A Waveguide-to-Balanced-Line Transition with embedded Balun for mm-Wave Measurement Setups

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***Abstract*— Differential signaling has been the preferred choice in radio-frequency circuits due to its inherent immunity towards common mode noise and cross-talk. However, the standard lab equipment is available with single-ended coaxial connectors or rectangular waveguide (WR) interface. It makes baluns and WR-to-planar transitions the essential blocks in the measurement setups for chipsets and antennas with differential microstrip line (DMSL) feeds. For this purpose, the authors propose a novel co-design of waveguide transistion and planar balun at 60 GHz on a RF PCB with WR flange interface. The PCB design acts as a balun converting 100 Ω DMSL to 50 Ω single-ended microstrip without involving the flange. Whereas, when the flange is attached to the PCB, it redirects the signal from DMSL to the waveguide, disconnecting the single-ended microstrip port. In this way, a single differential device under test can be tested using both single-ended coaxial and WR lab equipment. In this work, the design as well as validating simulations are presented at 60 GHz license-free band. To the best of the authors' knowledge, this type of structure has not been previously reported in the literature.**

***Keywords*— Balun, Coupled line, Differential strip line, Marchand, Millimeter wave PCB, Waveguide to differential microstrip, Waveguide transition.**

I. Introduction

The advancement in semiconductor and packaging technology has enabled the economical availability of application-specific integrated circuits (ASICs) off-the-shelf. Their typical availability is in the form of system in package (SiP) encapsulated in a ball grid array (BGA) or quad-flat no-leads (QFN) type packages [1], [2]. In contrast to bare dies, these packages can not be probed, instead, they are soldered onto an evaluation board, which is then connected to the laboratory equipment [3]. In the case of validating mmWave ASICs or antennas with differential circuitry, the interfacing setup with the single-ended coaxial or rectangular waveguide (WR) lab equipment becomes complicated.

Differential signaling is widely used in high-speed circuits due to its immunity to ground bounce, common-mode interference, and crosstalk. However, single-ended designs are still in use in modern electronics due to their simplicity. In particular, standard laboratory equipment are available with single-ended coaxial interfaces. In the case of measuring a differential device under test (DUT), there are three state-of-the-art approaches: (1) standard S-parameters, (2) mixed-mode S-parameters, and (3) utilization of a balun. Post-measurement mathematical calculations are required for the first two approaches, while the most accurate one is the balun approach, providing a true differential excitation [4]. A preferable approach is to integrate a planar balun on the DUT board to reduce measurement fixture [5], [6]. In this context, several PCB-compatible balun structures have been reported in the literature [7]–[10].

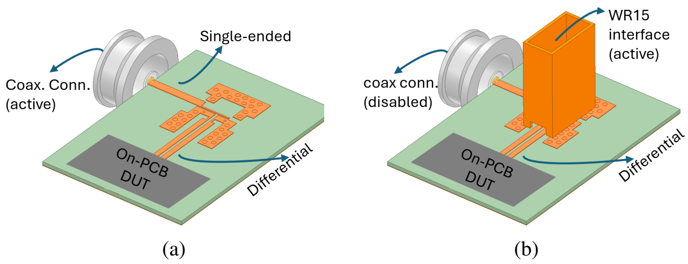


Fig. 1. (a) As a balun without flange; (b) as a WR-to-DMSL with flange.

Waveguide interface is also common for lab equipment, e.g. mmWave frequency extenders. The interfacing of PCB circuits or antennae with that equipment is preferable through a waveguide-to-planar transition directly on the DUT board [11]. In these transitions, a customized waveguide flange is fixed onto a tailor-made footprint on the PCB providing the output signal on a microstrip or DMSL as required by the ASIC or antenna. State-of-the-art WR-to-DMSL transitions utilize a $\lambda/4$ cavity, radiating patch inside the WR or field pattern matching through a ridged structure [6], [12]–[17].

For a complete validation of a DUT, devices with both coaxial and WR devices may be required. In order to simplify the measurement procedures and for a higher reliability of the measurements, a single DUT should be able to connect to both type of equipment. Consequently, in this paper a unique approach to embed a balun in the PCB launch-pad of the DMSL-to-WR transition flange is proposed. The planar structure is a 0.25 mm thick Isola I-Tera MT single-layer PCB with vias, which connects the differential DUT to a single-ended coaxial connector and works as a balun in the absence of the detachable flange, as depicted in Figure 1a. The flange can be connected to the launch pad using screws and the internally designed structure of the flange redirects the power from DMSL to WR while disconnecting the single-ended port, as shown in Figure 1b. Balun design is given in Section II. Section III presents the WR transition and integration of the balun in it. The conclusion is given in Section IV.

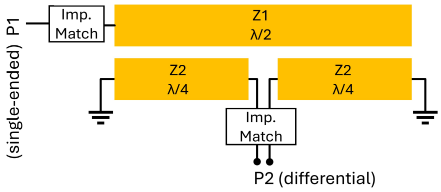


Fig. 2. Schematic of a planar Marchand balun.

II. Coupled-line planar balun

N-section and log-periodic baluns comprise microstrip bends and junctions which are not practical at mmWave frequencies. Therefore, coupled line baluns become favorable, from which, Marchand balun is one of the popular techniques due to its simplicity [18]. A Marchand balun is composed of a half-wavelength open-circuited primary conductor trace, coupled to two quarter-wavelength short-circuited conductor traces, as depicted in the schematic in Figure 2. For the commonly available PCB substrates, the quarter-wavelength approach the matched trace width at mmWave frequencies. These impractical length-to-width ratios of the transmission lines are a challenge. This work presents a solution to address these challenges by designing the balun with a higher reference impedance instead of 50 Ω. This section provides a design as a proof-of-concept, which will be purposefully modified in the next section for integration into the waveguide transition pad. Using a higher reference impedance of 100 Ω allows for practical length-to-width ratios of the microstrip sections, though at the cost of increased insertion loss. Tapers are applied at all ports to match the balun impedance with the required port impedances. Cadence AWR design environment is used with a 2.5D Axiem simulator for optimization. Figure 3 shows the optimized layout of a balun structure, where Port 1 serves as the unbalanced microstrip tuned for a 50 Ω impedance, while Ports 2 form a DMSL tuned for a 100 Ω differential impedance. The design ensures a minimum trace width, trace-to-trace clearance, and via diameter of 0.1 mm each, making it compatible with a standard PCB process.

Simulation results in Figure 4a present the amplitude response of the input matching at single-ended and differential ports of the balun. Each port is tuned for its peak resonance at slightly different frequencies around 60 GHz, providing an overall wider impedance bandwidth. The 10 dB return

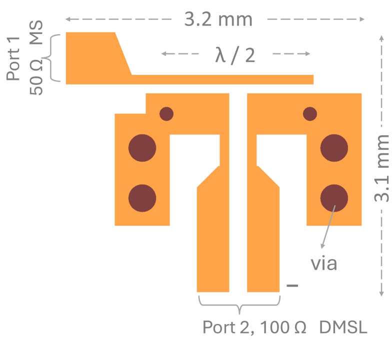


Fig. 3. Optimized layout of the planar Marchand balun.

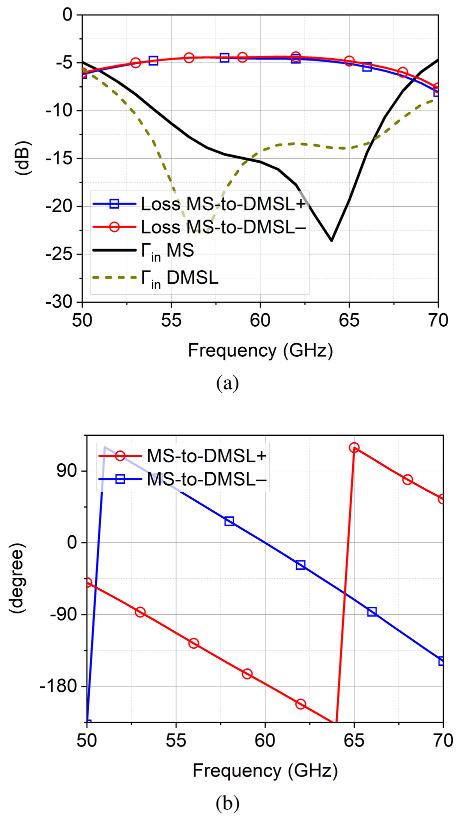
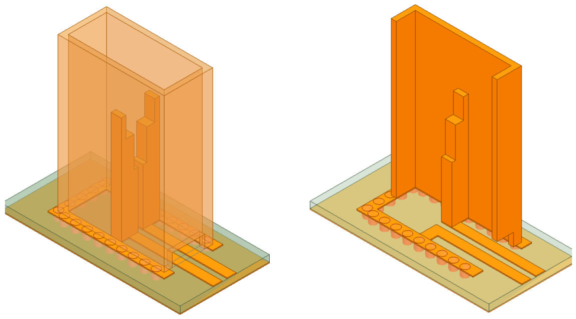


Fig. 4. Marchand balun simulation response: (a) amplitude; (b) phase.

loss bandwidth is 13.5 GHz. The amplitude imbalance in the differential port is < 0.5 dB within the impedance-matched bandwidth. Figure 4b show the maximum phase imbalance in the differential port is 12° occurring at 66 GHz. Based on the input matching criteria, this balun achieves a relative bandwidth of 22 %. The bandwidth and conversion loss performance is slightly inferior to the previously reported planar balun on the same frequency and substrate [9]. However, this design is significantly simpler and avoids the design and manufacturing complexity of bondwire interconnects at a millimeter wave band [19].

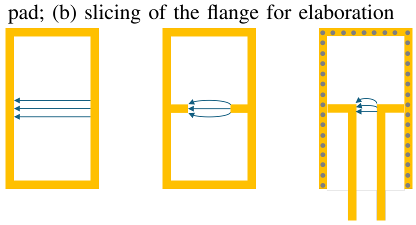
III. Planar-to-waveguide transition

For the transition design, a ridged waveguide approach is adopted eliminating the need for a back-cavity, as proposed in [17]. WR15 waveguide size is considered, which covers 40 – 75 GHz with the fundamental mode. The transition design features a double-ridged WR15 flange. The ridges sequentially expand towards the waveguide center and finally touch the corresponding contact pads on the PCB, which are quarter-wave in length, exciting a DMSL as illustrated in Figure 5. A tunnel on the narrow side allows DMSL's exit from the waveguide's metallic body, without short-circuiting with it. A via fence on the launch pad boundary prevents signal leakage into the substrate. In this way, the structure progressively confines the field pattern from fundamental mode to the ridged waveguide and then excites the DMSL as step-wise shown in Figure 6.



(a) (b)

Fig. 5. Structure of the WR-to-DMSL transition: (a) flange placed on the designed PCB pad; (b) slicing of the flange for elaboration

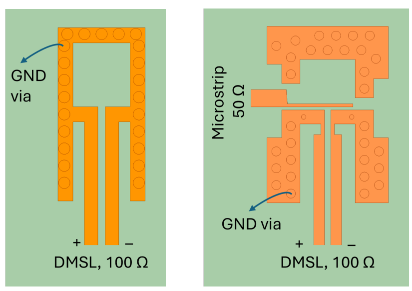


(a) (b) (c)

Fig. 6. Electric field pattern: (a) fundamental WR mode; (b) confinement due to ridges, (c) at the contact pads.

This work introduces a novel approach to introduce the balun into the described pad structure by taking advantage of the already existing short-circuited quarter-wavelength pads. A half-wavelength open-circuited stub is coupled with them realizing a Marchand balun, as shown in Figure 7. The microstrip exits from the pad boundary through a discontinuity in the via fence. The size of the pads is re-optimized to support adequate coupling for the balun in the absence of the flange, as well as, minimize the reflections in WR when the flange is interfaced. The planar balun becomes operational in the absence of the flange, whereas, when the metal flange is attached to the pad, it creates a short circuit for the single-ended microstrip since it does not have any tunnel for it, as it has for DMSL. In this way, the DUT on the PCB can be connected to coaxial or WR15 equipment just through the placement and removal of the flange.

Ansys HFSS has been used to validate the idea and produce an optimized design at 60 GHz. Simulation results are given in Figure 9. Figure 9a plots the input reflection coefficients of the integrated balun, whose structure is modified



(a) (b)

Fig. 7. Alteration of the PCB pad: (a) original pad; (b) modified for balun

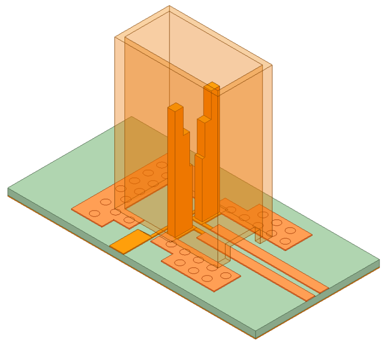
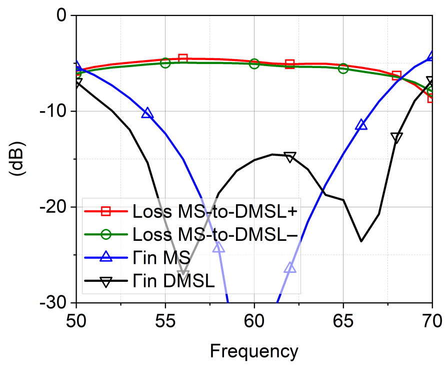
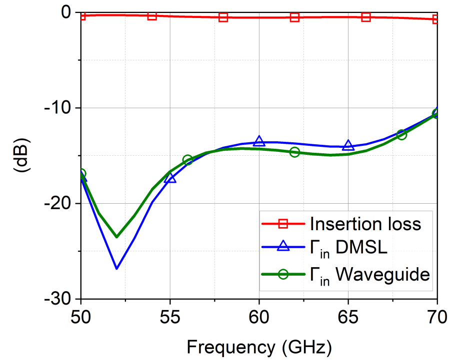


Fig. 8. The perspective of the proposed structure



(a)



(b)

Fig. 9. Simulation results: (a) balun function, when the flange is removed; (b) WR-to-DMSL transition, when the flange is on place.

from the original design given in Figure 3. The input-matched bandwidth is almost the same i.e. 54 – 66 GHz, however with a slightly increased insertion loss, especially at higher frequencies. Additionally, the amplitude imbalance is also slightly high. This is due to the upper portion of the waveguide launch-pad boundary, existing in the vicinity and coupling to the half-wavelength open stub. Figure 9b shows the input matching and insertion loss of the structure when the flange is placed on the pad, i.e., the input reflection coefficients at the WR15 and DMSL sides, and the conversion loss. This structure shows a broadband performance covering 47 – 70 GHz, i.e., a large portion of V-band with at least 10 dB input matching. The maximum conversion loss is 0.8 dB over the usable bandwidth. In terms of relative bandwidth, this design fairly competes with the one in [17].

IV. Conclusion

Differential signaling is a preferred choice in mmWave integrated circuits due to its noise immunity and signal integrity. The majority of the available mmWave ASICs in the market are already packaged, requiring the development of an eval-board for their application-specific validation in the lab. Measurements of differential eval-boards and their corresponding differential antennas require a complex mmWave measurement setup for their interfacing to single-ended coaxial or WR-type lab equipment. Standalone mmWave baluns are not widely available and off-the-shelf waveguide-to-planar transitions are very expensive. This work reports a planar 60 GHz balun and a waveguide-to-planar transition. Furthermore, this work presents an approach to merge the said two designs in to a two-in-one block; offering DMSL-to-single-ended and DMSL-to-WR transition, selectable by placement and removal of the WR-flange. In this way, a single DUT on the eval-board can be connected to both type of lab equipment. To the best of the authors' knowledge, this work is the first report for such a dual-function structure. The simulation results show the balun function covering 22% of relative bandwidth at 60 GHz, while the waveguide transition covers 38% relative bandwidth. This work provides the proof-of-concept through the simulation results, while the manufacturing and measurement will be carried out in the upcoming steps.

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