A Waveguide to Differential Stripline Transition for Planar mmWave Antenna Measurements

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***Abstract*—In this paper, a transition from rectangular waveguide to differential stripline is introduced, allowing a butt joint connection of the waveguide and a planar differential network, without using an elaborate manufacturing process or further elements like a $\lambda/4$ back-short waveguide. It can be used for different purposes, where microwave probe feeding isn't applicable or available, especially for undisturbed radiation pattern measurements of differential antennas. It is designed for a center frequency of 77 GHz, obtaining a relative bandwidth of 17 % for 10 dB return loss and a high common mode rejection. Design, simulation and measurement results of the transition are presented. The transition is used in a setup to measure planar balanced-fed millimeter-wave antennas. This setup together with additional measurement results of the antenna are shown.**

***Index Terms*—waveguide transition, differential stripline, multilayer substrate, W-band, millimeter-wave antenna, aperture-coupled antenna.**

I. Introduction

In the course of utilizing the millimeter-wave frequency regime for commercial applications, e.g. automotive radar or high speed wireless communication, more and more monolithically integrated circuits are available or are currently under development. These MMICs tend to use differential active circuits, requiring an optimal transition to the traditionally used waveguide structures at high frequencies. Several longitudinal transitions to single-ended microstrip lines have been reported, utilizing antenna-like or finline structures. On the other hand, the classical waveguide probe coupling as vertical transition offers a wide bandwidth, but needs a shorted quarter wavelength waveguide in extension. In [1] and [2], vertical transitions to single-ended microstrip lines are presented, using either two patches and a complex multilayer LTCC for gaining bandwidth, or a back-short waveguide with a microstrip probe feed. These designs are either too complex or not expandable for differential networks in a desired low-cost substrate multilayer configuration. In [3], a novel transition from waveguide to differential microstrip line is presented, which offers a wide bandwidth, but suffers from the needed metal cap in extension of the waveguide.

Our aim is to present a simple transition from rectangular waveguide to differential stripline, which can be easily adapted to many different multilayer substrate configurations. After introducing the proposed design, simulation and measurement results of the transition are shown. It is used in the characterization of a planar balanced-fed millimeter-wave antenna [4], where the feeding network and the radiating structure is seperated by a ground plane in the multilayer. The radiation parameters are obtained without disturbance by the measurement setup, in contrast to the typical differential microwave probe setup. The measurement setup is presented together with simulation and measurement results of the antenna.

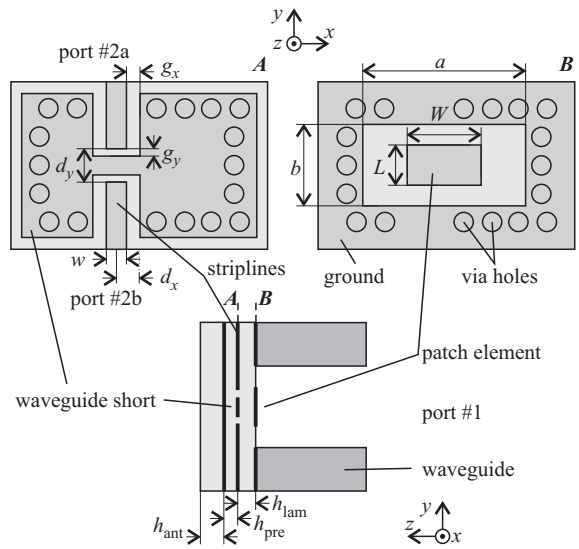

Fig. 1. Cross-sectional views of the transition and its parameters

II. Design Of The Transition

A promising transition is presented in [5], where the mode conversion between the waveguide and two in-phase excited microstrip lines is achieved by using the resonance of a patch element. This is therefore independent from a defined $\lambda/4$ back-short waveguide. Utilizing this design as a basis, a second stripline is embedded to realize the differential output. In Fig. 1, three cross-sectional views of the proposed transition are shown. The planar structure consists of two low-cost substrate layers (RO4350/RO4450 laminate and prepreg by Rogers Corporation), embedding the shorted waveguide end and the inset striplines (view ***A***, single-ended ports #2a and #2b) between two ground layers. The waveguide short is connected to the lower ground layer by several via holes, extending the rectangular waveguide (port #1) into the substrate.

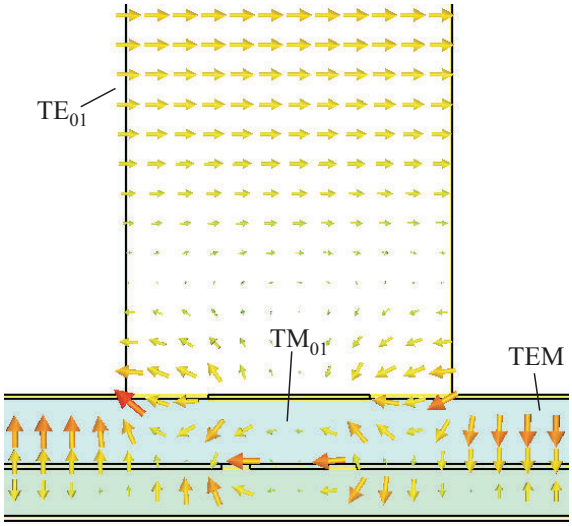

Fig. 2. Electric field distribution and modes in the transition at 79 GHz

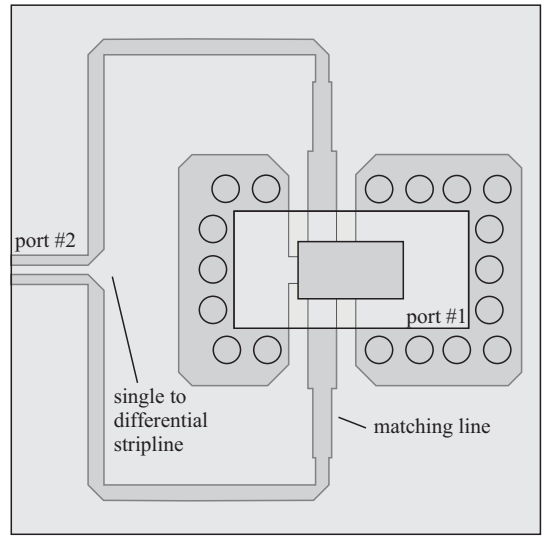

Fig. 3. Top view of the transition including matching network and differential output

This lower ground layer has a cut-out with the size of the used WR-10 waveguide, gaining clearance for the rectangular patch element (view $\boldsymbol{B}$).

The functional principle can be easily explained using the electric field distribution, shown in Fig. 2. The dominant TE_{10} mode of the waveguide is converted to the TEM mode of the stripline by exciting the dominant TM_{01} mode of the patch. By placing the two striplines in opposite to each other, the desired phase difference of 180° can be achieved over a wide frequency range. Both striplines are offset from the middle of the patch, in order to not excite the higher order TM_{20} mode of the wide patch [5]. The parameters of the patch L and W are used to tune the TM_{01} mode of the patch to match the operation frequency of the transition and the requirements of the multilayer substrate system, defined by the height of the laminate h_{lam} and its permittivity $\varepsilon_{r,lam}$. The parameters of the stripline, its width w, spacing d_y and excentricity d_x, as well as the gaps g_x and g_y can be optimized for optimal transmission, yielding good return loss and high bandwidth. Considerations upon theese parameters are presented in [5] and can be transfered one-to-one.

In order to combine the two out-of-phase single-ended striplines, a single-to-differential stripline T-section is designed. Aiming towards a differential line impedance of 100 Ω, the optimal single-ended line impedance was calculated to 55 Ω, which has to be matched to the input impedance of the transition. The resulting design can be seen in Fig. 3, showing the stripline layer with the combined differential port #2 and the slight transparent waveguide port #1, surrounded by via holes.

For the desired millimeter-wave antenna, the multilayer consists of two sheets of RO4350 laminate with heights of $h_{lam} = 0{,}254$ mm and $h_{ant} = 0{,}338$ mm, connected by a sheet of RO4450 prepreg with a height of $h_{pre} = 0{,}2$ mm. The dielectric parameters of the substrate are set to $\varepsilon_{r,lam} = 3{,}9$, $\varepsilon_{r,pre} = 3{,}8$ and $\tan\delta_\varepsilon = 0{,}008$ in the simulation, gathered from a previous characterization of the substrate, since the values in the datasheet are specified only for 10 GHz.

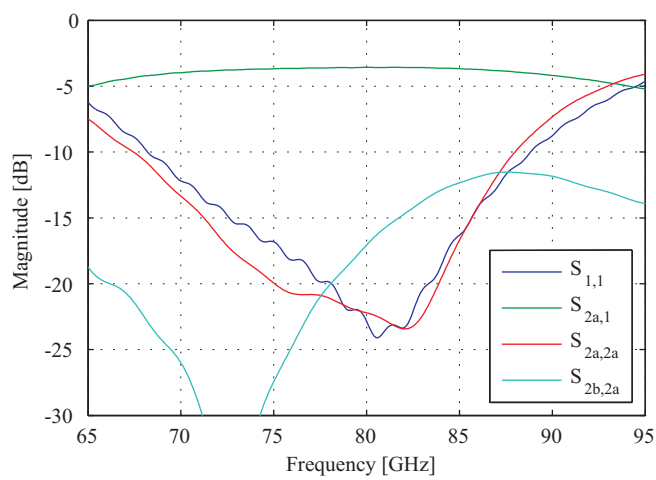

Fig. 4. Simulation result of the single-ended transition

III. Simulation And Measurement Results Of The Transition

In the first design step, the transition was optimized without the single-to-differential stripline T-section, as shown in Fig. 1. As can be seen in the simulation results in Fig. 4, the return loss at all ports of the transition is better than 10 dB between 68,2 GHz and 88 GHz. The power is divided equally with a 180° phaseshift to the single-ended striplines, which are isolated better than 12 dB over the entire band.

In order to measure the transition with our setup, which consists of two frequency converters ZVA-Z110 together with the four-port network analyzer ZVA24 by Rohde&Schwarz, a back-to-back configuration with two transitions and a 23 mm long differential stripline inbetween has been manufactured.

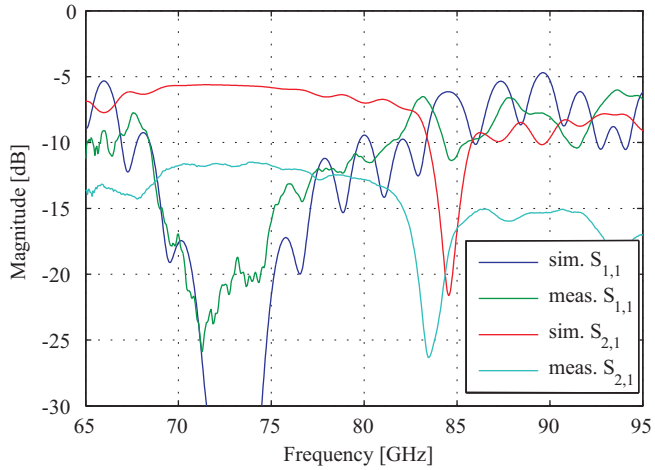

Fig. 5. Simulation and measurement results of the back-to-back setup of the transition

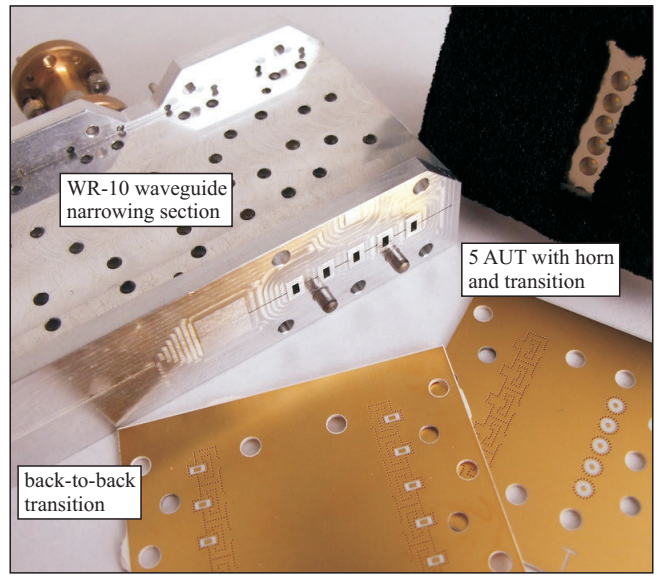

Fig. 6. Parts of the measurement setup: multilayer back-to-back transition, multilayer transition for feeding a millimeter wave antenna, standard WR-10 waveguide feed splitblock, frontplate with horn

The parts of the surrounding hardware are shown in Fig. 6. The simulation and measurement results of the proposed transition are presented in Fig. 5 and are in very good agreement. The return loss of the back-to-back measurement exhibits a 10 dB bandwidth of more than 13 GHz, although there is a ripple due to some reflections. The measured insertion loss in the desired band shows higher attenuation than expected, which is caused by higher dielectric losses, but is still acceptable. Due to the symmetric design, this transition exhibits a low conversion but high rejection of the common mode, which contributes to the seen ripple in the results. By surrounding the whole transition with via holes, the crosstalk to neighbouring transitions in a row configuration can be suppressed effectively.

IV. Antenna Measurement Setup

The most usefull feature of the proposed transition is its robustness in a measurement setup and simplicity of design, together with the possibility to adapt it to different multilayer setups for miscellaneous measurement tasks. One of the demanding tasks is e.g. the measurement of radiation pattern of planar millimeter-wave antennas, especially if they are differential fed, without disturbing the measurement by the feeding structure. Two antennas presented in [4], a straight and a rotated by 45° balanced-fed patch-excited horn antenna, are measured using the proposed transition, utilizing the aforementioned frequency converters and a network analyzer, some standard WR-10 waveguide parts and, for a row of up to five antennas, a narrowing waveguide splitblock. These parts are shown in Fig. 6 and can be easily mounted on each other. For measuring the radiation pattern, the antenna under test together with the frequency converter is attached to a test-positioner system in an anechoic chamber, allowing for a spherical scan over the whole hemisphere without disturbance. Due to moving constraints of the farfield measurement setup, angles bigger than 60° could not be reached.

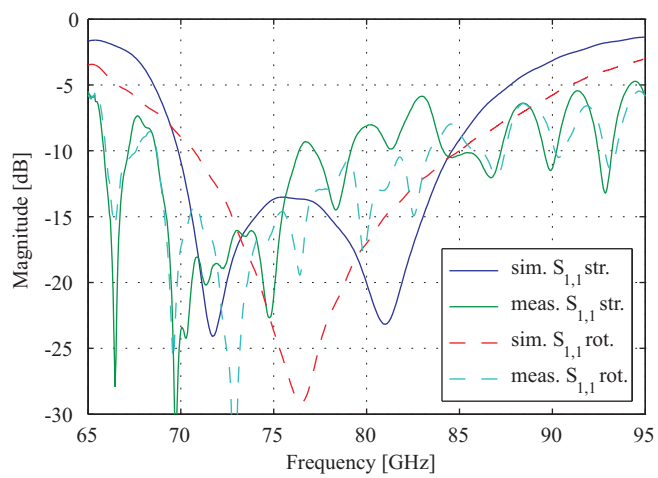

Fig. 7. Simulation and measurement results of two different antenna designs: straight antenna (solid line) and rotated antenna (dashed line)

V. Simulation And Measurement Results Of The Antennas

At first, the simulated and measured scattering parameters of the two antennas are discussed. The results are shown in Fig. 7, exhibiting a 10 dB bandwidth of minimum 11 GHz for the straight, and minimum 15 GHz for the rotated antenna, taking into account the ripples of the return loss. The resonance frequency is slightly shifted downwards, resulting from manufacturing tolerances and variations in the permittivity. Due to the lack of appropriate calibration standards, the measured results suffer from the influence of the transition, expecially above 80 GHz. Nonetheless are the results in good agreement and prove the case for the antenna design.

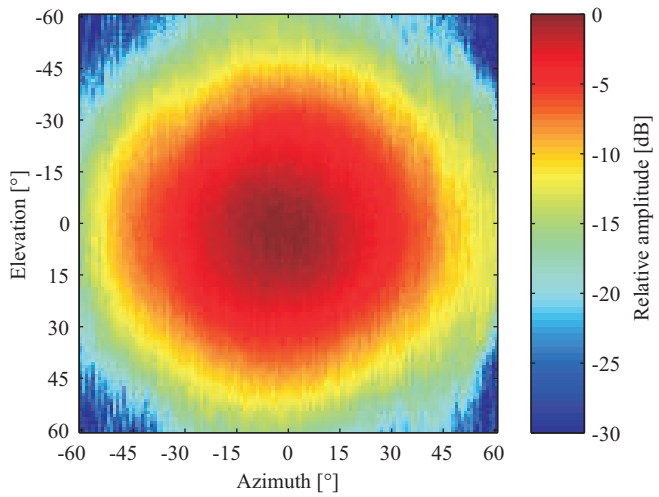

Fig. 8. Measured copolarized amplitude pattern of the straight antenna at 79 GHz

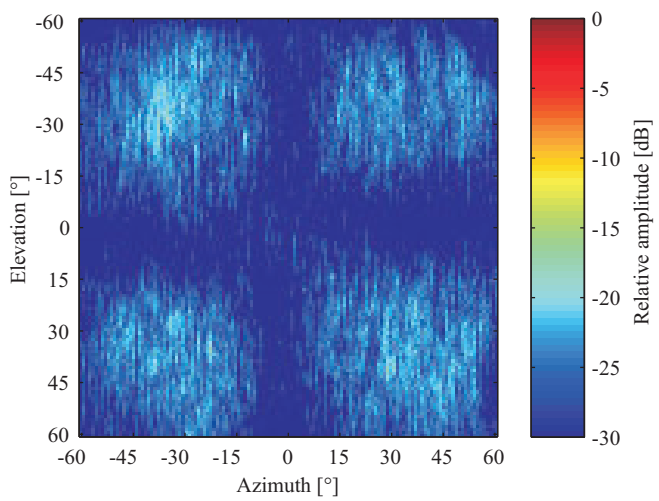

Fig. 9. Measured crosspolarized amplitude pattern of the straight antenna at 79 GHz

At last, some radiation pattern results of the straight antenna are shown at 79 GHz. Normalized to its measured gain of about 9 dBi, Fig. 8 and Fig. 9 illustrate the copolarized and crosspolarized radiation amplitude pattern. Beamwidths in the E-plane (azimuth) and H-plane (elevation) are almost identical at 50° with very low sideway radiation and no sidelobes. The crosspolarized component is at least 18 dB below the maximum in each quadrant. Another important figure of merit is the phase pattern, which is presented in Fig. 10. The phase pattern is quite plain over a wide range of viewing angles, making the antenna very suitable for digital beamforming applications or synthetic aperture radar systems.

VI. Conclusion

A transition from waveguide to differential stripline at millimeter-wave frequencies is presented. Its simple construction is especially suitable for radiation pattern measurements of planar balanced-fed antennas, where disturbances due to

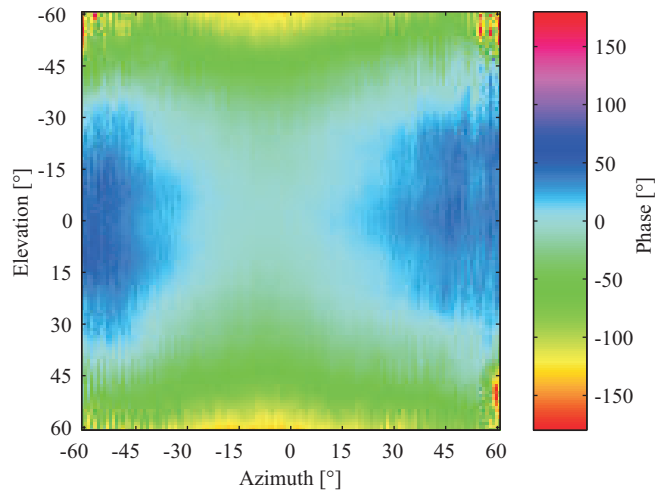

Fig. 10. Measured copolarized phase pattern of the straight antenna at 79 GHz

microwave probe measurements or adjacent metal parts are undesirable. The design can be easily adapted to miscellaneous multilayer setups. The design procedure together with simulated and measured results of the transition are presented and show good agreement, with a relative bandwidth of about 17 % for 10 dB return loss and acceptable insertion loss.

Parameters of a planar balanced-fed millimeter-wave antennas are measured, including return loss and amplitude and phase radiation pattern. Simulated and measured results agree very well, exhibiting a relative bandwidth of minimum 15 % for 10 dB return loss, a symmetric radiation pattern with low crosspolarization and a plain phase pattern.

Future research activities involve bandwidth enhancement of the transition by the use of parasitic patches and the measurement of different multilayer configurations, together with further antenna designs.

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