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Published in:
Proceedings of 2020 50th European Microwave Conference

Link to article, DOI:
10.23919/EuMC48046.2021.9338140

Publication date:
2021

Document Version
Peer reviewed version

A U-Band Rectangular Waveguide-to-Coplanar Waveguide Transition Using Metal Ridge

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***Abstract*— This paper presents a rectangular waveguide-to-coplanar waveguide (CPW) transition using metal ridge at U-band (40–60 GHz). By using an in-house printed circuit board (PCB) technology, a CPW with gap terminations is designed on a Rogers 6002 substrate and its performance is compared with a conventional CPW. As the critical part of the transition, a metal ridge is realized inside the rectangular waveguide and applied to the CPW from top forming an orthogonal structure. The proposed rectangular waveguide-to-CPW transition using metal ridge is designed, fabricated, and measured in a back-to-back configuration. The return loss remains better than 12 dB at U-band with an associated insertion loss of 2.6 dB. Thus, each fabricated transition introduces less than 1.3 dB insertion loss.**

***Keywords*— integrated circuit packaging, millimeter wave devices, millimeter wave propagation, transmission lines.**

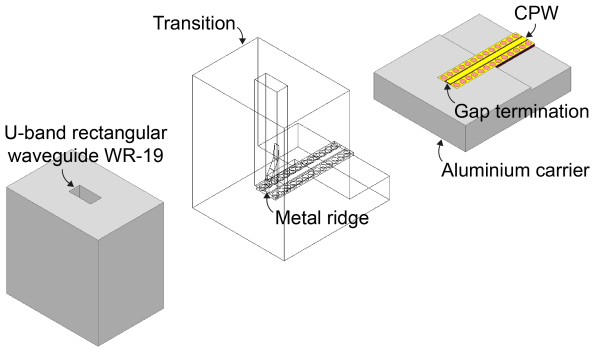

Fig. 1. Rectangular waveguide-to-CPW transition using metal ridge.

I. Introduction

At millimeter-wave and submillimeter-wave frequencies, rectangular waveguides have been widely used for system integration and packaging due to high power-handling capability, low transmission loss, and simple tubular metal structure. The width and height of rectangular waveguides are mainly determined by the cutoff frequencies of propagation modes. Thus, with predefined dimensions for each frequency band, air-filled rectangular waveguides become standard interfaces for connecting different components and systems. However, the circuits and chips at such high frequencies still rely on planar structures due to their fabrication processes. Under this circumstance, the transitions between rectangular waveguides and planar transmission lines, in particular rectangular waveguide-to-coplanar waveguide (CPW) transitions are under intensive study in the recent years and become an attractive topic in the literature [1]–[10]. The designs and implementations of such transitions are normally subjected to several concerns including operating frequencies, circuit dimensions, substrate materials, layer stacks, and interconnects. Different transition structures have been used for guiding electromagnetic waves while it is challenging to achieve a wideband matching with low insertion loss and at the same time being versatile for packaging the exiting circuits and chips. In [1], an E-plane probe transition was realized by inserting a patch into the rectangular waveguide through an aperture cut and it was used for packaging an amplifier. As is reported in [3], transitions using wire bonding probe exhibit competitive performances as well as versatile packaging approaches. Though wideband planar antennas are originally used for wireless applications, they can also be implemented as rectangular waveguide-to-CPW transitions [5]–[7]. Especially for dipole antennas, once being integrated on-chip, it shows the possibility of packaging circuits with large dimensions. Moreover, instead of adding extra connections, probes, or antennas at the circuit level, transitions can be formed by adding metal ridge inside rectangular waveguides [8]. In this case, the propagation mode in the rectangular waveguide converts to a CPW mode before it reaches the circuit. With the development of micromachining and accurate manufacturing techniques, metal ridge transitions become a promising packaging approach at millimeter-wave frequencies [9], [10].

Fig. 1 shows the basic structure of the proposed metal ridge transition at U-band between a WR-19 rectangular waveguide and a CPW. As a part of the transition, a gap termination is implemented at the end of the CPW where the signal trace terminates prior to the ground traces leaving a small gap between the end of the signal trace and the edge of the substrate. The aluminium carrier underneath provides ground connections to the edges of the substrate. In addition, vias going through the substrate are added along the ground traces in order to restrict parasitic modes. The CPW through line represents the interface of millimeter-wave circuits. The metal ridge is realized inside the rectangular waveguide and applied to the CPW from top forming an orthogonal structure.

In this work, a U-band rectangular waveguide-to-CPW transition using metal ridge is designed and analyzed by using full-wave electromagnetic simulations in Ansys EDT

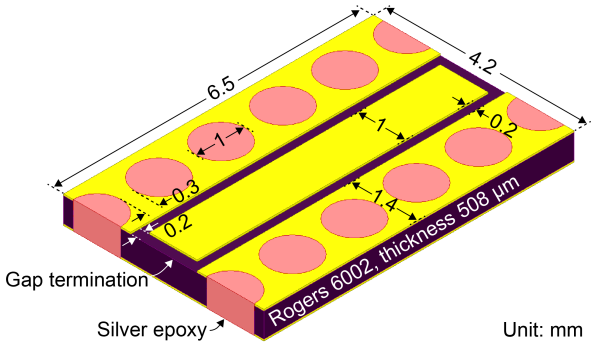

Fig. 2. Designed CPW with gap terminations.

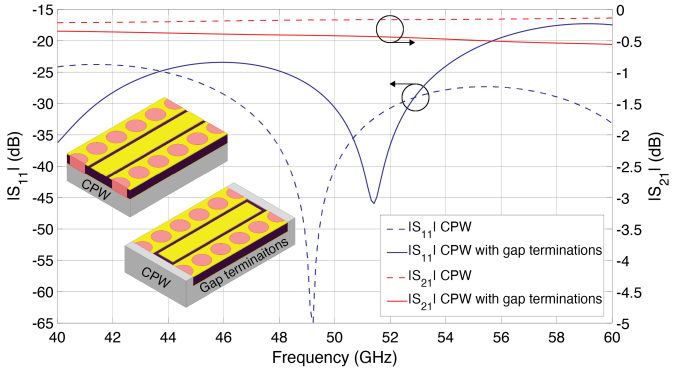

Fig. 3. Simulation results of the CPWs based on Rogers 6002 substrate.

(formerly known as HFSS). For proving the concept, a transition prototype is fabricated and measured in a back-to-back configuration. In section II, the design of CPW with gap terminations is introduced and the simulation results are presented. Besides, the design of metal ridge transition and the corresponding structure for prototyping are described in detail. The electric field distribution of the the proposed transition is also illustrated. In section III, the assembly structure and the fabrication of the transition prototype are addressed. The experimental setup is demonstrated and the measurement results are compared with the simulation results.

II. Design Procedure of Rectangular Waveguide-to-CPW Transition

A. CPW with Gap Terminations

For a conventional CPW patterned on the top of a dielectric substrate, the signal trace is aligned in the middle of two separated ground traces. In this case, the electric waves concentrate in the gaps between the signal and ground traces. Since the conductor traces are located at the boundary between air and dielectric substrate, a quasi-TEM mode propagates along the CPW. The characteristic impedance of the CPW is related to the width of the signal trace (S), the width of the gap (G), the dielectric constant, and the thickness of the substrate. For a certain dielectric substrate, when keeping a constant ratio of $S/(S+2G)$, the same characteristic impedance can be achieved by CPWs with different dimensions.

Fig. 2 shows the designed CPW with gap terminations as a part of the proposed metal ridge transition at U-band. The thickness of the Rogers 6002 substrate is 508 μm. Copper is used as the material of the conductor layers and the thickness is 35 μm. The dimensions are also illustrated and the characteristic impedance is designed to be 50 Ω.

For CPWs based on thin dielectric substrates, the electric waves exist not only in the gaps but also between the signal trace and the bottom ground plane. As a result, the propagation mode becomes a combination of conventional CPW and microstrip-like modes. Besides, at such high frequencies, it may easily cause radiations or higher-order modes. When vias going through the substrate are added along the ground traces and filled with silver epoxy, the electric waves are limited to a specific region on the substrate and parasitic modes are restricted. Compared with a conventional CPW, the signal trace terminates 200 μm prior to the ground traces at both ends. Once being inserted into a rectangular waveguide, the edge of the substrate touches the broadwall forming a gap termination on the signal trace which helps to excite the electric waves at the metal ridge inside the rectangular waveguide.

The solid lines in Fig. 3 represent the simulation results of the CPW with gap terminations while the dashed lines are the simulation results of the convention CPW. The simulation structures are presented and the performances are comparable at U-band. In both cases, the return loss is better than 17 dB and the insertion loss is less than 0.6 dB. As a result, the effect of adding gap terminations can be neglected, so that it becomes possible to package the existing circuits without modifying the layout or adding extra structures on the substrate.

Table 1. Dimensions of the designed metal ridge.

Stage	1st	2nd	3rd	4th	5th
Length (L)	2600 μm	1600 μm	1500 μm	900 μm	1160 μm
Height (H)	238 μm	1058 μm	2008 μm	2188 μm	2188 μm

B. Metal Ridge Transition

As is demonstrated in Fig. 4, a metal ridge is realized inside a WR-19 rectangular waveguide which is perpendicular to the substrate forming an orthogonal structure. The designed metal ridge consists of five stages starting on the top broadwall of the rectangular waveguide and the height increases gradually. At the last stage, the distance between the metal ridge and the bottom broadwall reduces to 200 μm so that the electric waves are guided to the gap termination on the signal trace smoothly.

The detailed dimensions are listed in Table 1. The thickness of the metal ridge is designed to be 1 mm in order to fit the width of the signal trace. Besides, the thickness of the substrate is compensated by a recess on the aluminium carrier and the CPW is aligned accurately with the metal ridge. Under this circumstance, an aperture cut with a height of 1 mm is realized at the end of the top broadwall of the rectangular waveguide where the electric waves can be guided out to the connected CPW without being affected by the transition structure.

The packaging structure of the the proposed metal ridge

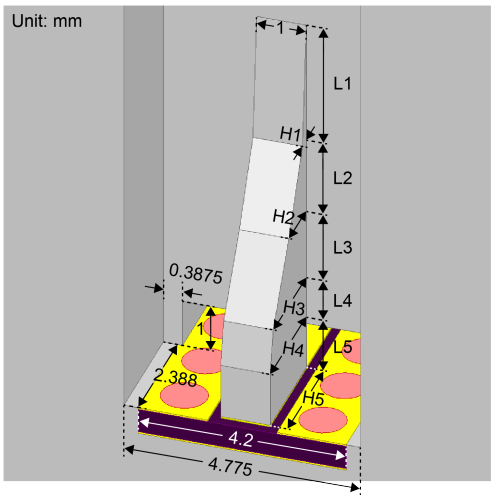

Fig. 4. Designed metal ridge transition.

transition in a back-to-back configuration is illustrated in Fig. 5. It consists of two WR-19 rectangular waveguides with a length of 5 cm, two metal ridge transitions, and a CPW in the middle. The length of the CPW is optimized so that the distance between the input and output is large enough for connecting two standard rectangular waveguide flanges next to each other. As the excitation scheme for simulations, wave ports are assigned to the input and output rectangular waveguides. For a better understanding of the wave propagation through the designed metal ridge transition, the electric field distribution at the cross-section along the E-plane in the middle of the rectangular waveguide is investigated and shown in Fig. 5. At the beginning, the electric waves are guided along the rectangular waveguide until the metal ridge appears. With the height of the metal ridge increasing gradually, the electric waves start changing their direction and being coupled to the metal ridge. At the last stage, the electric waves become concentrated in the gap and a CPW mode is excited on the substrate. The electric waves are guided out through the aperture cut and propagate along the CPW.

III. Fabrication and Experimental Results

In order to prove the concept, by following the designed metal ridge transition shown in Fig. 4 and the proposed packaging structure illustrated in Fig. 5, a transition prototype was fabricated in a back-to-back configuration. Fig. 6 demonstrates the corresponding assembly structure as well as the fabricated transition prototype including the CPW with gap terminations, the metal ridges, and the WR-19 rectangular waveguides. The CPW was patterned on a Rogers 6002 substrate using an in-house printed circuit board (PCB) technology which involves ultraviolet (UV) exposure and wet chemical etching. The positions of the vias were also marked on the substrate during the patterning process. After that, the holes were drilled on the substrate by using a spinner with a radius of 500 μm and filled with silver epoxy. In order to fix the CPW on the aluminium carrier, the substrate was extended in the middle and four Teflon screws were used.

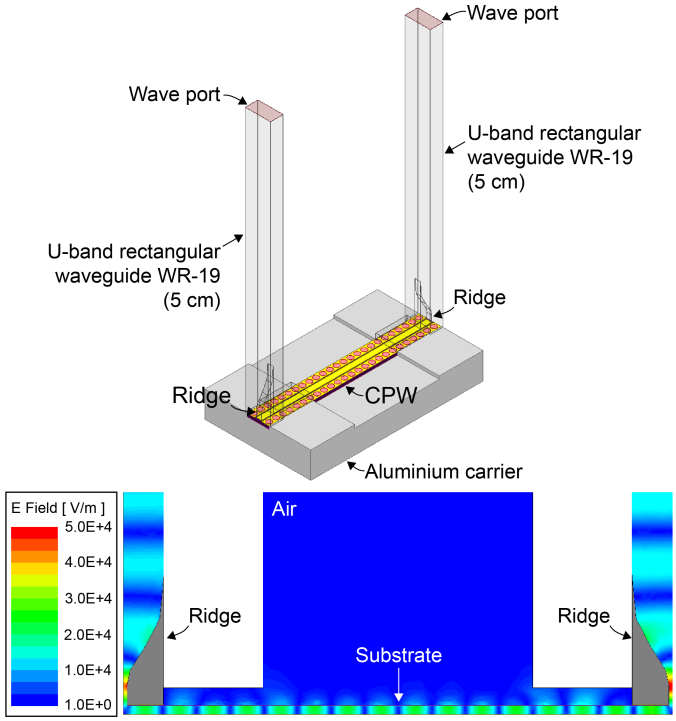

Fig. 5. Packaging structure of the proposed transition in a back-to-back configuration and the magnitude of electric field distribution at 50 GHz.

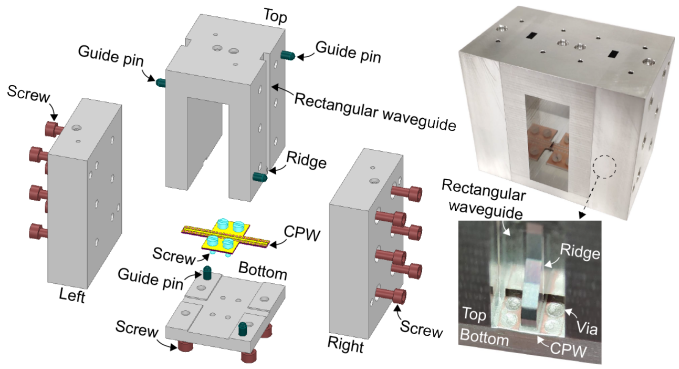

Fig. 6. Assembly structure and fabrication of the proposed rectangular waveguide-to-CPW transition using metal ridge.

For easier fabrication, alignment, and assembly, the packaging structure was divided into four parts and each part was fabricated using an aluminium block by a milling process. The metal ridges together with the aperture cuts and WR-19 rectangular waveguides were realized on the top part. The left and right parts work as the bottom broadwalls of the input and output rectangular waveguides. The bottom part is used as a carrier for the CPW which contains a recess with the same thickness as the substrate. In addition, a slot opening with a height of 4 cm was implemented in the middle preventing the CPW being affected by the packaging structure . Two standard rectangular waveguide flanges were also fabricated at the input and output of the packaging structure. During the assembly process, the CPW was fixed on the bottom part and silver epoxy was used for filling the gaps between the substrate and

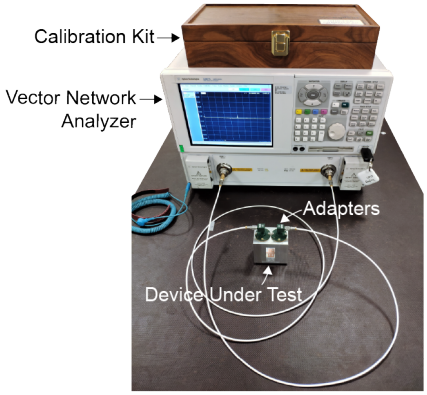

Fig. 7. Experimental setup showing the device under test, vector network analyzer, WR-19 rectangular waveguide-to-coax adapters, and calibration kit.

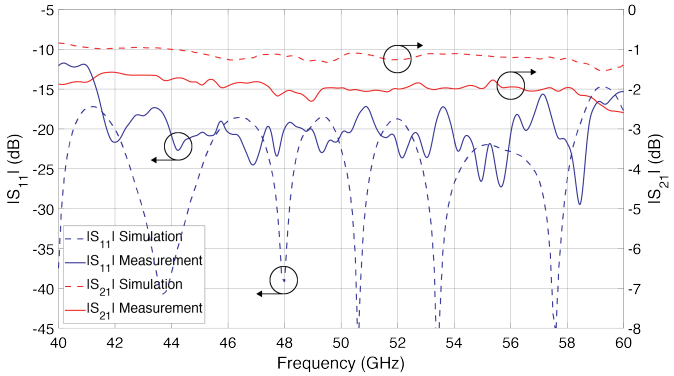

Fig. 8. Simulation and measurement results of the proposed rectangular waveguide-to-CPW transition using metal ridge.

the aluminium carrier. After that, the top part was applied and the metal ridge transitions were inspected visually for accurate alignment. The left and right parts were combined at the end.

Fig. 7 shows the experimental setup for measuring the fabricated transition prototype at U-band (40–60 GHz). The measurement system consists of a vector network analyzer (Agilent E8361A) and two WR-19 rectangular waveguide-to-coax adapters (FM 24094-VF50). For improving the accuracy, through-reflect-line (TRL) calibration was carried out using a waveguide calibration kit (Agilent U11644A). The scattering parameters are measured at the input and output of the fabricated transition prototype.

The measurement results of the proposed metal ridge transition in a back-to-back configuration are presented by the solid lines in Fig. 8. As a reference, the simulation results are shown by the dashed lines. The measured return loss remains better than 12 dB from 40 GHz to 60 GHz. When the bandwidth refers to the frequency band where the return loss is better than 10 dB, the proposed metal ridge transition can provide a bandwidth of 20 GHz with an associated insertion loss of 2.6 dB. Thus, each fabricated metal ridge transition introduces less than 1.3 dB insertion loss. Compared with the simulation results, a reasonable agreement is achieved. The differences are mainly caused by the tolerance of the patterning process as well as the alignment between the signal trace and the the metal ridge in the rectangular waveguide.

IV. Conclusion

The design of rectangular waveguide-to-CPW transition using metal ridge at U-band has been presented. As a part of the proposed transition, the CPW with gap terminations has been introduced. Compared with a conventional CPW, the gap terminations on the signal trace neither degrade the transmission line performance nor affect the on-wafer measurements at millimeter-wave frequencies. As a result, it provides a novel method for packaging the existing circuits or the circuits with large dimensions without adding extra connections, probes, or antennas. The metal ridge has been described in detail and the electric field distribution has been explained. A transition prototype has been fabricated and measured in a back-to-back configuration. The measured return loss remains better than 12 dB at U-band while each fabricated transition introduces less than 1.3 dB insertion loss. Though the concept has been proved by the fabricated transition prototype at U-band, it can be easily re-scaled to other millimeter-wave frequencies.

Acknowledgment

The authors would like to thank J. Lauridsen, M. Nielsen, and J. N. Mortensen at the Technical University of Denmark for machining the packaging structures.

References

[1] K. Eriksson, P. J. Sobis, S. E. Gunnarsson, J. Hanning, and H. Zirath, "InP DHBT amplifier modules operating between 150-300 GHz using membrane technology," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 63, pp. 433–440, Feb. 2015.

[2] J. Jakob, R. Sammer, F. X. Röhrl, W. Bogner, and S. Zorn, "WR12 to planar transmission line transition on organic substrate," *in Proc. 49th Eur. Microw. Conf. (EuMC)*, pp. 288–291, Oct. 2019.

[3] Y. Dong, V. Zhurbenko, P. J. Hanberg, and T. K. Johansen, "A D-band rectangular waveguide-to-coplanar waveguide transition using wire bonding probe," *J. Infrared Millim. Terahertz Waves*, pp. 1–17, Nov. 2018.

[4] M. Moallem, J. East, and K. Sarabandi. "A broadband, micromachined rectangular waveguide to cavity-backed coplanar waveguide transition using impedance-taper technique," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 4, pp. 49–55, Jan. 2014.

[5] H. Song, H. Matsuzaki, and M. Yaita, "Sub-millimeter and terahertz-wave packaging for large chip-width MMICs," *IEEE Microw. Compon. Lett.*, vol. 26, pp. 422–424, June. 2016.

[6] T. Tajima, H. J. Song, H. Matsuzaki, and M. Yaita, "LTCC-integrated H-plane bends for THz antenna-in-package solution," *IEEE Microw. Compon. Lett.*, vol. 27, pp. 440–442, May. 2017.

[7] Y. Dong, T. K. Johansen, V. Zhurbenko, and P. J. Hanberg, "A rectangular waveguide-to-coplanar waveguide transition at D-band using wideband patch antenna," *in Proc. 48th Eur. Microw. Conf. (EuMC)*, pp. 1–4, Sept. 2018.

[8] G. E. Ponchak and R. N. Simons, "A new rectangular waveguide to coplanar waveguide transition," *in Proc. IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 491–492, May. 1990.

[9] Y. Dong, V. Zhurbenko, P. J. Hanberg, and T. K. Johansen, "A D-band rectangular waveguide-to-coplanar waveguide transition using metal ridge," *in Proc. IEEE MTT-S Int. Microwave Symp. (IMS)*, pp. 1050–1053, June. 2019.

[10] C. Wang, Y. Yao, J. Wang, X. Cheng, J. Yu, and X. Chen, "A wideband contactless CPW to W-band waveguide transition," *IEEE Microw. Compon. Lett.*, vol. 29, pp. 706–709, Nov. 2019.