Analysis and design of rectangular waveguide to substrate integrated waveguide transition with voltage and current probe in W-band

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Abstract: A single-layer broadband transition between air-filled rectangular waveguide (ARW) and substrate integrated waveguide (SIW) operating in W band is proposed. Voltage and current probes are employed to implement the transition. A back-to-back prototype of the proposed transition is designed, fabricated, and measured. Good agreement of the simulated and measured results are obtained. From 80.2 to 98.1 GHz, the measured results show that the insertion loss (IL) is less than 1 dB and the return loss (RL) is better than 10 dB.

Keywords: Transition, substrate integrated waveguide, air-filled rectangular waveguide, broadband, single layer.

Classification: Microwave and millimeter wave devices, circuits, and systems.

References

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1 Introduction

With the development of collision avoidance radar, foreign object debris (FOD) detection system, etc., the research of substrate integrated waveguide (SIW) antennas [1-3], SIW passive and positive circuits [4-7] working in microwave and millimeter-wave band have attracted increasing attentions in recent years. At the same time, the air-filled rectangular waveguide (ARW) is still widely used in millimeter-wave systems owing to its low loss. Hence, high performance transition between ARW and SIW is required.

The transitions between ARW and SIW can be divided into two types. One is horizontal structure transition (the ARW and the SIW are connected in horizontal direction) [8-11]. These transitions have wide bandwidth, but bulky volume. The other one is vertical structure transition [12-14], which consists of single-layer resonant structure and multilayer resonant structure. The single-layer resonant structure transitions own advantages of the low fabrication complexity, but narrow bandwidth. The multilayer resonant structure transitions’ bandwidth is increased.
but fabrication complexity is also increased.

This letter proposed a wide-band vertical-structure transition, which uses both voltage and the current probe for W-band applications. The single-layer substrate is applied for low cost and low fabrication complexity. To verify the proposed transition, a back-to-back transition prototype is designed, fabricated and measured. The measured results show the bandwidth wider than 20% for $|S_{11}| < -10$ dB.

2 Explanation of the transition

The proposed transition is shown in Fig. 1. The $TE_{10}$ mode in ARW is transformed to the quasi-TEM mode in quasi-coaxial by the voltage probe. Then, the quasi-TEM mode is transformed to $TE_{10}$ mode in SIW by the current probe.

![Fig. 1 Geometry of the proposed transition.](image)

2.1 Electromagnetic field mode transition

The electromagnetic field mode transition is implement with voltage and current probe. As shown in Fig. 2, the $TE_{10}$ mode in ARW changes to the quasi-TEM mode by the voltage probe (shown in Fig. 2b, at the section 1-1’, 2-2’, and 3-3’). The voltage probe is a $90^\circ$ fan-shaped patch. For broadband applications, the voltage probe radius ($r$) and the substrate thickness ($h$) are determined. To avoid high order mode, the $a_4$, $D_{\text{via}}$, $d_{\text{via}}$, and $\epsilon_r$ are restricted. The first upper mode is the $TE_{10}$ mode [15], and its cutoff frequency $f_{TE_{10}}$ is given by

$$f_{TE_{10}} = \frac{c}{2\sqrt{\epsilon_r}}(a_4 - \frac{D_{\text{via}}}{0.95d_{\text{via}}})^{-1} \quad (1)$$

where $\epsilon_r$ is the relative dielectric permittivity, $a_4$, $D_{\text{via}}$, and $d_{\text{via}}$ are dimensions shown in Fig. 2a. Then, the quasi-TEM mode changes to the $TE_{10}$ mode in SIW by current probe (shown in Fig. 2b, at the section 4-4’ and 5-5’). For broadband applications, the current probe radius ($D_{\text{probe}}$), $a_3$, $a_5$, $b_3$, and $b_4$ are determined. Where $a_3$, $a_5$, $b_3$, and $b_4$ are dimensions shown in Fig. 2a.
2.2 Analysis and simulation of the transition

According to Fig. 1 and the above electromagnetic-field-mode analysis, the AWG-to-SIW transition can be simulated with Ansoft HFSS electromagnetic (EM) simulation software [16]. The substrate is single-layer RT/Duroid5880 (thickness of 0.508mm, $\varepsilon_r=2.2$). The detailed dimensions of an optimized transition are given in Table I. From 80GHz to 99.6GHz, the simulated return loss (RL) is better than 10dB as shown in Fig. 3.

![Fig. 2 AWG-to-SIW transition structure and electromagnetic field mode transition process. a) Transition structure. b) Electromagnetic field mode transition process.](image)

| Parameter | Size (mm) | Parameter | Size (mm) | Parameter | Size (mm) |
|-----------|-----------|-----------|-----------|-----------|-----------|
| $a$       | 2.54      | $b$       | 1.27      | $r$       | 0.96      |
| $a_1$     | 3         | $b_1$     | 1.03      | $d_{via}$ | 0.5       |
| $a_2$     | 2.2       | $b_2$     | 2.45      | $D_{via}$ | 0.3       |
| $a_3$     | 1.2       | $b_3$     | 0.78      | $D_{probe}$ | 0.15     |
| $a_4$     | 0.95      | $b_4$     | 1.53      | $h$       | 0.508     |
| $a_5$     | 0.2       | $b_5$     | 0.47      | $h_1$     | 0.4       |
3 Fabrication and measurement of the transition

According to the above analysis and simulation, the single-layer broadband back-to-back transition, which is presented in Fig. 4a, is fabricated. The substrate is bonded onto aluminum-alloy cavity with silver paste. The waveguide flange is WR10.

Two back-to-back transitions of different length are manufactured as shown in Fig. 4b. Not only they can be used for measurement of transition performance, but also can be used to estimate the insertion loss (IL) of SIW. Through testing and calculation, the IL of 10mm SIW is 0.6 to 0.9dB from 80 to 100GHz. The simulated and measured S-parameter curves are shown in Fig. 5. In the range of 80.2 to 98.1 GHz, the measured IL of the back-to-back module is better than 2dB, and it can be derived that the measured IL of a single transition would be less than 1dB. Within the bandwidth, the RL of the back-to-back module is better than 10dB.

Table II summarizes the performances of the proposed transition along with previously published works. As compared with previous reported AWR-to-SIW vertical structure transitions, the bandwidth increases to 20 % and owns advantages of low fabrication complexity and low cost.

![Fig. 3 Simulated scattering parameter (S-parameter) curves of the AWG-to-SIW transition.](image)

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![Fig. 4 Photograph of the fabricated back-to-back transitions. a) The front and back of the transitions. b) Different lengths of the fabricated back-to-back transitions.](image)
5 Conclusion

A single-layer broadband AWR-to-SIW transition is proposed in W-band. Voltage and current probes are employed to implement the transition. A back-to-back transition with a bandwidth larger than 20% for $|S11|<-10$ dB has been fabricated and measured in W-band. The measurement and the simulation are in good agreement and show that the IL of a single transition is less than 1 dB from 80.2 to 98.1 GHz. Because of advantages of compact structure, wide bandwidth and low IL, the transition is attractive for millimeter-wave planar integrated circuit applications.

### Table II. Performances summary and comparison with different vertical structure integrated transitions

| Ref.  | Layer of dielectric substrate | Measured BW(GHz) | Relative BW (%) | Measured RL(dB) | Measured IL(dB) |
|-------|-------------------------------|------------------|-----------------|-----------------|-----------------|
| [2]   | single-layer Rogers 5880     | 90 - 98          | 8.5%            | 16              | 0.65            |
| [12]  | Multilayer LTCC               | 34.8 - 37.8      | 8.3%            | 13              | 0.26            |
| [13]  | Multilayer LTCC               | 86 - 97          | 12%             | 15              | 0.7             |
| [14]  | Multilayer Rogers 5880 V-band|                   | 35%             | 10              | 0.58            |
| This work | single-layer Rogers 5880 | 80.2 - 98.1      | 20%             | 10              | 1               |
| This work | single-layer Rogers 5880 | 80.2 – 95.1      | 17%             | 12              | 0.75            |

**Fig. 5** Simulated and measured S-parameter curves.