Broadband 100 GHz Substrate-Integrated Waveguide Couplers with Irregularly Shaped Via Holes for Higher-Order Mode Suppression

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Abstract—**This paper introduces a 3 dB and a 23 dB coupler in Substrate-Integrated Waveguide (SIW) technology for future applications in radio astronomy instrumentation. In order to meet the often challenging specifications of such equipment in terms of both operating frequency and bandwidth, via holes of irregular shape are used to suppress higher-order mode excitation commonly observed in waveguide couplers. Prototypes have been manufactured and measured. For the 23 dB SIW coupler, measurements across the 85-115 GHz band show an isolation level higher than 35 dB, an average insertion loss of 3.75 dB, a coupling factor of 27 dB and a reflection coefficient better than -16.7 dB. The phase difference between the direct and coupled ports is 94.3°±2.3°. In the 83-111 GHz band and in the case of the 3 dB coupler, isolation is higher than 20 dB, insertion losses are 4.2 dB±0.6 dB, and the reflection coefficient is better than -16.6 dB. The phase difference between the direct and coupled ports is 94.2°±2.1°.**

Keywords—Substrate integrated waveguide (SIW) technology, multi-branch couplers, H-plane couplers, millimeter-wave couplers.

I. INTRODUCTION

SIW technology has matured, e.g. [1], and is now considered to replace previously bulky waveguide components. In the millimeter-wave regime, the compromise is often between accurate and expensive CNC or EDM machining of waveguide technology on one hand, and inexpensive but higher-loss SIW circuitry on the other. Moreover, for broadband millimeter-wave applications, it is often difficult to satisfy all-metal waveguide design specifications as dimensional parameters become too small even for advanced fabrication techniques [2]. Directional couplers with tight coupling over a wide frequency range are especially prone to tight tolerances due to small distances between large coupling slots. Conversely, the small slots of low-coupling components are difficult to manufacture.

One such application is, for instance, a sideband-separating (2SB) receiver whose RF circuit requires one 3 dB and two 23 dB couplers. This waveguide circuit is similar to the one in [2] with the exception that 16 dB waveguide couplers are used in [2] because the 23 dB coupler apertures became too small to fabricate. In order to replace such waveguide couplers with SIW technology, a number of different SIW coupling configurations can be considered.

Since SIW technology is planar, H-plane-type components are preferred. They have been demonstrated in [3] – [7] for frequency ranges between 11 GHz and 40 GHz, and as power dividers/combiners at 8 GHz [8]. Other candidates include H-plane cruciform couplers, [9], [10], which have been applied up to 30 GHz.

This paper presents 3 dB and 23 dB H-plane SIW coupler designs for the 84-116 GHz frequency range. In order to meet the challenging specifications in terms of both operating frequency and bandwidth, new multi-branch SIW H-plane couplers on a single-layer substrate are proposed. Arbitrarily shaped via holes are employed to suppress higher-order mode excitation in the couplers. Measurements of two prototypes validate the design process.

II. COUPLER DESIGN

The initial coupler design is carried out using mode-matching techniques. For given coupler specifications, equivalent waveguide width of the SIW ports, e.g. [3], and aperture thickness, the initial synthesis follows well-known procedures, e.g. [11]. Note that due to the laser-cutting procedure of via holes in the fabrication process, the use of rectangular vias is envisaged [12], which specifies the thickness of the coupling apertures, i.e., the separation wall between the two waveguides (inset of Fig. 1). Two aspects differ from the straight-forward synthesis approach in [11]. First, the 3 dB coupler is designed as a tandem connection of two 8.34 dB couplers, which reduces the aperture sizes and thus increases the distance between apertures that are later to be manufactured by via holes. Secondly, fine optimizations for both the 3 dB and 23 dB couplers are required to ensure that all dimensions fall into the possible range of polygonal via holes. As an example, Fig. 1 shows the initial performance of a 24-slot, 3 dB dielectric-filled waveguide coupler realized as tandem operation of two 8.34 dB couplers. As is typical for such waveguide couplers in broadband and tight-coupling operation, the larger spaces within the coupler, created by large apertures, give rise to higher-order mode excitation [11]. This is clearly visible in the 110-115 GHz range in Fig. 1.

In the second step, the waveguide model is translated to an SIW structure with rectangular vias. This is shown in Fig. 2a. Also shown are additional rectangular vias of t=100 μm thickness, which are added to the top and bottom via walls in

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order to remove the higher-order effects of the waveguide model in Fig. 1. The lengths of coupling sections and center-line vias are then readjusted using HFSS to compensate for the effective reduction in coupler width.

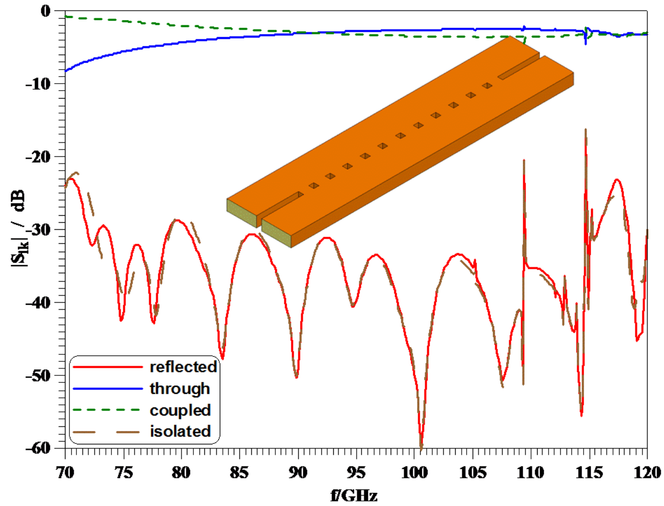


Figure 1. Performance of the initial 24-slot 3-dB coupler (tandem operation of two 12-slot 8.34 dB sections) based on the use of dielectric-filled rectangular waveguide.

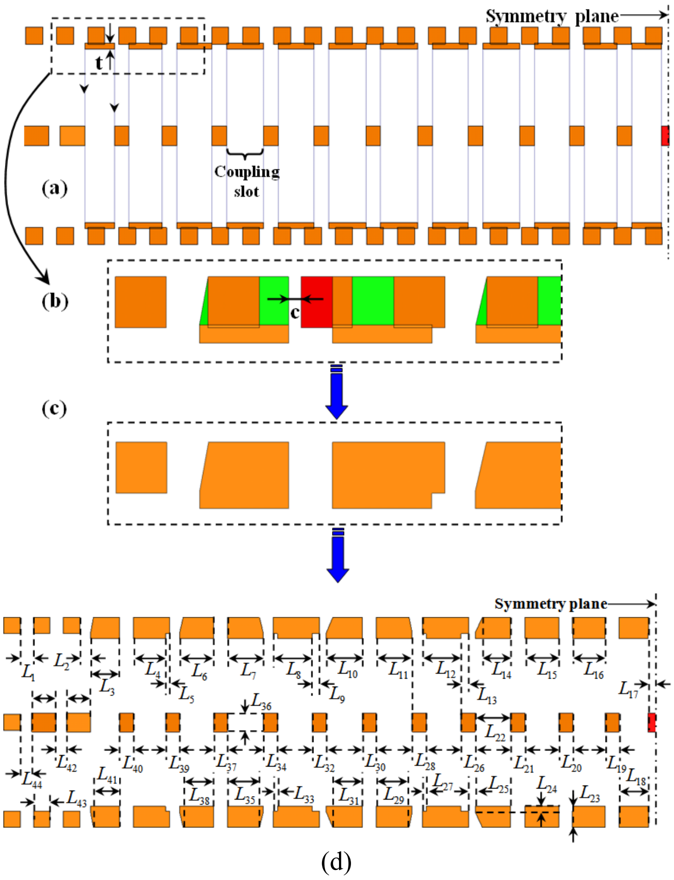


Figure 2. Four steps to minimize the higher-order mode effects; (a) insert vias in the coupling sections; (b) combine vias to form irregular shapes (c); (d) final layout of the 3-dB coupler and parameters according to Table I.

In the next step (Fig. 2 b), such vias are combined to form larger vias of different shapes. Note that other sections of vias might have to be removed (marked as red in Fig. 2b) due to fabrication requirements which specify the minimum distance between via holes to be c=100 µm. This leads to via-hole shapes shown in Fig. 2c which can be fabricated using a laser-driven cutting mechanism. One half of the final 3 dB coupler is shown in Fig. 2d, with dimensions added that are specified in Table I.

TABLE I. DIMENSIONS (IN MICROMETERS) OF THE 3-DB COUPLER

L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}	L_{11}	L_{12}	L_{13}	L_{14}	L_{15}
229	182	487	544	72	577	603	665	122	609	609	654	134	480	577
L_{16}	L_{17}	L_{18}	L_{19}	L_{20}	L_{21}	L_{22}	L_{23}	L_{24}	L_{25}	L_{26}	L_{27}	L_{28}	L_{29}	L_{30}
557	115	498	240	240	240	603	362	83	107	240	64	240	557	240
L_{31}	L_{32}	L_{33}	L_{34}	L_{35}	L_{36}	L_{37}	L_{38}	L_{39}	L_{40}	L_{41}	L_{42}	L_{43}	L_{44}	
499	240	76	240	539	320	240	517	240	240	440	180	279	198	

The same procedure is used for the 23-dB coupler, except that a tandem connection is not necessary for such weak coupling. Fig. 3 shows the respective layout with individual dimensions presented in Table II.

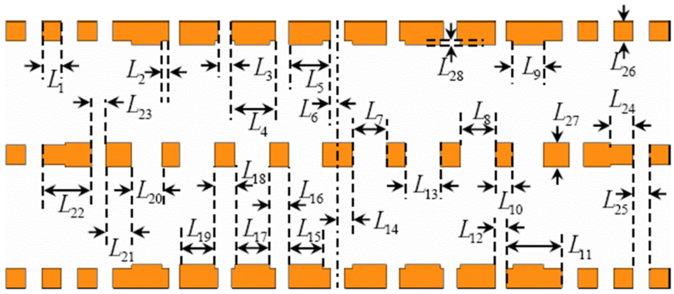


Figure 3. Final layout of the 23-dB coupler and parameters according to Table II.

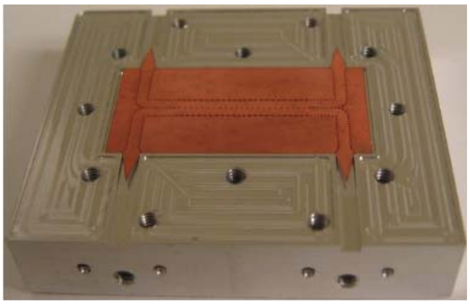
TABLE II. DIMENSIONS (IN MICROMETERS) OF THE 23-DB COUPLER

L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}	L_{11}	L_{12}	L_{13}	L_{14}
279	92	203	624	593	102	483	505	431	247	787	156	500	212
L_{15}	L_{16}	L_{17}	L_{18}	L_{19}	L_{20}	L_{21}	L_{22}	L_{23}	L_{24}	L_{25}	L_{26}	L_{27}	L_{28}
483	269	500	276	505	431	373	704	203	331	229	279	350	53

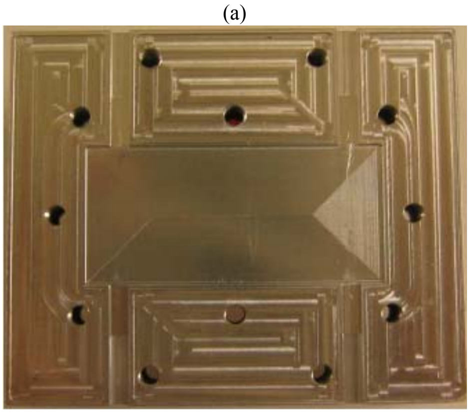
III. RESULTS

Prototypes of the two couplers were manufactured using RT Duroid/6002 substrate of 508 µm thickness. For measurement purposes, transitions between the SIW circuit and standard WR-10 rectangular waveguide equipment are used as shown in Fig. 4a. For details and dimensions of these transitions, the reader is referred to [12]. The entire coupler is embedded in a waveguide housing that opens up at the four ports (Fig. 4b) so that the tapered SIW regions are not in contact with the metal housing. Fig. 4c shows an enlargement to visualize the irregular via shapes in the coupler section.

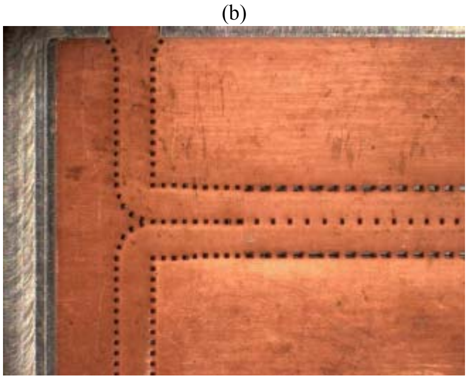
Fig. 5 shows a comparison between the simulated (HFSS) and measured responses of the 23 dB coupler. The simulations take into account dielectric and metallic losses of the SIW circuit. Reflection (Fig. 5a) and isolation (Fig. 5b) results are in reasonable agreement. Between 85 GHz and 115 GHz, the measurements show return loss and isolation levels better than 16.7 dB and 35 dB, respectively. However, both through (Fig. 5c) and coupled ports (Fig. 5d) suffer from an average additional insertion loss of 2.75 dB (through) and 5 dB (coupling). The through-port losses are attributed to the SIW transitions (2.8 dB for a back-to-back transition in [12]), whereas the remaining parts are assumed to be due to dielectric losses which have been taken at the nominal 10 GHz values in the simulations. The phase measurements (not shown here for lack of space) reveal differences between the through and coupled ports of 94.3°± 2.3°.



(a)



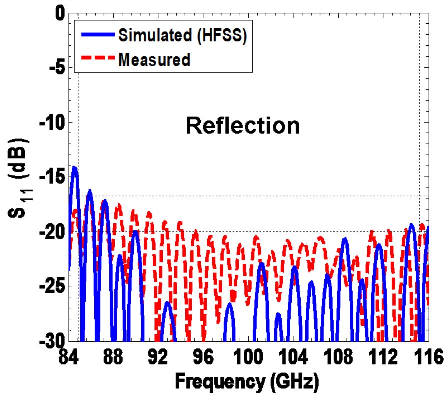
(b)



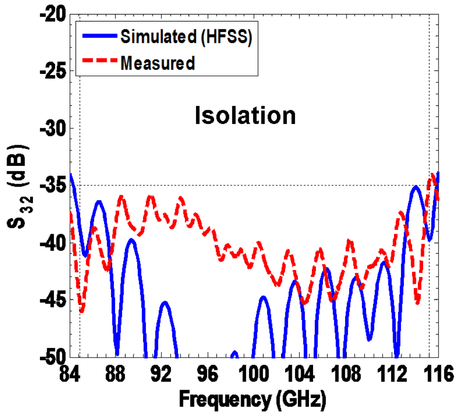
(c)

Figure 4. Photographs of the 3-dB coupler in the waveguide housing (a), top plate (b) and enlargement showing the irregulaly shaped via holes (c).

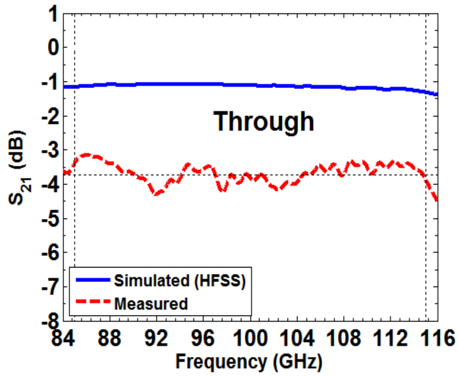
Fig. 6 shows the simulated and measured results for the 3-dB coupler. Between 83 GHz and 111 GHz, the measured return loss (Fig. 6a) is better than 16.6 dB and the isolation (Fig. 6b) better than 20 dB. Losses in the through and coupled ports (Fig. 6c) amount to an additional 3 dB compared to the simulations which we contribute to items raised for the 23-dB coupler above. Phase measurements (not shown here) demonstrate a difference of 94.2°± 2.1° between the through and coupled ports.



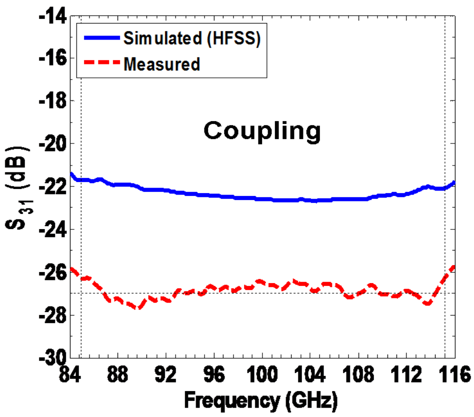
(a)



(b)



(c)



(d)

Figure 5. Simulated and measured performance of the 23-dB coupler: reflection (a), isolation (b), through port (c), and coupling (d).

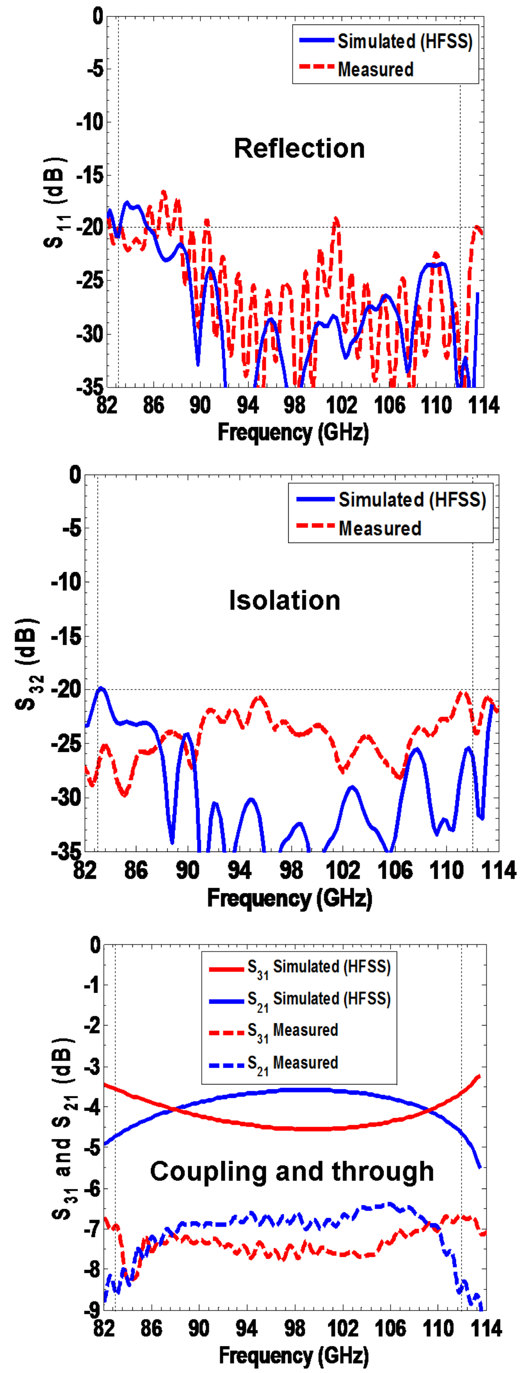


Figure 6. Simulated and measured performance of the 3-dB coupler: reflection (a), isolation (b), and coupled and through ports (c).

Note that compared to the all-dielectric waveguide coupler in Fig. 1, the spikes between 110 GHz and 114 GHz are removed from the frequency response of the SIW coupler due to the special shapes of the via holes as outlined in the previous section.

IV. Conclusions

Broadband directional couplers in SIW technology are presented for W-band applications. The specifications towards tight coupling and broadband performance require several stages in the design process. In order to overcome higher-order mode excitation commonly observed in the upper frequency range of components with tight coupling, via holes of irregular shapes are used which have been manufactured using a laser-cutting process. The performances of two prototype couplers for 3 dB and 23 dB demonstrate good agreement between HFSS simulations and measurements. However, the measured results for the through and coupled ports show additional losses between 2.5 dB and 5 dB. Although these are good results in the 100 GHz frequency range, the main contributions to loss appear to be caused by the waveguide-to-SIW transition and the dielectric substrate. Therefore, special emphasis will have to be placed on measurements procedures and loss analysis for future millimeter-wave applications of this technology.

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