Robust Microstrip-to-Waveguide Transitions for Millimeter-Wave Radar Sensor Applications

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***Abstract*—Two robust millimeter-wave microstrip-to-waveguide transitions are proposed in this paper. The central operating frequency is 77 GHz, for collision-avoidance radar applications. The microstrip line has been first transformed into an air-filled rectangular waveguide whose height is equal to the substrate thickness. Then, a conventional multisection $\lambda/4$ transformer has been used in the first transition, and a patch antenna in the second transition, to transform to the feeding WR12 waveguide. Experimental results for the first transition show an insertion loss less than 2 dB and a return loss better than 15 dB in a bandwidth of 3 GHz for the back-to-back transition.**

***Index Terms*—Millimeter-wave, microstrip line, rectangular waveguides, transition.**

I. INTRODUCTION

MANY advanced millimeter-wave systems have been implemented in miniature hybrid microwave integrated circuit (MHMIC) and monolithic microwave integrated circuit (MMIC) technologies in recent years. Due to the design simplicity, most of these integrated circuits have been built using microstrip transmission lines. Although MHMIC and MMIC are the predominant technologies used in modern millimeter-wave systems, devices such as antennas, high-quality-factor (HQ) filters and oscillators based on waveguide technology are sometimes required. Therefore, a microstrip-to-waveguide transition is obligatory to interconnect these circuits. Furthermore, such transitions are requested for device and circuit characterization with conventional waveguide measurement systems.

Several kinds of microstrip-to-waveguide transitions have been proposed in the millimeter-wave band, such as transition with short-circuited waveguide of 1/4 guide wavelength [1], transitions via antipodal fine line [2], or via ridged waveguide [3], [4]. They provide reasonably good results, but they typically are not very well suited for a simple, low-cost, and compact integration with planar circuits due to the fact that they are rather long and their fabrication is complicated [5]. Most recently, new kinds of microstrip-to-waveguide transitions have been proposed. They are based on the concept of slot-coupled and capacitive-coupled microstrip antennas [5]–[9]. In these transitions, the metal waveguide structure is situated on the backside of the microstrip line and perpendicular to the planar substrate. Both sides of the substrate have to be etched. This transition is not well suited between a single-layer slot-coupled or capacitive-coupled microstrip antenna and waveguide because the microstrip antenna elements must lie on the same backside as the waveguide metal structure. In addition, circuits with more than one transition cannot be built as small as possible because the size of the planar circuit is limited by the waveguide flange size, which is about 2 cm for WR15, WR12, and WR10.

In order to overcome the problem related to the first kind of microstrip-to-waveguide transitions (e.g., long and not cost-effective transitions) and the problem related to the second kind (i.e., minimal size of planar circuits limited by the waveguide flange size and the fact that some kind of microstrip antennas cannot use them as transitions to the feeding waveguide), we have developed two microstrip-to-waveguide transitions based on a new concept. The axis of the rectangular waveguides is parallel to the planar circuits so that the planar circuit can be made as small as possible.

II. NOVEL TRANSITION CONCEPT

The main idea is to connect first the microstrip line to an air-filled rectangular waveguide (whose height is equal to the substrate thickness), and then to use a conventional multisection $\lambda/4$ transformer (in the case of the first transition) or a patch antenna (in the second one) to transform to the feeding rectangular waveguide.

We note that the air-filled waveguide with the same height as the substrate can be of any length. For this aim, we used two transformers: a microstrip wave adapter and a $3\lambda/4$ tapered integrated waveguide transformer. Commercial full-wave software high-frequency structure simulator (HFSS version 10) of Ansoft Corporation was used for the design and simulation of the transitions.

Fig. 1 shows the microstrip wave adapter. It is composed of two sections of $\lambda/8$ transmission lines. Impedance matching is achieved by varying the widths $Wm1$ and $Wm2$ of these transmission line sections.

Fig. 2 shows the transition between the microstrip line and the air-filled waveguide with the same height as the substrate. It is composed of a microstrip line section, a microstrip wave adapter (shown in Fig. 1), the $3\lambda/4$ trapezoidal wave and impedance

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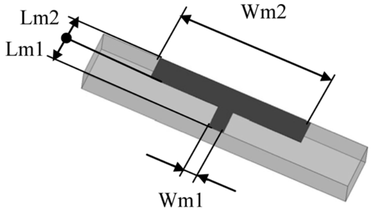

Fig. 1. Microstrip wave adapter.

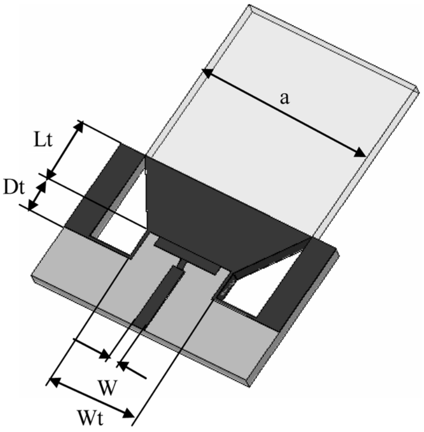

Fig. 2. Microstrip-to-air-filled waveguide transition; the height of the air-filled waveguide is the same as the substrate thickness.

transformer in substrate-integrated waveguide technology, and the air-filled wave guide with the same height as the substrate.

III. SIMULATION RESULTS

Two different transitions, described in Sections III-A and B, have been designed and simulated using the circuit of Fig. 2. The planar part is designed and fabricated on alumina substrate having a relative permittivity of $\varepsilon_r = 9.9$. The thickness is $h = 254\ \mu$m for the transition with a stepped transformer and $h = 127\mu$m for the transition with a patch antenna. The outgoing waveguide is the standard WR12 with 3.1 mm width and 1.55 mm height.

A. Transition With a Stepped Transformer

Fig. 3 shows the complete microstrip-to-waveguide transition with a stepped transformer. Three sections of $\lambda/4$ transformers have been used. Some corners of the machined waveguide transformers were rounded with radius of 406 μm, which is imposed by the milling machine requirements. The dimensions of the transition were optimized, and are as follows:

- The microstrip line width is $W = 0.22$ mm.
- Ffor the microstrip wave adapter, $Wm_1 = 0.11$ mm, $Wm_2 = 1.1$ mm, $Lm_1 = 0.167$ mm, $Lm_2 = 0.167$ mm.
- For the integrated waveguide taper; $Wt = 1.6$ mm, $Lt = 1.14$ mm, $a = 3.1$ mm, and $Dt = 0.5$ mm.
- For the air-filled waveguide sections with the same height as the substrate, $a = 3.1$ mm, $L_1 = 3$ mm, and $h_1 = 0.254$ mm.
- For the three section $\lambda/4$ transformers, $L_2 = 1.1$ mm, $h_2 = 0.43$ mm, $L_3 = 1.24$ mm, $h_3 = 0.8$ mm, $L_4 = 1.1$ mm, and $h_4 = 1.18$ mm;.

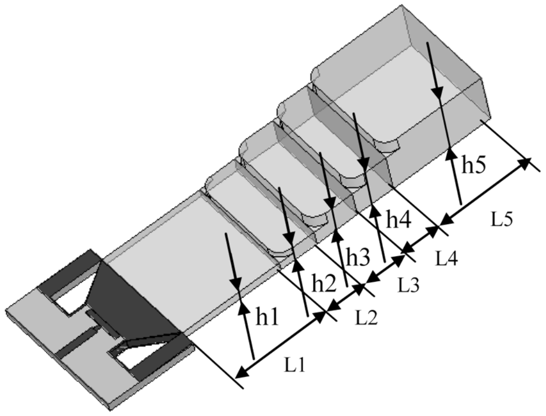

Fig. 3. Complete microstrip to waveguide transition with a stepped transformer. The waveguide is WR12.

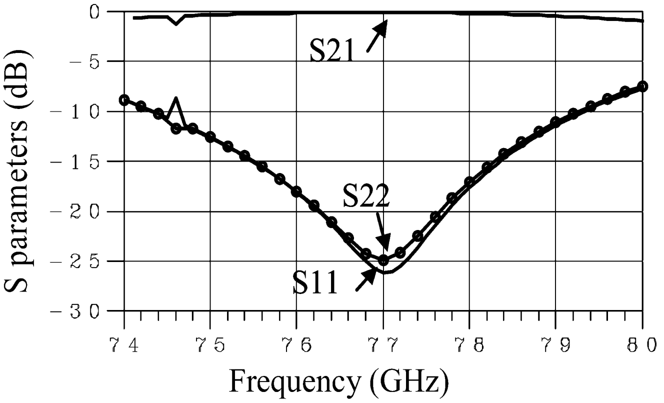

Fig. 4. Simulated S parameter magnitudes of the transition with a stepped transformer.

- For WR12 section, $L_5 = 3$ mm, $h_5 = 1.55$ mm, width $a = 3.1$ mm.

Fig. 4 shows the simulation results. Insertion loss and return loss of about 0.1 and 25 dB, respectively, are obtained at the central operating frequency of 77 GHz. The return loss values better than 15 dB are obtained in 3-GHz bandwidth. The very low insertion loss value at 77 GHz is due to the fact that the waveguide walls and the ground plane of the planar part are considered perfect conductors.

B. Transition With a Patch Antenna

Fig. 5 shows the complete microstrip-to-waveguide transition with a patch antenna. The open end of the waveguide section with the same height as the substrate acts as a slot antenna that illuminates the patch antenna. The patch antenna serves as a matching element.

Fig. 6 shows the patch antenna with its supporting substrate.

The dimensions of the transition were optimized for the central operating frequency of 77 GHz, a bandwidth of 3 GHz, and optimal values for insertion and return losses. The results are as follows:

- The microstrip line width is $W = 0.13$ mm.
- For the microstrip wave adapter, $Wm_1 = 0.11$ mm, $Wm_2 = 1.1$ mm, $Lm_1 = 0.173$ mm, $Lm_2 = 0.173$ mm.

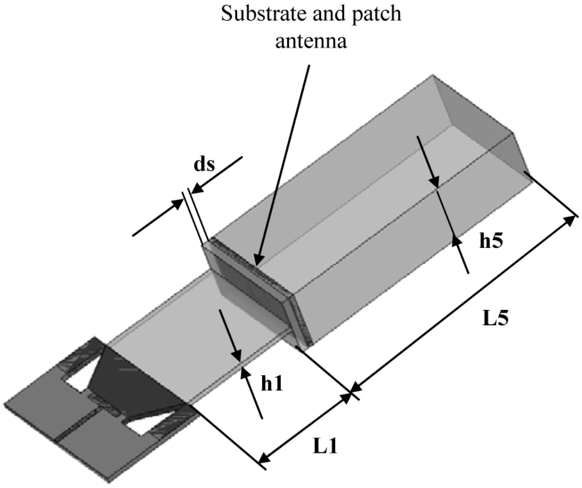

Fig. 5. Complete microstrip-to-WR12 waveguide transition with a patch antenna.

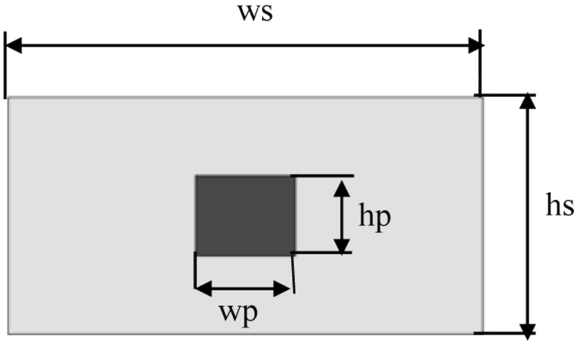

Fig. 6. Dimensions of the patch antenna on the substrate.

- For the integrated waveguide taper; $Wt = 1.57$ mm, $Lt = 1.1$ mm, $a = 3.1$ mm, and $Dt = 0.5$ mm.
- For the air-filled waveguide sections with the same height as the substrate, $a = 3.1$ mm, $L_1 = 3$ mm, and $h_1 = 0.127$ mm.
- For the patch antenna, $wp = 0.653$ mm, $hp = 0.52$ mm, $ws = 3.1$ mm, $hs = 1.55$ mm, $ds = 0.2$ mm.
- For WR12 section, $L_5 = 7$ mm, $h_5 = 1.55$ mm, width $a = 3.1$ mm.

Fig. 7 shows the simulation results of the transition with a patch antenna. As can be seen, insertion loss and return loss of about 0.15 and 30 dB, respectively, are obtained at the central operating frequency of 77 GHz. Return loss values better than 15 dB are obtained in 2-GHz bandwidth, which is lower than the first proposed transition. Insertion loss values are also very low due to the same hypothesis of perfect conductivity for waveguide walls and the ground plane of the planar part.

IV. EXPERIMENTAL RESULTS

As demonstrated by previous simulations, S parameter results for both transitions are quite similar. In order to validate these results, a back-to-back transition with a stepped transformer has been fabricated. After a parametrical study, this first topology is used due to the reduced influence of fabrication errors in the overall S parameter results.

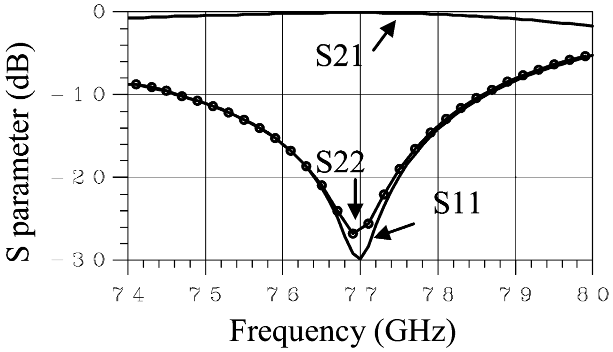

Fig. 7. Simulated S parameter magnitudes of the transition with a patch antenna.

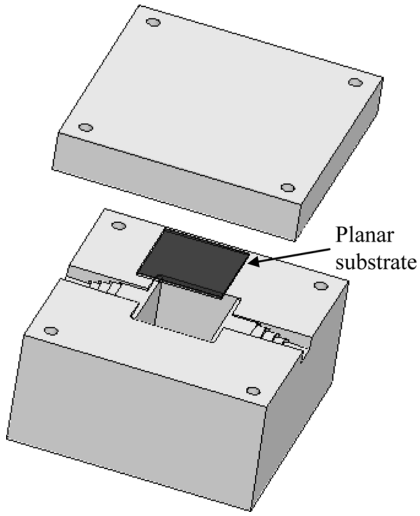

Fig. 8. Mounting configuration for the back-to-back transition.

The machined rectangular waveguides are fabricated using a computer numerically controlled milling machine. In addition, the integrated waveguide taper is fabricated by perforating trapezoidal holes using laser micromachining equipment. These holes are then metallized.

Fig. 8 shows the mounting configuration. The planar substrate of the back-to-back transition (containing the microstrip line and two microstrips-to-air-filled waveguide transitions) is placed in the top of the rectangular air-filled cavity. Stepped transformers are fabricated in the same metallic block. A metallic lid closes the whole structure.

Fig. 9 shows comparative return loss results of the back-to-back transition. Simulated and measured return losses are represented by a dotted line and a solid line, respectively. A good agreement between simulations and measurements is obtained; return loss values are better than 15 dB in a 3-GHz bandwidth for this back-to-back transition.

Simulated and measured transmission S parameters are shown in Fig. 10.

The same convention as for previous results is respected: simulations with a dotted line and measurements with a solid one. As seen, a measured insertion loss of around 2 dB is obtained in 3-GHz bandwidth for the back-to-back transition. The measured insertion loss is somewhat higher than the simulated one

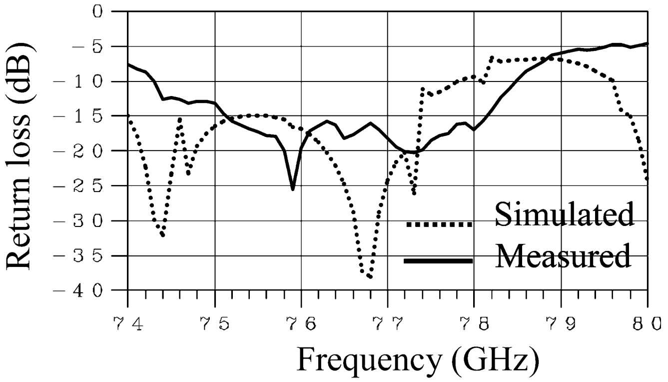

Fig. 9. Return loss of the back-to-to-back transition with a stepped transition.

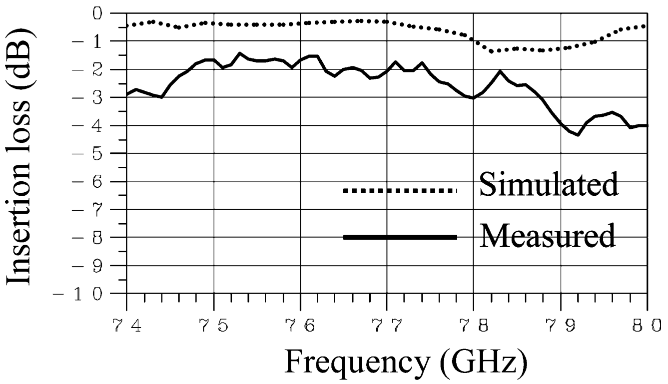

Fig. 10. Insertion loss of the back-to-back transition with a stepped transformer.

due to the fabrication errors and to the fact that not all kinds of losses are taken into account in the simulations. However, both return and insertion losses remain in acceptable limits for proposed applications.

V. CONCLUSION

Two simple and low-cost transitions from microstrip to rectangular waveguide have been designed for compact integration of waveguide components, such as antennas for radar applications. The microstrip line is first transformed into an air-filled rectangular waveguide with the same width as WR12 and same height as the substrate, and then transformed via a three-section $\lambda/4$ transformers waveguide transformer in the first transition and via a patch antenna in the second transition, into WR12. The fact that the planar circuit can be as small as possible renders this transition compatible with all kinds of millimeter-wave integrated-circuit technologies. Moreover, it is more suited as transition between all kinds of microstrip antennas and rectangular waveguide feedings. Experimental results for the transition with a stepped transformer show good agreement with the simulated ones.

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