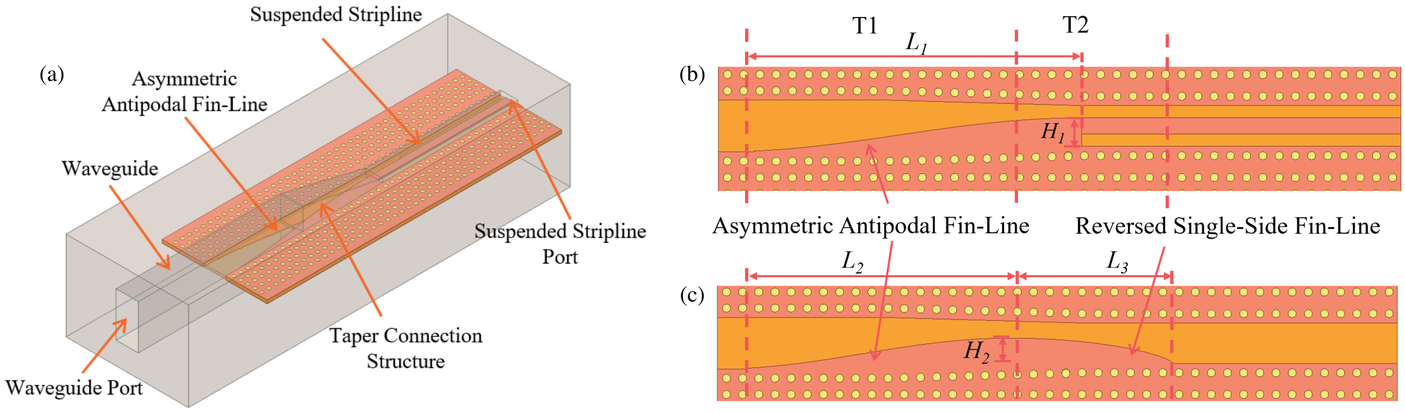

FIGURE 1. Structure of the proposed In-Line Waveguide-to-Suspended stripline Transition. (a) Three-dimensional mode of the transition structure. (b) Top view of the PCB. (c) Bottom view of the PCB.

connection structure and a combined fin-line structure printed on a printed circuit board (PCB) substrate. The taper connection structure serves as a continuous connection between the waveguide and the suspended stripline shielding structure. The length of the taper connection is denoted as T_L. The combined fin-line structure comprises two components, the former asymmetric antipodal fin-line structure and the later reversed single-side fin-line structure which are presented as T1 and T2 in Figures 1(b) and 1(c). The former asymmetric antipodal fin-line structure consists of two smooth curve structures with opposite directions, positioned on the upper and bottom layers, respectively. The later reversed single-side fin-line structure consists of a single smooth curve structure on the side of bottom layer, accompanied by the step connection between antipodal fin-line and suspended stripline on the top layer.

The operating principle of the proposed in-line waveguide-to-suspended stripline transition can be explained by mode conversion and impedance match. The proposed transition employs an asymmetric antipodal fin-line combined with a reversed single-sided fin-line, utilizing a Q-PPW as the intermediate transition structure. The reversed single-sided fin-line, equal in height to the shorter asymmetric antipodal fin-line, is directly connected to it. This combined structure partially lies beneath the elongated fin-line and partially beneath the central conductive strip of the suspended stripline, forming a Q-PPW. Mode conversion from the waveguide to the Q-PPW is facilitated by the asymmetric antipodal fin-line, while conversion from the Q-PPW to the suspended stripline is achieved by the reversed single-sided fin-line gradually diverges from the central strip and connects to the enclosure's side wall. The electric field (E-field) conversion process of the waveguide-to-suspend stripline transition is shown in Figure 2. The E-field structures for these cross-sections, as presented in Figure 2, have been redrawn based on the field results obtained from the simulation software. Notably, all simulated results and E-field distributions in this article are obtained using the ANSYS High Frequency Structure Simulator (HFSS). The E-field distribution from points A to G in Figure 2 demonstrates the mode transition from the waveguide to the suspended stripline. The simulated E-field patterns for the proposed transition are presented in Figure 3, where the mode conversion process can be further observed. Due to the graded structure of the asymmetric antipodal fin-line, broadband impedance matching can be effectively achieved from the high characteristic impedance of the waveguide to the lower characteristic impedance of the Q-PPW. To achieve optimal impedance matching, as represented in Equation (1), the profile of the asymmetric antipodal fin-line follows a sine-squared function. The contour of the asymmetric antipodal fin-line is derived from the first quarter cycle of this function. Calculations show that the slope of the sine-squared function is zero at the starting point, aligning it parallel to the waveguide edge. As the distance increases, the slope becomes zero again at the end of the quarter cycle. This characteristic is also evident in Figure 2(a). Consequently, this function enables a smooth transition between the waveguide and the centerline of the suspended stripline, as well as the reversed single-sided fin-line. According to the properties of Q-PPWs, at a separation distance of 0.127 mm,

$$\begin{cases} H^* \sin^2\left(\dfrac{x}{2*L}\right) & 0 < x < L*\pi \\ H_2^* \sqrt{\sin\left(\dfrac{x}{2*L_3}\right)} & L_3*\pi < x < 2L_3*\pi \end{cases} \tag{1}$$

Q-PPW within the W band is capable of transmitting only TEM mode EM waves [14]. Before transitioning to the suspended stripline, as the width of the quasi-Q-PPW changes and the height of the taper varies, the characteristic impedance gradually decreases with increasing distance, eventually reaching approximately 50 ohms. Given that the parallel plate transmission mode is a TEM mode and its characteristic impedance value closely aligns with that of the suspended stripline, the transition does not need to be excessively long. The contour of the reversed single-sided fin-line is determined by selecting a 1/4 to 1/2 period of the sine-root function, as shown in Equation (1). Additionally, calculations indicate that the slope of the function is zero at the starting point, allowing for a smooth connection with the antipodal fin-line in this design. The characteristic impedance of each section is depicted in Figure 4. The characteristic impedance is simulated in High Frequency Structure

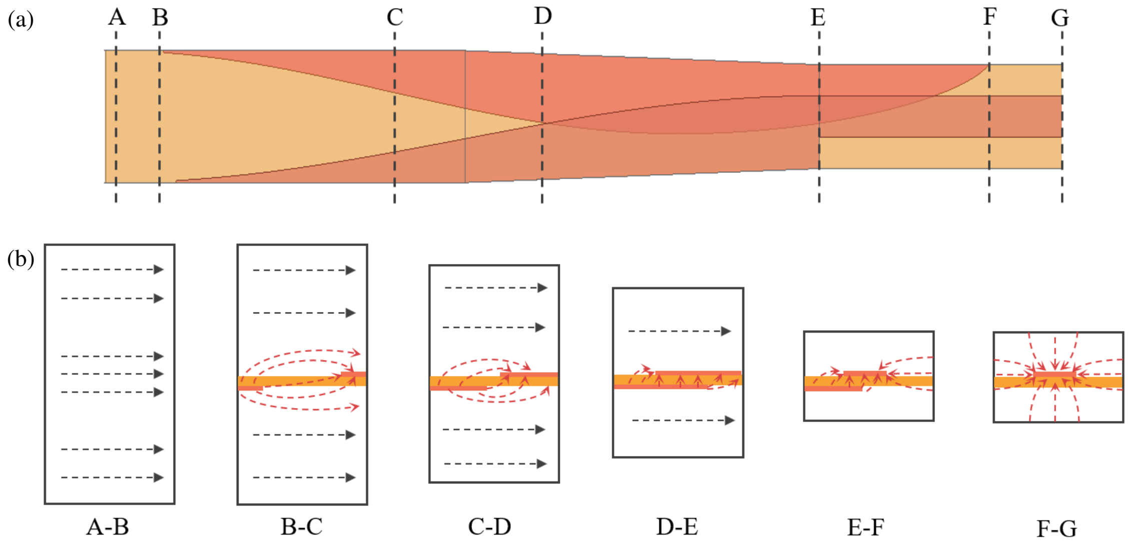

FIGURE 2. E-field conversion process of the waveguide-to-suspend stripline transition. (a) Position of the conversion process. (b) E-field distribution during the conversion process.

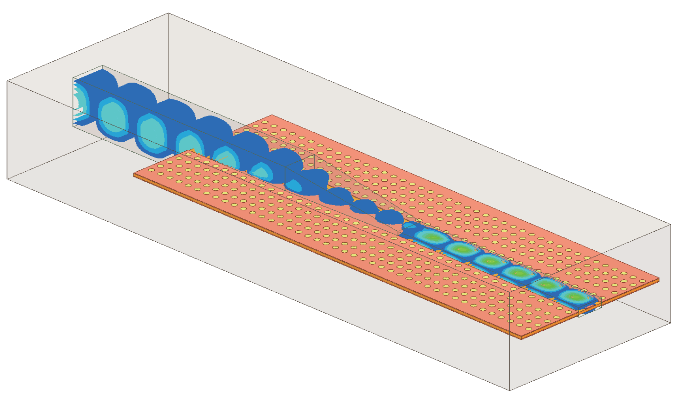

FIGURE 3. Simulated E-field distribution of the proposed transition.

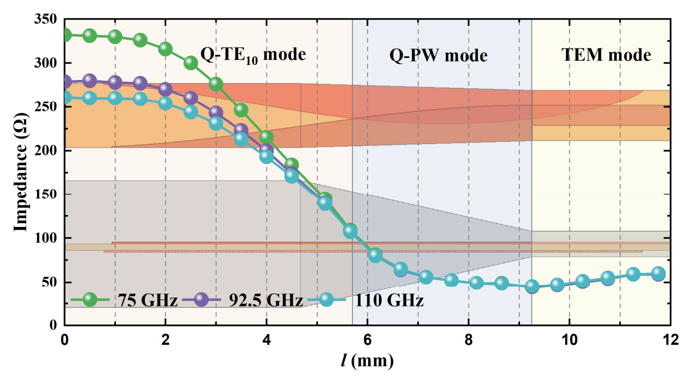

FIGURE 4. Simulated characteristic impedance of different cross sections.

Simulator (HFSS) by splitting the transition and setting wave ports in the section. By scanning the section position along length, all characteristic impedances can be obtained. Figure 4 demonstrates that the proposed transition effectively achieves impedance matching between the waveguide and the suspended stripline across a broad frequency range.

To provide a deeper understanding of the underlying principles of this design, the design steps of the proposed transition are presented in Figure 5. Different from MSL, a suspended stripline lacks a ground metal layer, necessitating the removal of the metal layer on the side where the antipodal fin-line is introduced. Typically, the MSL mode is employed as an intermediate transition mode, using metal on the side that needs to be removed as the ground plane for the MSL, withdrawing symmetrically to both sides, as illustrated in Figure 5(a). While this structure facilitates mode conversion from waveguide to suspended stripline, it exhibits a relatively narrow bandwidth, as simulation results provided in Figure 6 and [12]. The proposed design employs a reversed single-sided fin-line to enable the removal of one side of the antipodal fin-line, thereby achieving mode conversion. In this configuration, a reversed single-sided fin-line is directly connected to one side of the antipodal fin-line. As depicted in Figure 5(b), the overlapping region between the antipodal fin-line and reversed single-sided fin-line forms a Q-PPW, which enhances impedance matching and broadens the operational bandwidth of the transition, as evidenced by the simulation results in Figure 6. However, the introduction of the reversed single-sided fin-line creates a metal groove between the metal layer and the side of the enclosure. This groove can raise EM waves resonance, with resonant frequencies determined by the groove's width. Some of these resonant frequencies may fall within the desired frequency band, thus affecting the overall bandwidth, as shown in Figure 6. The simulated E-field distribution at these resonant frequencies is presented in Figure 5(b). To address this issue, as illustrated in Figure 5(c), the antipodal fin-line on the upper side was extended, positioning the Q-PPW, formed by the asymmetric antipodal fin-line and the reversed single-sided fin-line, at a more oblique angle, distancing it from the resonant metal wall. Sim-

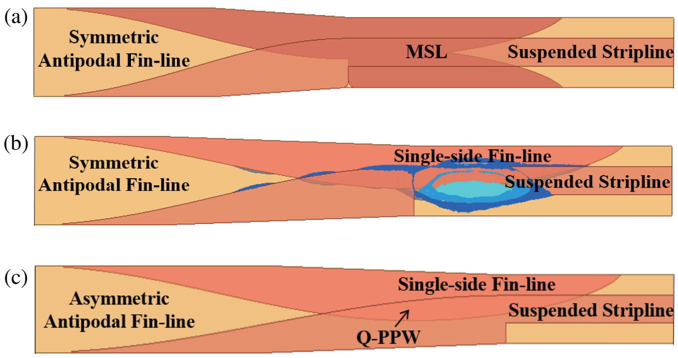

FIGURE 5. Design step of the proposed transition. (a) MSL intermediate transition. (b) Symmetric fin-line transition. (c) Proposed.

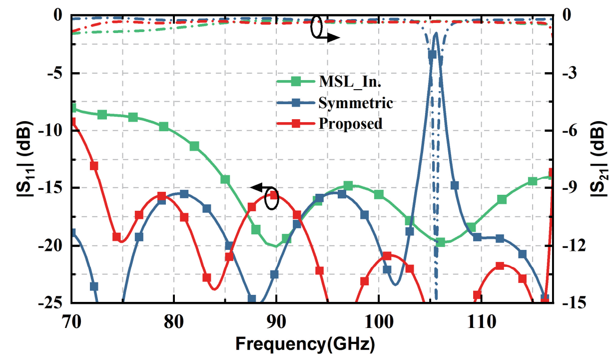

FIGURE 6. Simulation results of the waveguide-to-suspended stripline transition.

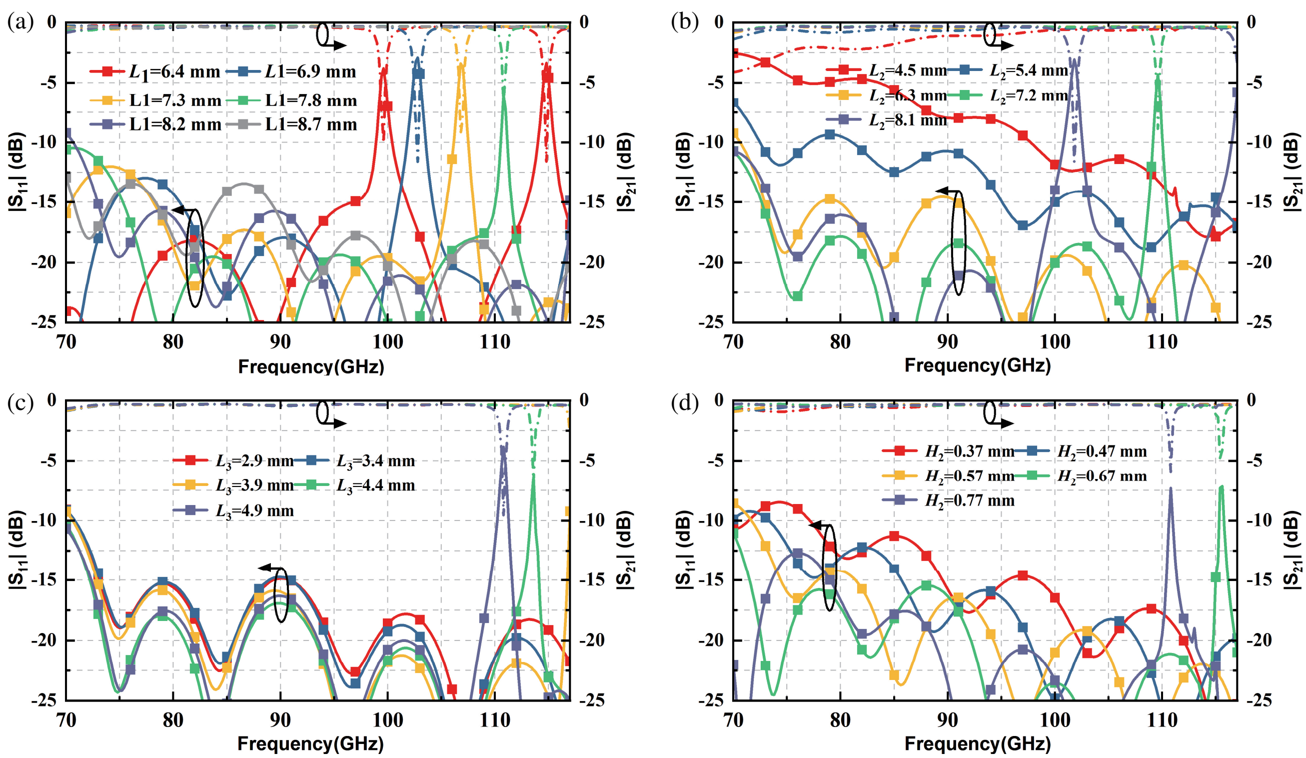

FIGURE 7. Simulated results. (a) Length of upper side antipodal fin-line. (b) Length of lower side antipodal fin-line. (c) Length of the reversed singleside fin-line. (d) Width of the reversed single-side fin-line.

ulation results in Figure 6 indicate that this configuration effectively suppresses the resonance point.

2.2. Design and Simulation

To validate the performance of the proposed in-line waveguide-to-suspended stripline transition, simulations are conducted. The implementation utilizes WR-10 waveguide and an RT/Duroid5880 substrate with a thickness of 0.127 mm and a dielectric constant (ε_r) of 2.2.

In Equation (1), variables H and L denote the height and length of the asymmetric antipodal fin-line structure, corresponding to H_1 or H_2 and L_1 or L_2 as depicted in Figure 1. The simulation results for asymmetric antipodal fin-line structures of varying lengths and widths, presented in Figures 7(a) to 7(b), demonstrate their impact on impedance matching and bandwidth performance. Adjusting the length of the upper-side antipodal fin-line (Figure 7(a)) shows that increasing the length shifts resonance points to higher frequencies and broadens bandwidth, but excessively long lengths degrade impedance matching at low frequencies. Conversely, changes to the lower-side antipodal fin-line length (Figure 7(b)) initially improve impedance matching across the frequency band and expand bandwidth, but excessive lengths introduce resonance points. For the reversed fin-line length (Figure 7(c)), variations have little effect due to minor characteristic impedance differences between the Q-PPW and suspended stripline; however, longer lengths decrease the distance between the Q-PPW and metal slot, causing resonance. Similarly, increasing the width of the reversed single-side fin-line (Figure 7(d)) improves impedance

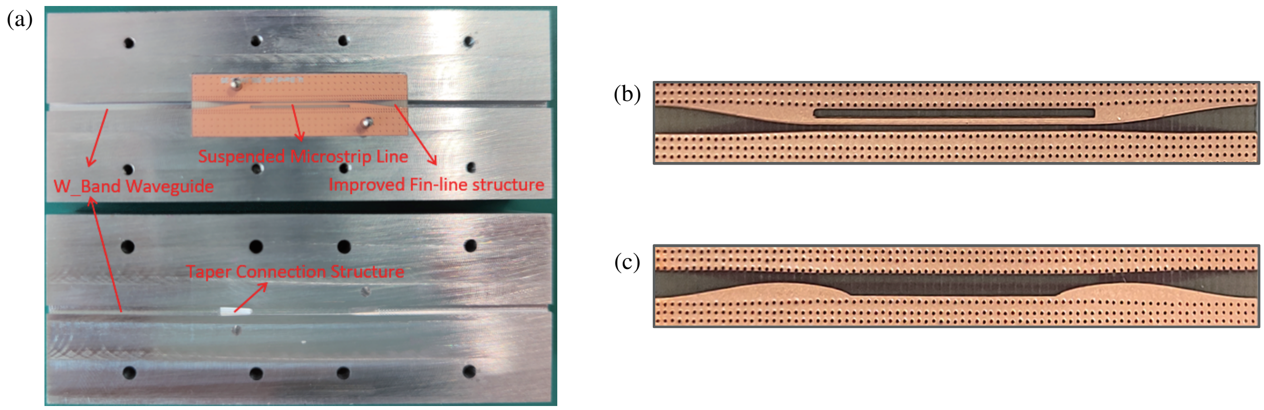

FIGURE 8. Photograph of the W-band back-to-back transition. (a) Whole view of the proposed W-band In-line transition. (b) Top view of manufactured PCB. (c) Bottom view of manufactured.

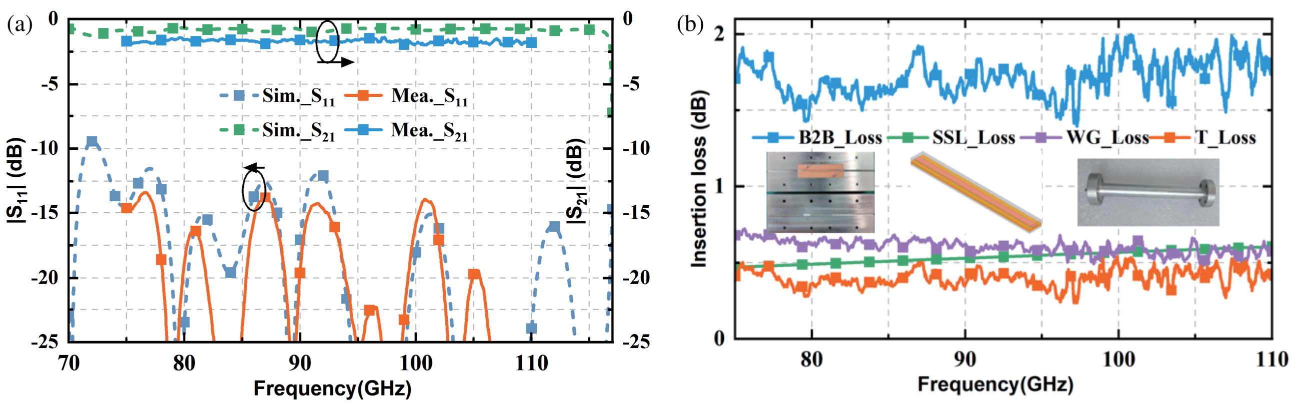

FIGURE 9. Results of the proposed transition. (a) Simulated and measured results of the W-band back-to-back transition. (b) Loss of the transition.

TABLE 1. Design parameters of the proposed transition.

Parameter	L_1	L_2	L_3	H_1	H_2	T_L
Dimension (mm)	8.2	6.5	3.9	0.7	0.62	4.7

matching and bandwidth until resonance appears due to reduced distance. After optimization, the simulated results of the proposed in-line transition, as shown in Figure 6, achieves a return loss greater than 15 dB over 73–117 GHz, corresponding to a relative bandwidth of 46%. The design parameters of the transition are as shown in Table 1.

3. MEASUREMENT AND RESULTS

To validate the performance of the W-band in-line waveguide-to-suspended stripline transition, a back-to-back transition structure is fabricated using an RT/Duroid5880 substrate. The shell of the waveguide-to-suspended stripline transition is constructed with a metal cavity made of aluminium. The suspended stripline is fabricated using PCB process. Figure 8 illustrates the fabricated W-bandin-line back-to-back transition structure. The measured results of the W-band in-line back-to-back transition are presented in Figure 9(a). It can be observed from the measurement results that the return loss remains better than 13 dB across the entire W-band. The insertion loss of the back-to-back structure ranges between 1.4 and 2.0 dB. The agreement between the simulated and measured results further confirms the effectiveness of the design approach. Furthermore, slight degradation in the measured reflection performance may be attributed to fabrication and installation tolerances. The deviations between the measured and simulated insertion losses can be attributed to the surface roughness of the metal cavity. It is worth noting that the reflection of the back-to-back transition is a superposition of the partial reflections from two individual transitions, which may explain the differences observed in the simulated $|S_{11}|$ curves depicted in Figures 6 and 9(a). In this back-to-back transition, the entire length of the waveguide with roughness surface is 46 mm, and its insertion loss in W band is estimated by measuring a 75 mm waveguide, with the measured results shown in Figure 9(b). Since the loss of the suspended stripline cannot be measured directly, the loss of the suspended stripline line used in this design is estimated through simulation. The simulated loss

TABLE 2. Comparisons of published transition.

Ref.	Freq (GHz)	FBW (%)	RL (dB)	IL (dB)	Par. No.	Length (λ_0)	Type
[8]	37–49.8	29.5	> 15	< 0.25	12	1.1	Vertical
[9]	30.9–35.2	13.0	> 15	< 0.22	5	0.67	Vertical
[11]	130–150	14.3	$> 20^*$	< 0.9	5	0.26	Vertical
[12]	140–213	41.4	> 10	< 2	11	2.1	In-line
[13]*	180–230	24.4	> 15	< 0.5	12**	N/A	In-line
This work	75–110	37.8	> 13	< 0.54	6	3.2	In-line

* — Simulation results. ** — Estimated based on the data in the paper. Par. No. — the structural parameter number of the coupling and matching circuit.

of 30 mm suspended stripline is also shown in Figure 9(b). Since the back-to-back structure is symmetrical, the insertion loss of a single transition is half of the back-to-back structure, which can be calculated from measured and simulated results, which are shown in Figure 9(b). The transmission conversion structure exhibits an average loss of 0.4 dB, with a maximum observed loss of 0.54 dB across the entire W-band. The performance of the proposed transition is compared with other published waveguide-to-suspended stripline transitions, and the results are summarized in Table 2. In comparison to previously reported designs, the proposed in-line transition offers benefits such as broad bandwidth and simple structure. It is important to note that the frequency range supported by the standard WR10 test instrument is limited to 75–110 GHz. Therefore, only the 75–110 GHz frequency range is presented in the comparison table. Nonetheless, as demonstrated in Figure 9, the consistency between the measured and simulated results within the testable frequency range is excellent. This suggests that the performance of the transition outside the testable range is likely to be very close to the simulation results. Additionally, the simulated bandwidth of the back-to-back structure, where S_{11} is less than -10 dB, extends to 47% (72.6–117 GHz).

4. CONCLUSION

In this paper, a novel in-line waveguide-to-suspended stripline transition operating in the full W-band is introduced. A prototype of the W-band in-line transition has been successfully developed. Across the entire W-band, the results of the back-to-back structure demonstrate that the reflection coefficient is better than -13 dB, and the insertion loss is less than 0.54 dB. Compared to previously reported works, the in-line waveguide-to-suspended stripline transition, based on the proposed structure, offers advantages, including wideband and simple structure. These features make it suitable for various millimeter-wave applications.

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