Top-Layer Wideband Transition from Waveguide to Planar Differential Line for 60 GHz Applications

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***Abstract* — The paper describes a waveguide to planar differential line transition realized on Rogers RO4350B substrate and operating in the V band. The transition is based on a differentially-fed patch radiating element that excites a rectangular waveguide through a compact U-shaped metal adapter. The response of a single transition has been extracted from the measurement results of the fabricated back-to-back structure using a TRL calibration standard realized on the same substrate. It also allowed to accurately calibrate the differential line loss. The transition provides maximum 0.8 dB insertion loss and more than 15 dB return loss over the 57-64 GHz frequency band, whereas differential line loss of 1.3 dB per centimeter is mainly determined by the chosen substrate material. High performance and cost-effective design makes the proposed transition highly promising for different mmWave transceivers and for verification of custom planar devices using standard waveguide test equipment.**

***Keywords* — waveguide transition, differential line, V band, TRL calibration.**

I. Introduction

MmWave frequencies are becoming essential for wireless applications because of continuous data throughput growth provided by different communication systems. One of the most promising frequency spectra nowadays is the V band occupying frequencies from 50 to 75 GHz. For instance, the license-free frequency band 57-64 GHz is widely used for multi-Gbit/s point-to-point links as well as for Wi-Fi networks.

Modern mmWave devices operating in this band are based on highly integrated RFIC components that exploit often a balanced output interface. The benefits are in neglecting of common-mode interference and even-order distortions as well as in simplification of RF grounding issues which become extremely critical at higher frequencies.

However, V band filters, diplexers, orthomode transducers and antennas are mainly designed on the traditional hollow waveguide approach that provides low transmission loss at mmWave frequencies.

Considering the above, a high-performance but simple and low-cost transition from waveguide to planar differential line is of current interest for the mmWave wireless applications. Such a transition should have small insertion loss and sufficient bandwidth as well as be compact and easy in fabrication. The additional practical requirement is that the transition should provide flexibility in selection of a multilayer PCB substrate that can be required by any transceiver design.

Wideband waveguide to differential line transitions operating in V and W bands were proposed, for example, in [1] and [2]. They are based on a unilateral finline mounted in the E-plane of a rectangular waveguide. Smooth tapering of the finline that is several wavelengths long allows to reach the transition relative bandwidth of 52 %. However, such “inline” transition where the finline PCB is fixed between two halves of the rectangular waveguide requires at least two precisely milled housings connected with screws and alignment pins. It makes transition casing more complex.

In [3], a single metal piece housing has been implemented using a short-circuited slot line, fixed at the narrow wall of the rectangular waveguide. However, to make the lateral dimension smaller, the transitions [1]–[3] require an additional 90° waveguide bend for connection to a waveguide aperture antenna. That also makes transition housing more complex.

In the transition, presented in [4], a pair of triangular patches connected directly to a differential line effectively excite a rectangular waveguide which is attached perpendicular to a printed circuit board. But, there is a need for a metal backshort representing short-circuited quarter-wavelength waveguide section disposed at the opposite side of the transition PCB. In addition, in case of a multilayer transition PCB, each layer should be made of a low-loss material to minimize dielectric losses. It makes fabrication cost of the transition higher. In [5] a differentially-fed patch antenna coupled with a short-circuited parasitic patch directly excites a rectangular waveguide. Such transition uses only one top PCB layer.

All above references [1]–[5] to waveguide to differential line transition designs include the measurement results obtained by simple back-to-back structure testing. However, such measurement approach does not provide a full scattering matrix of the transition itself. Thus, to get a complete S-parameters matrix of the single transition, the “TRL” (Transmit-Reflect-Line) standard and a special calibration procedure are employed in this work.

The paper presents a V band, cost effective, compact and low-loss waveguide to planar differential line transition based on the differentially-fed patch antenna approach introduced in [5]. The transition is adapted for use in the backhaul wireless radio link operating in the 57-64 GHz band. Full-wave simulation results as well as fabrication tolerances analysis are presented and discussed. The developed transition prototypes have been fabricated and accurately measured using both back-to-back test structures as well as the TRL calibration standard.

II. Transition Description

A. Substrate Stack-Up

The transition PCB stack-up is shown in Fig. 1. Although the transition itself requires only one high frequency dielectric layer, four additional FR4 layers were added on the bottom to increase mechanical rigidity of the test PCB. Also, utilization of the hybrid "Rogers+FR4" stack-up in mmWave transceivers has a practical benefit: a low-loss Rogers layer is used to reduce the insertion loss in microwave circuits, whereas low-cost FR4 layers are aimed for low frequency signal, control and power lines that provides PCB design flexibility and effective shielding of the RF signal portion.

A transition top-layer substrate is made of relatively low-cost Rogers RO4350B substrate that is 0.168 mm thick. The dielectric constant of this material is 3.48 while the loss tangent is 0.0037 both specified at 10 GHz. Electrodeposited copper cladding with ENIG plating is ~45 um thick.

For some applications the insertion loss performance is more critical than the price aspect. In that case another substrate (for example, PTFE-based) which has a smaller loss tangent as well as smooth rolled copper cladding can be chosen to reduce dielectric and metal losses.

B. PCB and Adapter Design

The PCB topology of the transition is shown in Fig. 2. It consists of a patch radiating element coupled with a short-circuited parasitic patch, and both patches are etched inside a rectangular area that equals to the WR15 waveguide cross-section. The radiating lengths of both patches (1.2 mm) are tuned to be equal to a half of the equivalent wavelength at the transition center frequency of 60 GHz. The corners of the main patch are slightly rounded to increase the transition bandwidth. For the same purpose, the differential line end point has been shifted by approximately a quarter of the effective wavelength (0.55 mm) from the waveguide edge. Also, a matching high-impedance differential line has been added ~1.8 mm away from the transition to improve the reflection coefficient. Finally, the whole layout perimeter has been shielded by two rows of 0.3 mm via holes separated by 0.5 mm between each other. All dimensions shown at the layout drawing were optimized using full-wave simulations to get the best transition response.

To make the proposed design cost effective and easy in manufacturing, a simple low-profile waveguide adapter has been developed. It is formed by a 2 mm thick U-shaped aluminum plate facing the transition PCB at the bottom and the rectangular waveguide at the top as it is shown in Fig. 3. The slot walls of the adapter are aligned with the input waveguide walls as well as with the transition layout. The adapter height and length are optimized to be small enough to reduce transition dimensions and at the same time to decrease parasitic radiation of the patch through the adapter slot.

Fig. 3 also shows an RFIC component like, for example, BGT60 from Infineon Technologies [6] or a front-end PA/LNA directly connected to the differential line right at the end of U-shaped adapter. Thus, the length of the differential line and, consequently, its insertion loss are significantly reduced, and the RFIC-to-waveguide path loss is decreased.

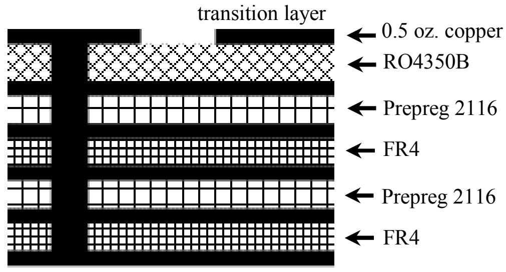

Fig. 1. Transition PCB stack-up

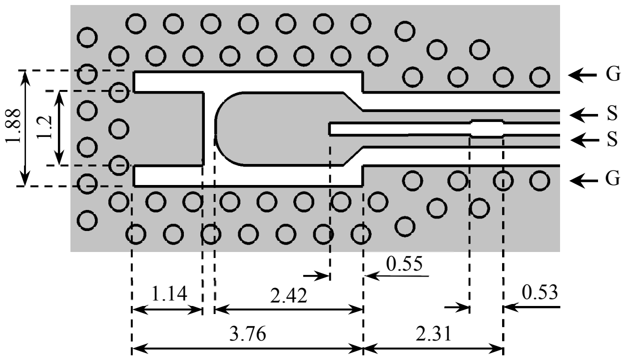

Fig. 2. Top layer PCB topology

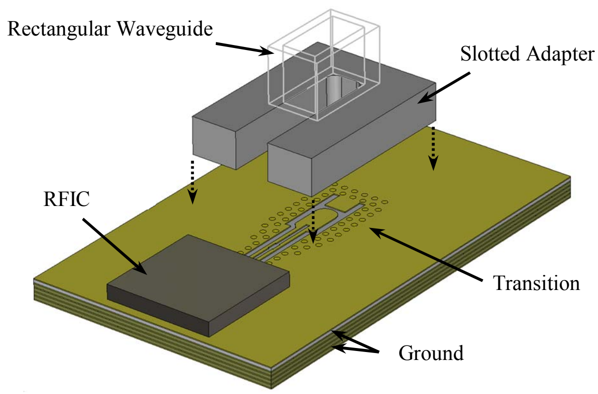

Fig. 3. Transition 3D model

C. Tolerance Analysis

Full-wave simulations as well as the parametric analysis have been performed using CST Microwave Studio to investigate the fabrication tolerances impact on the transition response. The used PCB process and Rogers 4350B laminate tolerances are specified as follows: ±0.05 for a substrate permittivity, ±0.018 mm for a substrate height, ±0.05 mm for a via hole diameter, and ±0.02 mm for widths of traces and patches etched. Simulated deviations of the transition response for the specified tolerances assuming random variations of all the above parameters are shown in Fig. 4. The transition reflection coefficient does not exceed −10 dB for any parameter set in the 57-64 GHz band. Thus, the simulation results show that the developed waveguide to differential line transition is robust to specified manufacturing mismatches.

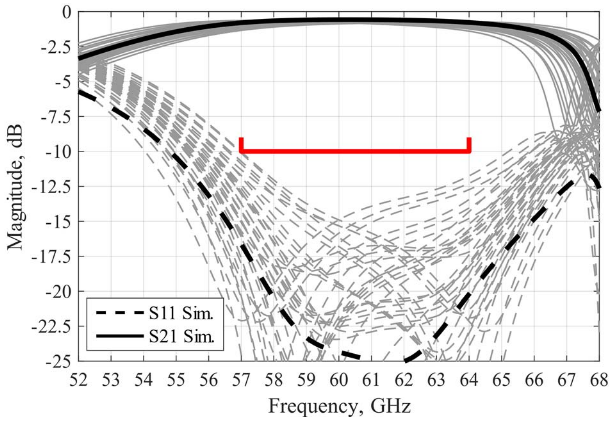

Fig. 4. Simulation results for transition S-parameters deviations due to fabrication tolerances (bold black curves for nominal sim)

III. Transition Prototypes & Measurements

A. Fabricated Samples

The fabricated test PCB shown in Fig. 5 contains the TRL calibration standard: Reflect, Line and Through circuits and the back-to-back (waveguide-to-line-to-waveguide) transition. U-shaped adapters are also shown on the right test structure. Each adapter has a standard waveguide flange, alignment pins and screw holes to facilitate VNA-based measurements.

The TRL calibration process is described, for example, in [7]. The idea of the calibration is to calculate the responses of the two fixtures on both sides of the device under test (DUT) and to de-embed it further from the back-to-back response to get the DUT scattering matrix. The DUT in the fabricated back-to-back transition is the 10 mm center portion of the differential line. And the "fixtures" consist of the designed single waveguide to differential line transitions together with the adjacent 10 mm differential lines.

The full scattering matrix of the DUT can be extracted by measurements of the Through, Reflect and Line circuits first. The differential lines lengths of these circuits for the considered case are 20 mm, 10 mm and 20.8 mm respectively. Next, the scattering matrices of both fixtures are evaluated under the assumption that they are identical. As a result, considering "Fixture A" is equal to "Fixture B", one can evaluate S-parameters of a single waveguide to differential line transition.

B. Extraction of Differential Line Loss

The measured responses of the 10 mm differential line for 3 samples as well as the simulation results are presented in Fig. 6. As far as RO4350B dielectric loss tangent is specified up to 10 GHz only, the effective loss tangent, which includes dielectric losses and rough copper cladding conductivity losses, has been extracted from the measurement data as 0.012 at 60 GHz. The simulated 10 mm differential line response, using effective tan δ value, fits well to the experimental curves. The measured differential line losses vary from 1.25 to 1.35 dB per a centimeter. In a practical RF module design (refer to Fig. 3), it gives roughly 0.7 dB insertion loss of the 5 mm long path from the transition to the RFIC input.

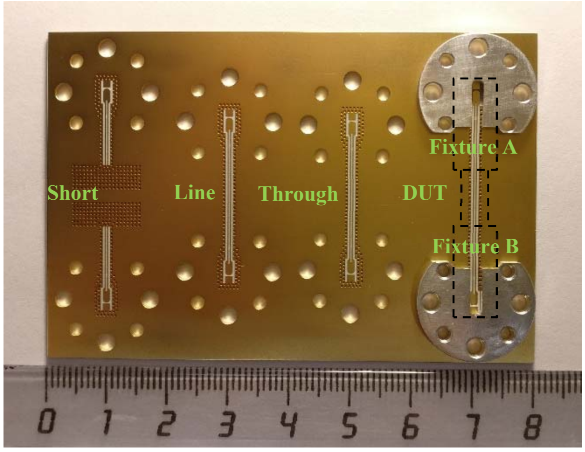

Fig. 5. Fabricated test PCB of designed waveguide to differential line transition: Short, Line, Through circuits and final test structure (from left to right)

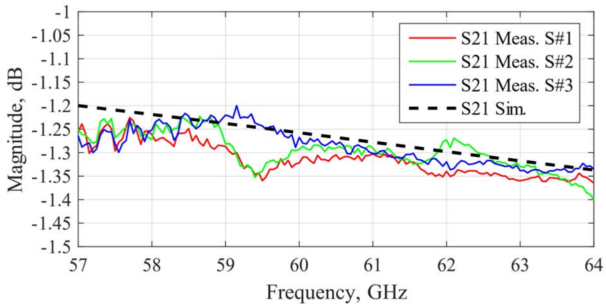

Fig. 6. Measurement and simulation S_{21} of 10 mm length differential line

C. Back-to-Back Transition Response

Measured S-parameters of the back-to-back transition connected through 20 mm differential line for 3 fabricated samples as well as the simulation results are presented in Fig. 7. It is clearly shown that the return loss suffers from strong periodic distortions caused by multiple signal reflections between the two transitions. Thus, the response of a single waveguide to the line transition can't be accurately evaluated. Nevertheless, measured responses are quite stable between 3 samples and correspond well with the simulated one.

D. Extraction of Scattering Matrix of Single Transition

The TRL calibration procedure was further applied to the collected measurement data and the scattering matrix of the developed waveguide to differential line transition has been extracted. The resulted S_{11} and S_{21} are depicted in Fig. 8 and Fig. 9 together with the simulations. The return loss curves are still susceptible by small oscillations whereas the simulation response is smooth. This can be explained by the fact that the calibration algorithm supposes the "Fixture A" response to be completely identical to the "Fixture B" response. But, in practice, the transitions fabricated on the left and right sides of the back-to-back arrangement have slightly different responses addressed to unavoidable fabrication and assembling mismatches. Nevertheless, the estimated transition return loss and insertion loss correspond well with the simulation results.

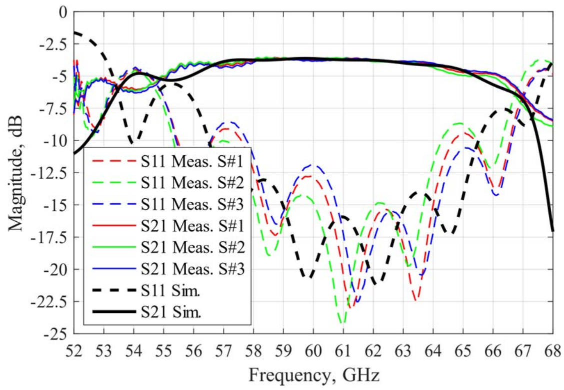

Fig. 7. Measurement and simulation results for S-parameters of back-to-back transition with a 20-mm differential line

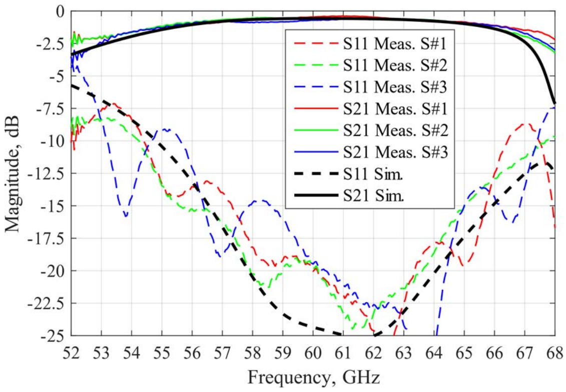

Fig. 8. Measurement and simulation results of single transition S-parameters

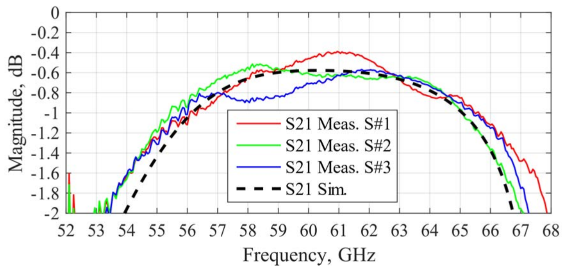

Fig. 9. Measurement and simulation result of single transition insertion loss

It is shown that the TRL-based extraction of a single transition characteristics is much more clearly exposes its performance rather than simple back-to-back structure testing. The 10-dB transition bandwidth is 12 GHz (20%), whereas 15-dB bandwidth is 8 GHz (13%). The maximum insertion loss is ~0.8 dB in the frequency range of interest: 57-64 GHz that is mostly defined by the substrate material loss tangent.

Performance comparison of the developed transition with several other waveguide to differential line transitions known from the literature is presented in Table 1. Based on the presented results the designed mmWave transition looks very promising for the mmWave transceiver applications. Moreover, it is fabricated on a single-layer RO4350B substrate and requires a compact and easy in manufacture U-shaped adapter and no backshort.

Table 1. Comparison of waveguide to differential line vertical transitions

Parameter	**Reference**			
	[3]	**[4]**	**[5]**	**This work**
Center freq.	80 GHz	75 GHz	96 GHz	60 GHz
Bandwidth	20 %	25 %	11 %	13 %
Insert. loss	1.9 dB	0.5 dB	0.5 dB	0.8 dB
Return loss	10 dB	15 dB	15 dB	15 dB
PCB layers required	single-layer	multi-layer	single-layer	single-layer
Adapter height	~5 mm (90° bend)	~2 mm (cap)	1 mm	2 mm
Substrate	ε=3.72 tan δ=0.029	RO3003	TLE95	RO4350B

IV. Conclusion

The paper presented a waveguide to differential line transition fabricated on a single-layer RO4350B substrate and operating in the 57-64 GHz frequency range. Back-to-back transition test structures as well as accompanying TRL calibration circuits were fabricated for experimental measurements. The impact of fabrication tolerances has been investigated through parametric simulations that proved good robustness of the developed transition to manufacturing and substrate mismatches. The application of TRL calibration allowed to extract the response of the single waveguide to differential line transition well agreed with the simulation results.

The transition provided 15 dB return loss over 8 GHz bandwidth, whereas the maximum insertion loss is 0.8 dB. The differential line loss has been experimentally estimated as 1.3 dB per centimeter. The transition requires only a compact and thin U-shaped adapter that is very easy in manufacturing and located between the PCB and the input waveguide. Thus, no backshort is needed and the RF top layer can be effectively shielded by the internal ground plane from the rest of low frequency and control signals and noises.

The presented results confirmed that the developed transition is cost effective and has high performance in comparison with several known designs and is perspective for use in different mmWave applications and for test purposes.

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