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Novel Low Loss Millimeter Wave Transition from Waveguide to Microstrip Line Suitable for MMIC Integration and Packaging

A. Uz Zaman, *Member, IEEE,* V. Vassilev, H. Zirath, *Fellow, IEEE* and N. Rorsman, *Member, IEEE*

Abstract— **This paper presents a unique low loss transition from microstrip to full height rectangular waveguide at W-band. This microstrip transition can be made as a part of the mm-wave MMIC of arbitrary size and thus avoid the use of bond wires at the high frequency port of the MMIC circuit. As a result, the MMIC can be coupled directly to the waveguide. The working principle of the transition is based on electromagnetic coupling where the coupling between the microstrip mode and the TE$_{10}$ waveguide mode is achieved via a resonant cavity. A Perfect Magnetic Conductor (PMC) surface is placed over the cavity to facilitate smooth coupling of EM energy from the microstrip line to the cavity and then from the cavity to the waveguide. The PMC surface also suppresses the unwanted waveguide mode coupling to the oversized MMIC substrate. The measured back to back transition works over the frequency band 80-114 GHz (relative BW of 35%) with minimum return loss of 13.5dB. The total insertion loss of the manufactured prototype is found to be varying from 0.54-0.803 dB which implies a single transition loss of less than 0.27-0.4015 dB in W-band.**

Index Terms— **E-plane probe, Perfect magnetic conductor (PMC) packaging, Perfect electric conductor (PEC), Electromagnetic coupling, etc.**

I. INTRODUCTION

MILLIMETER-WAVE frequency bands are receiving increasing interest for many wireless applications such as high-resolution imaging, high-speed wireless data links, short-range radar etc. Most of the millimeter-wave integrated systems demand better loss performance, greater miniaturization with complex circuit functionality and enhanced reliability. Although MMICs are very essential components in any wireless module, devices such as antennas, high-quality-factor (HQ) filters based on waveguide technology are also required. Therefore, low-loss microstrip-to-waveguide transitions are also essential for packaging and integration of these circuits. Several kinds of microstrip-to-waveguide transitions have been proposed in the millimeter-wave band recently. E-plane probe transitions [1-3], vertical transitions [4] and the inline transitions with stepped waveguide height [5, 6] are the most popular ones. Among these, the E-plane probe has been used extensively due to wideband performance and modular simplicity. The vertical transitions are typically narrow band and the inline transitions require galvanic contact and rather long waveguide as there are 3 or 4 quarter wavelength stepped sections.

However, the typical E-plane type of transition suffers from some drawbacks. The sizes of the channel that holds the microstrip substrate and the E-plane probe must have very small width and height so that all the higher order waveguide modes are under cut-off within the band of operation [7]. Nevertheless, due to practical reasons (dc pads, bias lines etc.), a highly integrated multi-functional MMIC usually has bigger size and does not fit in that narrow channel. In many of the MMIC integration case, there is an extra piece of substrate with sub-critical dimension for the microstrip probe and it is placed in the narrow waveguide channel as an overstretched part of main MMIC [8]. The main MMIC is usually placed in a separate cavity and the RF output of the MMIC is electrically connected to the microstrip probe by bond wires which are unwanted due to parasitic effects such as high series inductance. Also, wire bonding to the miniature sized RF pads is linked to repeatability and yield issues. Moreover, E-plane transitions are not always suitable as packaging solutions for integrating RF electronics to the components such as H-plane filters, antenna beam forming networks and waveguide slot arrays. For these components, the waveguides are usually split in H-plane and usually inline transitions are more of interest.

In this work, we propose a novel inline solution for the above mentioned applications and we use a transition in an oversized substrate inside the waveguide split-block without allowing any higher order mode coupling to the substrate. At this moment, we have validated the concept with passive back to back transition. The measured results agree well with the simulation and we are able to demonstrate a very good coupling between the RF signals in the microstrip line and the waveguide section over a significant bandwidth.

II. PROPOSED CAVITY BASED TRANSITION WITH PMC LID

The schematic of the proposed microstrip to waveguide transition is shown in fig.1. The waveguide is split in H-plane in this case and the transition consists of two metal blocks. The operating principle of the transition is based on the EM coupling via a resonant cavity and the proposed transition is
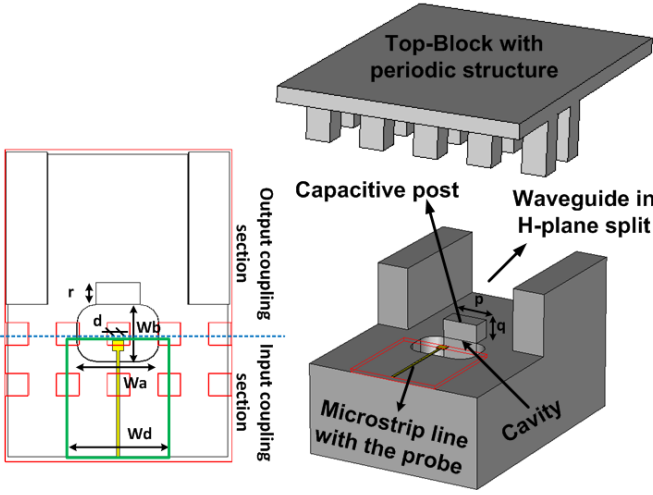
Fig.1 Schematic of the transition, W_d = 2mm, W_a = 1.575 mm, W_b = 1mm, r = 0.4mm, d =0.2mm, p = 0.8mm, q = 0.4mm, depth of the cavity = 0.75mm

composed of three sections: a metal cavity, input coupling section for the cavity and the output coupling section for the cavity. The cavity is designed for the first order resonant mode and the depth of this cavity is about λ/4. A microstrip line with a square probe section is placed above the cavity which couples the Q-TEM mode of the microstrip line to the cavity. This is considered as an input coupling section for the cavity. It is important to note that, the part of the substrate which is extended over the cavity does not have a ground plane. Similarly, at the other end of the cavity, a waveguide section also couples the TE_{10} mode to the cavity via a capacitive post. This section could be considered as the output coupling section for the same cavity. In order to effectively enable the electromagnetic coupling, a PMC surface with periodic texture has been placed on top of the cavity section. The PMC surface suppresses any radiation from the open ended waveguide and forces the electromagnetic field to couple to the bottom cavity. Also, it suppresses any unwanted substrate mode in the oversized substrate [9] and also provides backward isolation of -40dB for this transition prototype. The substrate is soldered on the bottom split-block and can be of any thickness between 80-125μm. Also, the shape of the cavity is chosen to be rectangular with corners having a radius of 0.25mm for practical and manufacturing implication.

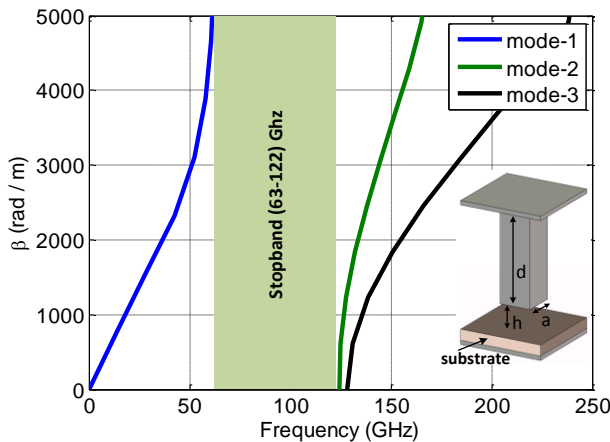Fig.2 Dispersion diagram of the pin; a = 0.425 mm, d = 0.82 mm, pin period = 1 mm and h = 0.200 mm, substrate thickness = 80μm, $ε_r$ = 9.9

On the top split-block, we have used a periodic metal pin structure which acts as a perfect magnetic conductor (PMC) and suppresses all unwanted radiation from the open ended waveguide and forces the field from the waveguide to couple to the cavity. Also, it suppresses any higher order mode coupling to the microstrip line without disturbing the desired microstrip mode. This theory of suppressing higher order parallel-plate modes by using PEC-PMC parallel-plate cutoff condition is well described in [9, 10]. The periodic pin structures are designed by considering the height of the pin to be approximately λ/4 and then looking at the dispersion diagram of a single pin unit cell within a periodic boundary condition enforced around the unit cell. Fig.2 shows the dimensions of the designed pin to be used in this work and the computed dispersion diagram for the single pin unit cell.

III. SIMULATED AND MEASURED RESULTS FOR THE PROPOSED TRANSITION

The single transition has been designed at W-band and simulated first with smooth top plate and top block with periodic metal pins. In case of the periodic metal pin, we have kept 0.2 mm gap between the pins and the substrate. The simulated S-parameters for the proposed transition are presented in fig.3(a). As is seen from fig.3(a), the transition does not work in case of smooth metal lid. But in case of the periodic pin lid, the waveguide field couples effectively to the microstrip line.
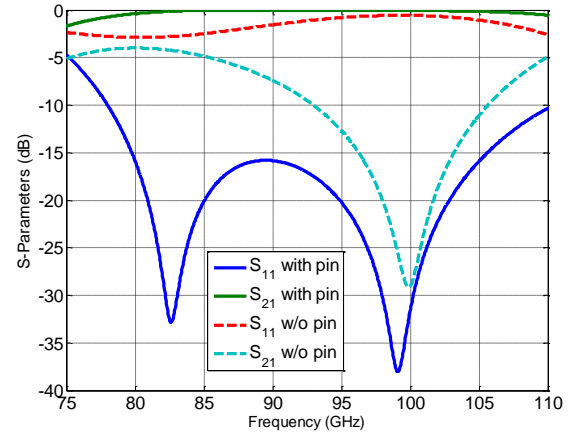

Fig.3(a) Simulated results for the single transition with and without metal pins, substrate thickness = 80μm, $ε_r$ = 9.9
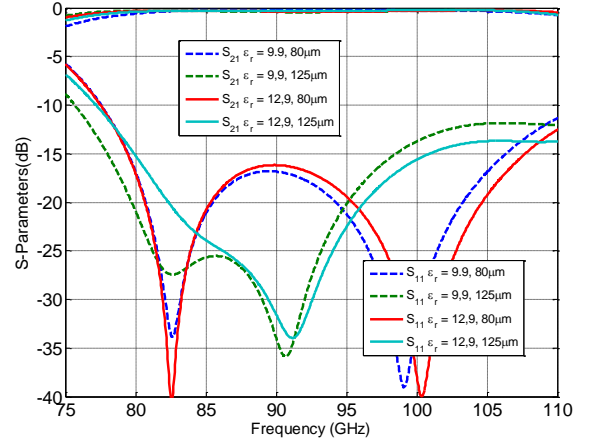

Fig.3(b) Simulated results for the single transition with substrate thickness and $ε_r$ variation.

To check also the robustness of the transition, we have simulated the transition with the typical values of substrate thickness and ε_r used for RF MMICs at millimeter wave frequency range. These results are shown in fig.3(b) and we can conclude that the performance of the proposed transition is not effected drastically due to substrate thickness and ε_r variation.

In order to validate the design, a back-to-back prototype with periodic metal pin lid has been fabricated in brass. We have used an 80µm SiC substrate ($\varepsilon_r = 9.9$) which was fabricated by our in house process at Chalmers. The total substrate size is 2×1.75 mm^2 and on this substrate a microstrip line with two probes has been printed. The prototype has been measured with Agilent PNA (N522A) and Agilent extender modules (N5260-6003). The measured results and the picture of the prototype are presented in Fig.4 and Fig. 5 respectively.
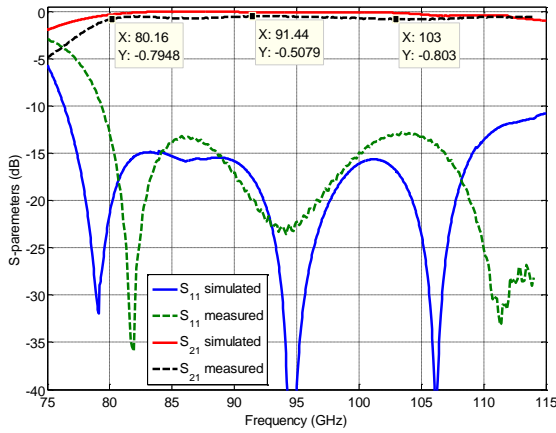

Fig. 4 Simulated and measured S-parameter results for the back-to-back transition.
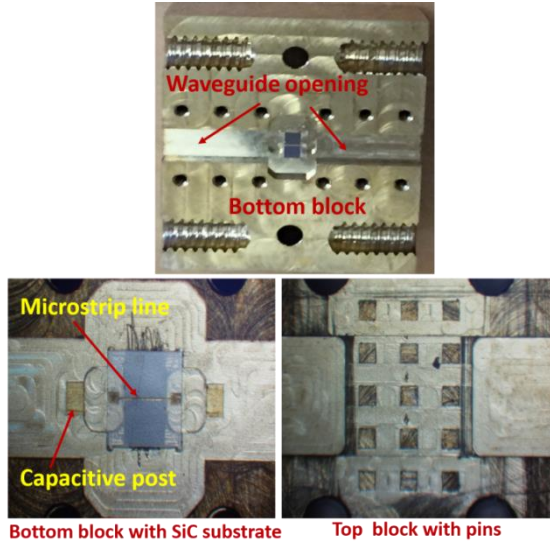

Fig. 5 Manufactured back-to-back transition with metal pin lid.

Measured back-to-back prototype is found to work within 80-114 GHz (BW: 35%) with reasonable S_{11} and S_{21} parameters. The measured S_{11} is consistent with its simulated values. The small discrepancy between the simulated and measured S_{11} is attributed to mechanical assembly errors which is unavoidable at W-band. The measured $|S_{21}|$ of the back-to-back prototype is maximum 0.803 dB over the entire 80-114 GHz frequency range and follows well the trend of the simulated S_{21}. We also want to mention here that the S_{21} consists of transition losses, the losses in the 1.75mm mm long microstrip line and also the waveguide conductor losses. Considering all these losses, the loss per single transition can be considered to be lower than 0.4dB. It is also important to remind that, no unwanted mode coupling occurs within the band of interest and the S_{21} remains quite flat over a relatively large bandwidth.

IV. CONCLUSION

In this paper, we have demonstrated a low loss millimeter wave transition from microstrip to rectangular waveguide where the microstrip transition is located in an oversized substrate and the substrate can be placed inside the waveguide block. The transition is designed with the help of a resonant cavity which electromagnetically couples the EM field from the microstrip line to the waveguide. To facilitate effective EM coupling, a top metal block having periodic metallic pins with $\lambda/4$ height has been used. The measured results show low insertion loss, good return loss and broadband performance for the back-to-back prototype of the proposed transition. This novel transition scheme is appropriate for a multifunctional MMIC integration where the substrate parameters and size does not play critical role. Also the integration can be performed without the need of RF bonding which is a big advantage compared to today's state of the art techniques.

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