Design of Millimeter-Wave Wideband Gap Waveguide Transitions Considering Integration into the Antenna System

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***Abstract*—Two wideband vertical transitions from inverted microstrip gap waveguide to rectangular waveguide (WR-15) for 60 GHz antenna array applications are proposed. These transitions are aimed to interconnect the WR-15 with the gap waveguide feed-network employed to provide feeding to the radiating elements of slot/horn antenna arrays. The wideband field transformation is achieved without the need of adding a quarter-wavelength cavity backshort on a metal block placed over the transition. First, we replace this backshort by creating a cavity in the radiating layer when this is made in Substrate Integrated Waveguide (SIW) technology, and thereafter we use an air-filled pin cavity in the radiating layer. The simulated *S*-parameters show that the presented transitions cover the unlicensed 60 GHz band (57-64 GHz) with good margins.**

***Index Terms*— Gap waveguide, Perfect Magnetic Conductor (PMC), Artificial Magnetic Conductor (AMC), feed-network, Substrate Integrated Waveguide, transition, millimeter-wave circuits.**

I. Introduction

Recently, there has been an increasing interest in communication systems that operate in the millimeter-wave frequency range. The unlicensed 60 GHz band becomes very attractive for applications such as multi-gigabit short range wireless communications, or high data rate video transmission. At these frequencies, planar circuit technologies (microstrip, coplanar waveguide) and hollow waveguides are extensively employed.

The gap waveguide technology is a new type of waveguide which was theoretically introduced in [1]-[2] and experimentally validated in the microwave frequency range in [3]-[4]. Nowadays, the main focus of the gap waveguide research is on realizing millimeter-wave high gain gap waveguide antennas [5]-[7]. In fact, there is a special interest on investigating horn/slot antenna arrays with feed-network based on *inverted microstrip gap waveguide* [6] for 60 GHz applications. This gap version was introduced in [8] and its configuration (illustrated in Fig.1) consists of a thin dielectric layer supported by a uniform pattern of pins placed opposite to a smooth metal lid. This pin periodic pattern behaves as an Artificial Magnetic Conductor (AMC) which artificially emulates the Perfect Magnetic Conductor (PMC) condition, and together combined with the smooth metal plate ensures the suppression of parallel-plate modes and surface waves within a

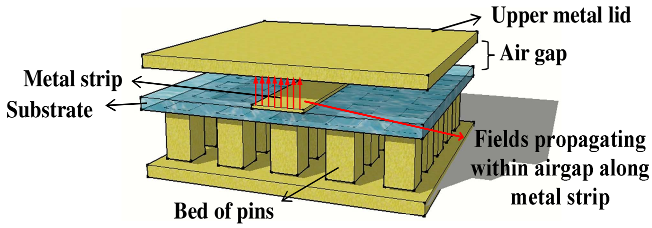

Fig. 1. Inverted microstrip gap waveguide geometry.

stopband [9]-[10], as long as the air gap that separates both layers is smaller than quarter wavelength. The field propagation is allowed along a copper strip etched in the substrate material. Therefore, the *inverted microstrip gap waveguide* becomes a low loss alternative to the standard microstrip since the fields are confined within the air gap, and the line dimensions become wider which reduces the conductive loss. Moreover, the manufacturing is more flexible and simpler than in the case of hollow waveguides. The latter is due to the fact that there is no need for good electrical contact between the different plates, since all possible field leakage is removed by the parallel-plate cutoff principle, upon which the gap waveguide is based.

In spite of the potential of the *inverted microstrip gap waveguide* at millimeter waves, the work in [6] is realized in X-band. This was due to the lack of compact and wideband transitions that could interconnect vertically the *inverted microstrip gap waveguide* with a standard WR-15 which is the common interface with millimeter-wave test equipment. This issue motivated the investigation of a 60 GHz *microstrip-ridge gap waveguide* antenna [7] and the design of a suitable transition to ensure compatibility with the measurement set-up [11]. In this new gap approach, the pin surface is embedded in the substrate material as metalized via holes. Parallel work has been done in order to find good transitions from *inverted microstrip gap waveguide* [12]-[13] to WR-15, and to create a similar antenna to the one presented in [7] with an *inverted mirostrip gap waveguide* corporate feed network. The transition in [12] is vertical and it extends upwards from the inverted microstrip circuit. This is a critical limitation if the transition is meant for an antenna application since the connection to the waveguide does not need to be in the same plane as the radiating elements. Reference [13] introduces a downwards vertical transition where the inverted microstrip circuit faces a waveguide backshort, having a return loss better than 15 dB over 10.5% bandwidth.

The goal of the present work is to investigate two millimeter-wave vertical transitions from inverted microstrip gap waveguide to standard rectangular waveguide that ensure optimum matching and insertion loss over a wide frequency bandwidth (better than that obtained in [11] and [13]), as well as suitable integration into the layer that contains the radiating elements of the antenna system. Transition designs are presented and are numerically analyzed by considering back-to-back configurations.

II. Design of Transition Integrated into SIW Cavity

The downwards transition presented in [13] consisted of a probe inserted into a waveguide through an aperture made in the broad wall of the waveguide. It was needed to use a waveguide backshort above the employed Printed Circuit Board (PCB) in order to force the fields to propagate down into the rectangular waveguide. This was a preliminary design but in practice the ideal would be to integrate this backshort in the radiating layer of the antenna to reach the most compact approach. On the other hand, any complex modification in the waveguide structure is preferably avoided in order to simplify manufacturing and assembling, as well as we allow a simple integration of the transition into the WR-15.

The first transition design under study consists of two double-sided PCBs as shown in Fig. 2. The lower PCB contains a microstrip circuit without ground plane that is supported by a bed of pins. This constitutes, together with an upper metal lid, the inverted microstrip gap waveguide. The upper PCB incorporates a cavity realized by Substrate Integrated Waveguide (SIW). The substrate characteristics for both layers are presented in Table 1.

The employed pin dimensions that constitute the gap waveguide layer, as well as the obtained stopband for a unit cell are illustrated in the dispersion diagram of Fig. 3.

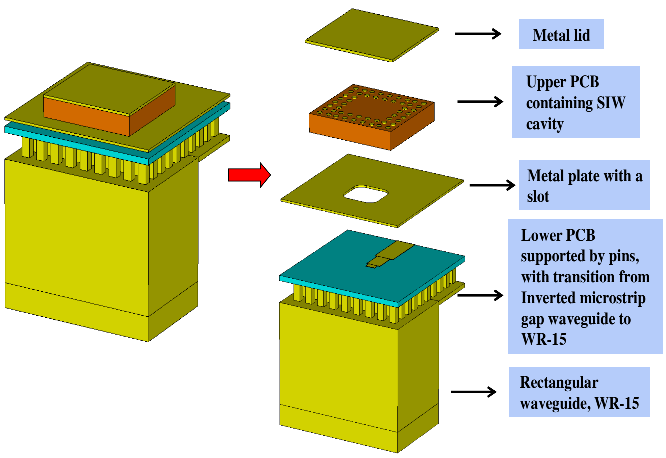

Fig. 2. 3-D view of the different components of the transition integrated into SIW cavity.

TABLE 1. Substrate material properties

	Lower PCB	Upper PCB
Substrate material	Rogers RO3003	Rogers RT/Duroid 5880
Permittivity, ε_r	3	2.2
Thickness, h	0.25 mm	0.78 mm
Loss tangent, tanδ	0.0013	0.0009

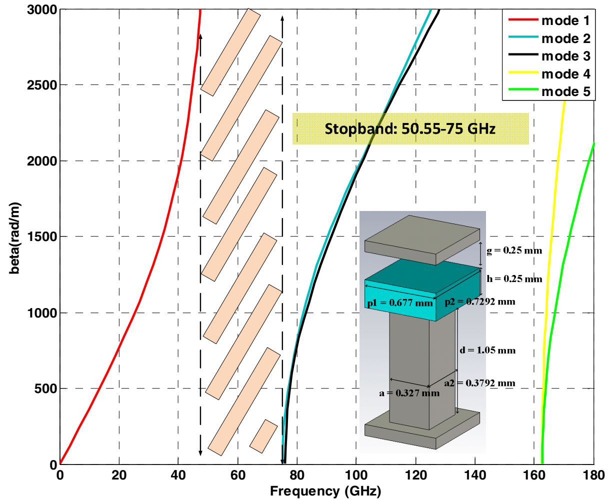

Fig. 3. Dispersion diagram for a unit cell with the shown dimensions.

The transition aims to cover the 60 GHz band (57-64 GHz), and it is designed by means of an inverted microstrip gap 50 Ω line that ends in a probe with a two-step matching section. The dimensions and location of these matching steps have been optimized in order to achieve optimum transition performance. Moreover, the E-fields travelling within the air-gap in the inverted microstrip gap waveguide need to be transformed in such a way that they propagate down into the rectangular waveguide, which has the same dimensions as the standard WR-15. For this aim, a cavity is designed in the upper SIW layer. This SIW cavity replaces the effect of the waveguide cavity backshort, which is commonly used for this type of probe-transitions [13]-[14]. The lower metal plate of the SIW layer contains a slot with dimensions that set the cavity size. The slot dimensions are fine-tuned in order to suitably establish an open boundary condition in the upper plane of the inverted microstrip probe and force the fields to propagate downwards, as well as avoiding excitation of higher order modes into the SIW cavity. We have used the same via-hole dimensions as those employed in [7], but the period and position of the via-holes are slightly different. The final geometry of the transition and the cross-section of the complete design are shown in Fig. 4.

The transition has been simulated in a back-to-back configuration with a 10 cm inverted microstrip gap waveguide feed-line between the two opposite transitions, using the time domain solver in CST Microwave Studio [15]. The resulting *S*-parameters are presented in Fig. 5. The periodic peaks of the S_{11} parameter are due to the multiple reflections between the two transitions placed on the sides of the 10 cm line. The corresponding return loss is larger than 10 dB from 55.3 to

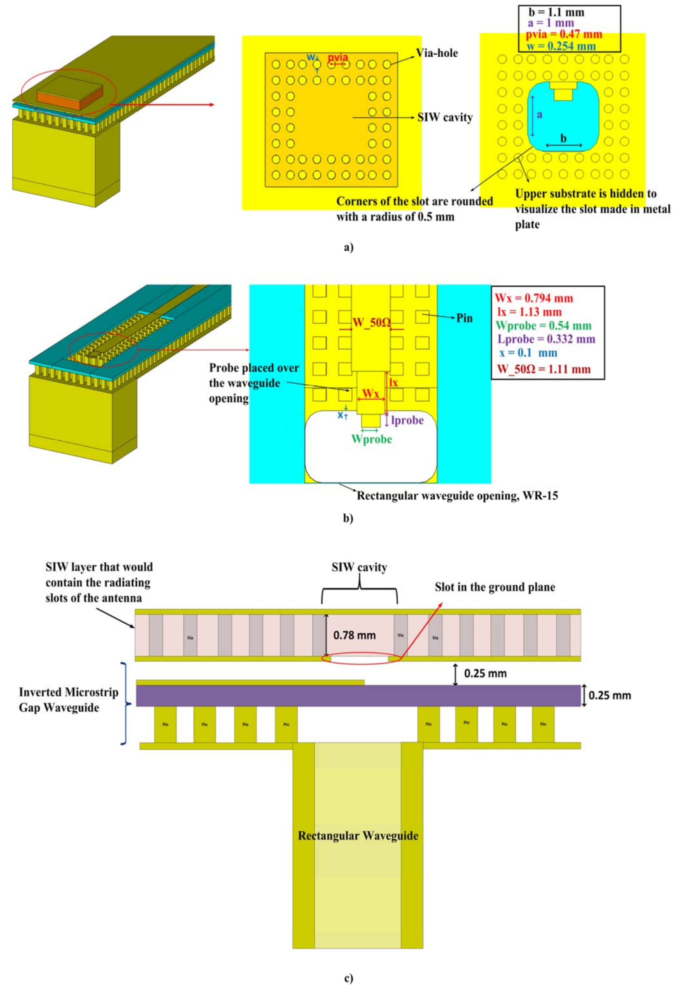

Fig. 4. 1st transition geometry integrated into antenna layer. a) Upper PCB with SIW cavity, perspective view and top view, b) Lower PCB with inverted microstrip gap waveguide probe (part of substrate is hidden to reveal transition details), perspective view and top view, c) cross section of the complete structure.

67.6 GHz, which represents 22.4% bandwidth and covers the desired 60 GHz frequency band with large margins. If we remove the mismatch factor from the simulated S_{21} parameter, the resulting insertion loss is smaller than 1 dB over this bandwidth. This implies that the corresponding loss for a single transition would be 0.5 dB.

III. Design of Transition Integrated into Air-Filled Pin Cavity

There is ongoing parallel research work related to finding new types of radiating slot element for a 60 GHz planar array antenna. One alternative is to replace the SIW cavity proposed in [7] by an air-filled pin cavity [16]. This motivates the need to find another wideband and compact transition from inverted microstrip gap waveguide to WR-15 ensuring integration with the new air-filled pin cavity radiating layer. The new transition will make possible the interconnection between test equipment and the gap waveguide feed network. The corporate feed network would provide feeding to radiating slots backed by an air-filled pin cavity. Unlike the

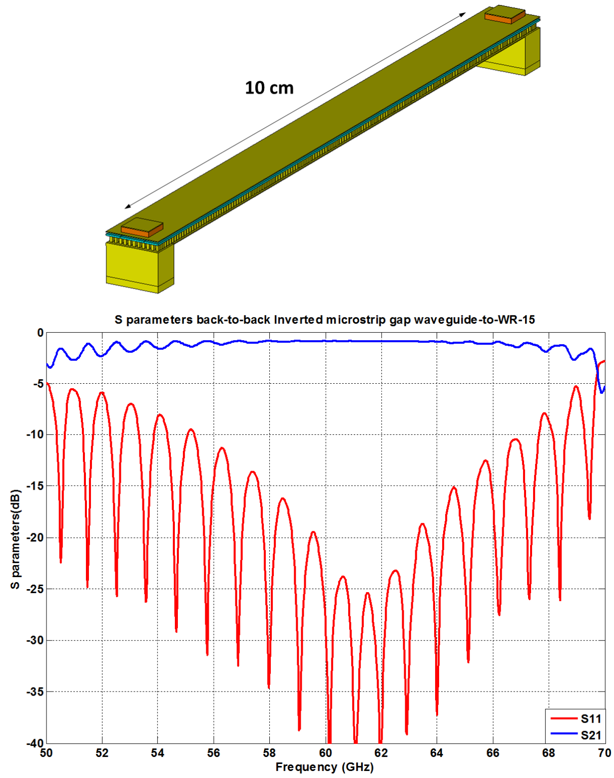

Fig. 5. Simulated S parameters of the proposed back-to-back transition (integration with SIW cavity).

design proposed in section II, this second transition configuration does not include a PCB in the upper antenna layer since the cavity is filled with air and surrounded by pins. A 3D-sketch of the geometry is illustrated in Fig. 6.

The initial point of the transition design is the same as that explained in section II. We consider the same dielectric material characteristics and pin dimensions for the inverted microstrip gap waveguide layer. The upper pin layer that contains the air-filled cavity has the same pin dimensions as the lower pin surface, with the exception of the pin height which is 1.2 mm.

A 50 Ω inverted microstrip feeding line ends in a probe that contains a matching section with several impedance steps. The probe is placed over the rectangular waveguide opening in a certain position. This location and the matching section dimensions have been optimized to attain the best possible matching. The mode conversion between the Quasi-TEM mode of the inverted microstrip gap waveguide, and the dominant TE_{10} mode of the rectangular waveguide is achieved by creating an air-filled pin cavity in the upper layer. The lower plate of the pin cavity incorporates a slot with fine-tuned dimensions to ensure a "backshort" effect and establish an open boundary condition above the probe which forces the fields to propagate downwards into the WR-15. All the layout details of this transition geometry that includes integration into an air-filled pin cavity layer are specified in Fig. 7.

The proposed transition design is simulated as a back-to-back structure with 10 cm length. The simulated S-parameters are presented in Fig.8. showing that the resulted return loss is better than 10 dB between 52.15 and 72 GHz (which means 38% relative bandwidth). Furthermore, the insertion loss (after extracting the mismatch factor) is smaller than 1.4 dB over the whole mentioned bandwidth. Therefore, the loss associated with a single transition is 0.7 dB.

IV. CONCLUSIONS

In this paper, two wideband and compact transitions from inverted microstrip gap waveguide to rectangular waveguide have been presented, for 60 GHz antenna array applications. For both cases, the rectangular waveguide structure extends vertically, and it is placed on the back side of the inverted microstrip circuit. There is no need to use any test-fixture port as in [12], or modification on the rectangular waveguide walls [13]-[14] (like making a window on the broad wall of the waveguide to introduce the PCB, which complicates highly the manufacturing) simplifying the connection between both technologies. We avoid using a quarter-wavelength waveguide backshort since the field transformation is suitably achieved by means of a SIW cavity and a new type of air-filled pin cavity, which are placed in an upper layer over the inverted microstrip gap waveguide. Thereby, the proposed designs make it possible to directly integrate an inverted microstrip gap waveguide feed-network (like the one in [6]) below a radiating SIW cavity-backed slot- antenna layer as that introduced in [7], or into the air-filled pin cavity-backed slot antenna which is currently under investigation [16].

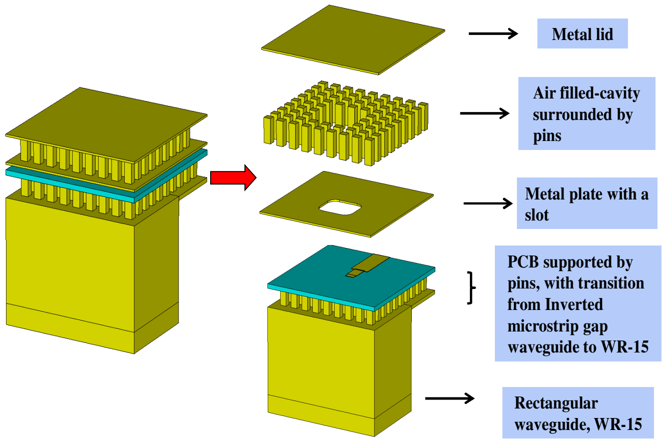

Fig. 6. 3-D sketch of the different layers of the transition integrated into an air-filled pin cavity.

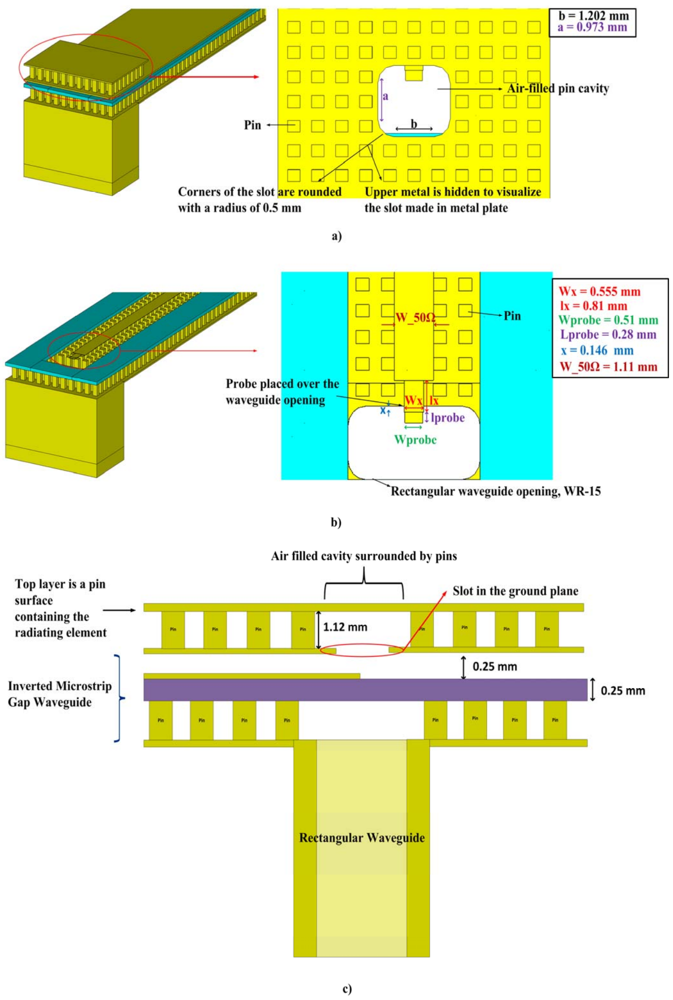

Fig. 7. 2nd transition geometry integrated into antenna layer. a) Upper air-filled pin cavity, perspective view and top view, b) Lower PCB with inverted microstrip gap waveguide probe (part of substrate is hidden to reveal transition details), perspective view and top view, c) cross section of the complete structure.

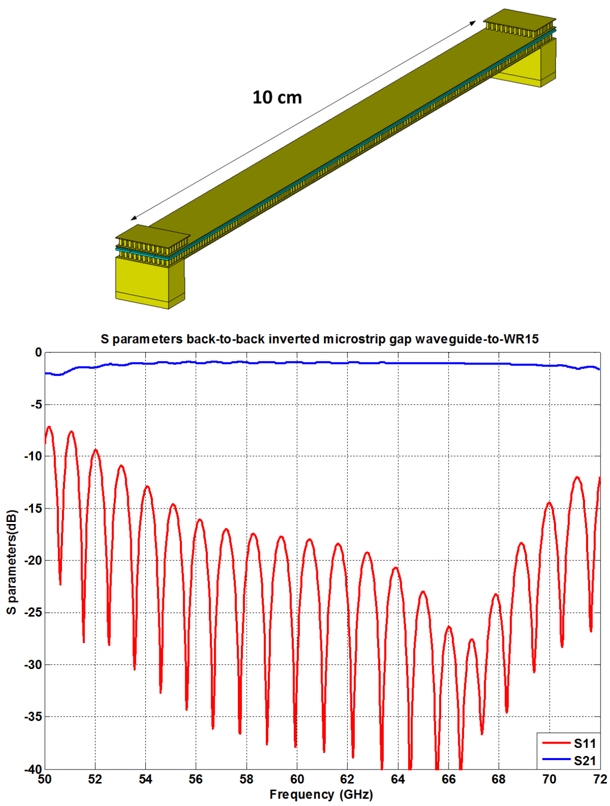

Fig. 8. Simulated S parameters of the proposed back-to-back transition (integration with air-filled pin cavity).

Simulation results show that both transition designs cover widely the unlicensed 60 GHz band with optimum matching and insertion loss.

In the work done in [7] a microstrip-ridge gap waveguide feeds the SIW cavities by using coupling slots. In spite of the promising results presented in [7] and [11], the most critical limitation of the microstrip-ridge gap waveguide is the complexity of design and high manufacturing cost due to the big number of via holes. However, the simple inverted microstrip gap waveguide approach has big potential to be used to create low loss distributed feed networks of 60 GHz directive planar arrays. The manufacturing of the pin layers is planned to be realized by using fixed metal posts on a metal plate fabricated by milling, sawing or casting. In the case of the air-filled pin cavity radiating layer, the upper thin metal plate (that would contain the radiating slots) will then be soldered to the metal pins by heating the structure in an oven. The mechanical assembling needs to be arranged in such a way that we can provide the suited gap. This gap can be fixed by using metal steps placed on the sides of the upper metal lid. In order to ensure a good contact between the pins and the PCB, we can fill up the gap with a thin foam which should have a thickness equal to the air gap and a permittivity as close to 1 as possible.

This paper has proposed two transition geometries that ensure connection with test equipment and transmitting/receiving amplifiers as well as a compact integration into the antenna layer.

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