A Broadband Low-Loss 60 GHz Die to Rectangular Waveguide Transition

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***Abstract*—This letter describes a broadband CPW to standard WR-15 rectangular waveguide transition designed for low-cost PCB technology. This low-loss transition can be be directly integrated to a flip-chipped millimetre-wave integrated circuit. The measured fractional bandwidth of this module is 25%, covering from 52 to 67 GHz. The average measured insertion loss of the transition including a quasi-coax section is 0.5 dB over the 60 GHz band, and the return loss is higher than 15 dB.**

***Index Terms*—Backhaul, CPW, flip-chip, millimetre wave, PCB, 60 GHz, transition, waveguide.**

I. Introduction

RAPID development of 60 GHz semiconductor technology has offered low-cost millimetre-wave (mm-wave) chipsets aimed for consumer electronics market. Availability of low-cost mm-wave radio, paves the road for other applications, such as mm-wave backhaul and fixed infrastructure links, which require high-gain antennas to accommodate longer ranges (from 50 to 1000 m). High gain mm-wave antennas with standard waveguide input, such as reflectors or horn antennas have been available for a long time, but a low-loss, low-cost, and broadband transition from mm-wave chip to waveguide must be used to transfer energy to the antenna [1].

There are several ways to assemble a mm-wave die to a substrate, such as flip-chipping, wire-bonding, and use of an interposer. Flip-chipping gives the lowest insertion loss and parasitic effects [2]. Moreover, the easiest way to access RF pads of a flip-chipped die is through a coplanar waveguide (CPW) interconnect [3]. So, the motivation behind this work is to design a low-loss, broadband CPW to waveguide transition using a low-cost fabrication technology suitable for commercial applications, which can be integrated to a mm-wave die.

In [4], a grounded CPW to rectangular waveguide transition for 60 GHz, implemented in LTCC technology, is described. Although the minimum insertion loss is 0.3 dB at 59 GHz, it increases to 2 dB at 63 GHz due to poor matching. In [5], a bandwidth enhanced CPW to waveguide transition, which requires a fairly complex excitation method, is proposed. The measured bandwidth of the fabricated transition in Alumina is significantly less than the simulated one. In [6], a microstrip to rectangular waveguide has been designed in LTCC at W-band, with a measured insertion loss of 0.7 dB from 86 to 97 GHz. For an integrated solution a CPW to microstrip transition must be added to this structure, which adds to the loss and size.

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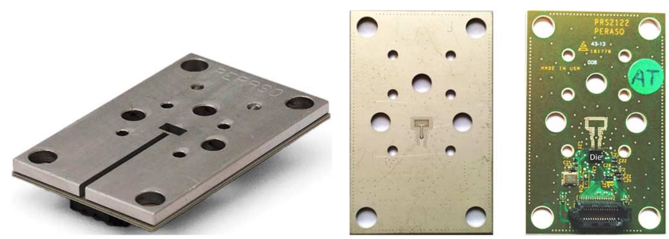


(a) (b) (c)

Fig. 1. 60 GHz backhaul module (25 mm × 40 mm) with WR-15 interface. (a) With metal enclosure, (b) top view of the integrated transition, and (c) bottom view showing the flip-chipped die (2.1 mm × 2.1 mm).

In this letter, we present a 60 GHz CPW to standard WR-15 waveguide transition suitable for direct integration to flip-chipped die. The transition implemented in a six layer PCB board, has a measured insertion loss of 0.5 dB and 25% fractional bandwidth. Recently, this design has been integrated to a 60 GHz die and incorporated in a commercial integrated system-in-package solution with a size of 25 mm × 40 mm shown in Fig. 1 [7].

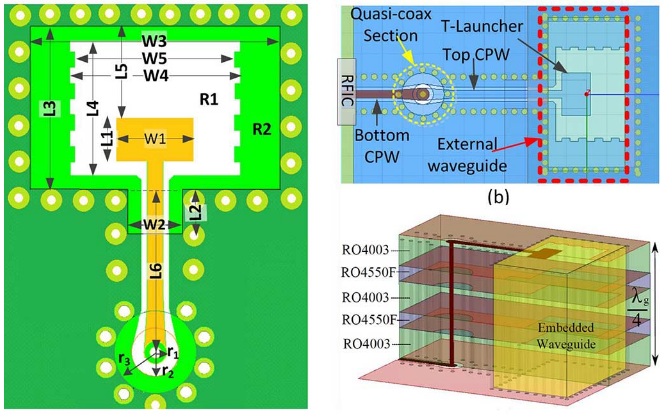
II. CPW to Waveguide Transition Design

A. General Structure

Fig. 2(a) shows the top view of the proposed transition and design parameters. The mm-wave die is flip-chipped to the bottom side of the PCB, while the external waveguide is assembled to the top side. The transition structure, demonstrated in Fig. 2(b), consists of top and bottom CPW lines, T-shape launcher, which excites the rectangular waveguide, quasi-coax section and openings in ground planes. Fig. 2(c) displays the exploded 3-D view of this structure. Inside the substrate and under the external waveguide an embedded dielectric waveguide is formed using Through Hole Via (THV) fences. The quasi-coax section joins the top CPW line to the bottom one, which is connected to the 60 GHz die.

B. T-Launcher

The top CPW line is connected to a T-shape launcher, which excites the primary mode of the rectangular waveguide (TE_{10}). This T-shape microstrip section, shown in Fig. 2(a), is characterized by its width, $W1$ (0.95 mm), length, $L1$ (0.53 mm), and



(a) (c)

Fig. 2. (a) Proposed transition with design parameters, (b) transition structure, and (c) transition exploded view showing the six-layer stack-up.

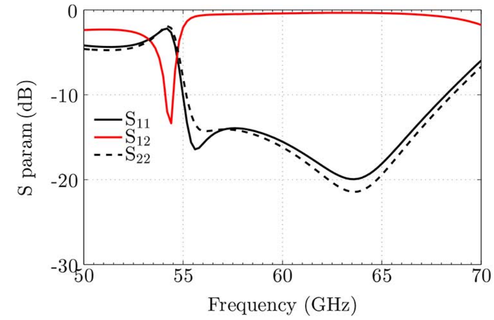
the spacing from the edge of the ground, $L5$ (1 mm). To improve matching a cut is made in the top ground layer at the intersection of the CPW line and the T-launcher, denoted by $L2$ (0.56 mm) and $W2$ (0.7 mm) in Fig. 2(a).

C. *Embedded Dielectric Waveguide*

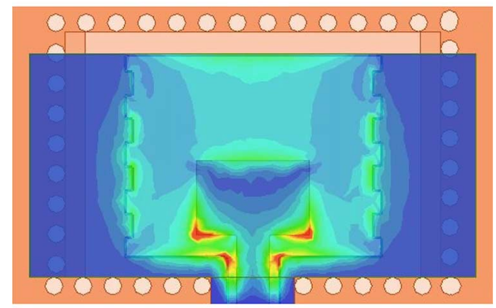
THV fences make a vertical dielectric waveguide in the substrate, as shown in Fig. 2(c). The bottom side is shorted to reflect the energy back to the waveguide. The total substrate thickness is close to the quarter of the guided wavelength (λ_g) at the operating frequency. With this condition, the EM energy that is propagating downward will reflect back toward the launcher, where it combines in-phase with the incident wave. The width of the embedded waveguide is defined by openings in the inner metal layers $(R2)$, described by $L3$ (2.07 mm) and $W3$ (3.16 mm). The opening in top ground layer $(R1)$ is smaller than $R2$ to obtain the desired matching. Besides, the left and right edges of $R1$ are corrugated to suppress undesired resonances and smooth the frequency response. In Fig. 2(a), $L4$ (1.7 mm), $W4$ (2.15 mm) and $W5$ (2.02 mm) describe the opening in top metal.

D. *Optimized Quasi-Coax Section*

Die and other components must be flip-chipped to the bottom side of the substrate to leave a flat surface on top for waveguide assembly. In this design, a CPW line printed on the bottom side carries mm-wave signal to/from die. To connect the top and bottom CPW lines a quasi-coaxial transition is designed. This transition consists of a central signal via surrounded by grounding vias forming a cylinder, and circular openings in all metal layers. The CPW tail is tapered to improve matching. In Fig. 2(a) $r1$ (0.14 mm), $r2$ (0.3 mm) and $r3$ (0.5 mm) denote, the radius of tapered tail of top CPW line, the radius of opening in top GND, and the radius of opening in inner layers, respectively. One advantage of using CPW transmission lines rather than microstrip lines is that the signal trace width and gap size can be different on the top and bottom layers without changing the dielectric thickness. For example, on the bottom side the CPW size can be adapted to the die pad-pitch, as much as fabrication limits allow.



(a)



(b)

Fig. 3. (a) Simulated S_{11} and S_{12} of the transition with quasi-coax section (solid) and without it (dashed). (b) Formation of TE_{10} mode at the interface of PCB and external waveguide at 63 GHz.

E. *Simulation Results*

The proposed transition is designed for 60 GHz frequency band considering PCB technology limits. To design the substrate stack-up, three layers of 8 mil Rogers 4003 material, with a dielectric constant of 3.55 and a dielectric loss of 0.003, and two layers of 4 mil Rogers 4450F are used as shown in Fig. 2(c). The total substrate thickness is 32 mil (800 μm), which is close to a quarter wavelength. All THVs used in this design have a diameter of 6 mil, and a via-pad of 11 mil. The CPW trace width and ground-signal gap are 200 μm, and 90 μm, respectively.

The simulated S_{11} and S_{12} of the transition with quasi-coax section and without it are shown in Fig. 3(a). The quasi-coax structure adds less than 0.2 dB to the total insertion loss. The 10-dB impedance bandwidth with and without quasi-coax structure is 13.2 GHz (55.2–68.4 GHz), and 13.5 GHz (55.1–68.6 GHz), respectively. Fig. 3(b) shows how the T-launcher excites TE_{10} mode inside the waveguide.

III. Transition Measured Results

Fig. 4(a) shows the back-to-back structure used to measure the transition properties, which is formed by extending and joining the bottom CPW lines of two identical transitions. Fig. 4(b) displays the Scanning Electron Microscope (SEM) image of the substrate cross-section (quasi-coax section) used for post-fab analysis. The measured total thickness was 5% more than the design value, which is within the fabrication tolerances. The copper thickness was slightly higher than the values used in simulation (22 μm versus 15 μm).

The measurement setup is shown in Fig. 4(c). The black cables of the 67 GHz network analyser are connected to the transition through coax to waveguide adaptors. Two aluminium

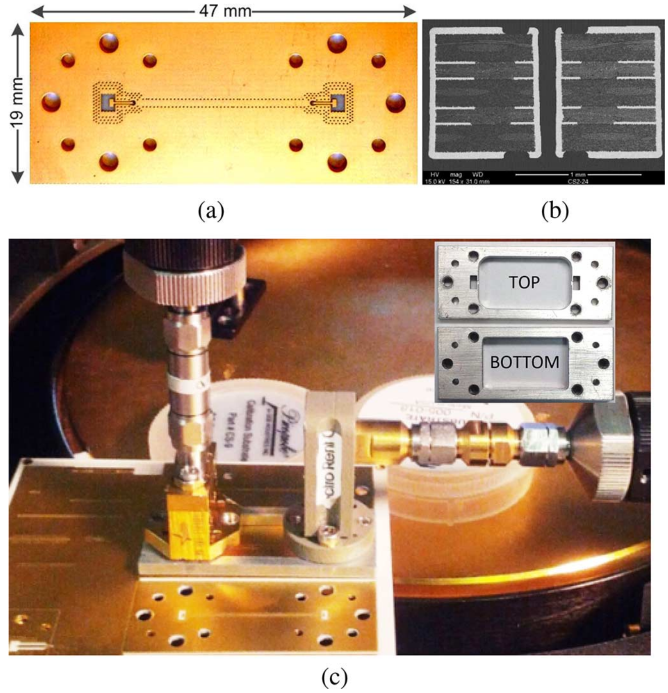


Fig. 4. (a) Fabricated back-to-back transition. (b) High-resolution SEM image of the substrate cross section. (c) Measurement setup used for transition characterization. The inset shows the top and bottom metal plates.

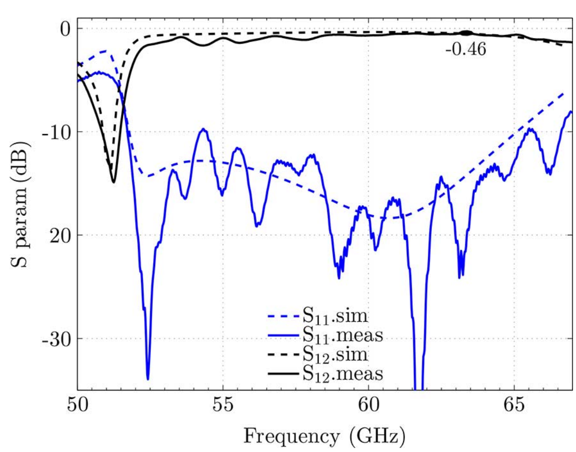


Fig. 5. Measured bandwidth and insertion loss of the CPW to rectangular waveguide transition compared with post-fab simulations.

TABLE I
COMPARISON OF THIS WORK WITH 60 GHz WAVEGUIDE TRANSITIONS

Ref.	Freq. (GHz)	Bandwidth (%)	Loss (dB)	Techno-logy	Cost	THV
[4]	57–63	10	0.35	LTCC	Med.	No
[5]	55-65	17	1	Alumina	High	No
[8]	50-72	36	0.3	Alumina	High	No
[9]	53-64	18	1	PCB	Low	No
This work	52–67	25	0.4-0.8	PCB	Low	Yes

plates, labeled as top and bottom in Fig. 4(c), are designed to protect the PCB and facilitate the connection of adaptors to transition. The thickness of the top plate, which has two WR-15 waveguide flanges, is 3 mm. The proper alignment between adaptors, aluminium plates and transition is achieved by extending the standard waveguide flange pattern inside the substrate as shown in Fig. 4(a), and use of the adaptor pins. The setup is calibrated to the tip of the waveguide adaptors using the high-precision calibration kit.

Fig. 5 compares the measured S_{11} and S_{12} of the transition (after the de-embedding extended CPW line) with post-fab simulations with the realized sizes obtained from SEM images. The measured 10 dB impedance bandwidth is 15 GHz (52–67 GHz), and the mean insertion loss over the 60 GHz band is 0.5 dB. A 3 GHz left shift in frequency response is observed compared to initial simulations in Fig. 3, because the dielectric constant of Rogers 4003, extracted from group velocity measurement of transmission lines, is 3.75 at 60 GHz compared to 3.55 used to generate Fig. 3.

IV. CONCLUSION

A novel CPW to rectangular waveguide transition designed for 60 GHz spectrum with a measured bandwidth of 15 GHz (25%), and a mean insertion loss of 0.5 dB was presented in this letter. An optimized quasi-coax section connects the transition on top to the CPW line and eventually flip-chipped die on the bottom. The transition was realized in a 6-layer PCB and integrated to a 60 GHz die.

Table I compares this work with other 60 GHz waveguide transitions. The highest bandwidth and lowest insertion loss are reported in [8], where a costly and complex housing is used. This work and [9] use PCB technology which has the lowest cost among other fabrication technologies; however, in [9] the insertion loss is twice this work. Furthermore, all other transitions lack a through hole via (quasi-coax section), which is necessary for an integrated transition, where die is flip-chipped to the bottom of the package, such as the one shown in Fig. 1. The THV adds to the total loss (0.2 dB in this work) and reduces the bandwidth slightly (0.3 GHz).

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