Modified Broadband Half Mode Substrate Integrated Waveguide Cruciform Coupler

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Abstract **─** In this paper, a cruciform coupler with Half Mode Substrate Integrated Waveguide (HMSIW) structure is presented. The prototype coupler consists of four half mode SIW structures, which are crossing each other at right angles. Also, two metallic posts are inserted in free section of junction in order to make coupling properties. Compact size and broadband operation are the features of this coupler. The size of coupler is reduced 24% in comparison to previous HMSIW cruciform couplers. A fractional bandwidth of about 35% is obtained. The coupler is designed and simulated by HFSS13. Here, the simulation results are compared with experimental results.

Index Terms **─** Cruciform coupler, directional coupler, half mode SIW, millimeter wave, substrate integrated waveguide.

I. INTRODUCTION

90 degree hybrids have been used in many applications in telecommunication circuits such as modulators, mixers, feed networks and other microwave devices. Branch line, Lange, Bethe hole, short slot and cruciform coupler are well-known conventional types of 90 degree hybrids [1]. The cruciform couplers are attractive due to some advantages such as compactness, simplicity, planar structure, right-angled input/output ports, high power handling capability, flat coupling and broadband properties [2-3]. In designing cruciform couplers, realization of wide bandwidth and small size are two important goals.

A new structure called substrate integrated waveguide is useful for high frequency applications. It is a kind of rectangular waveguide in which sidewalls are replaced by a row of metallic posts. Low loss, high Q factor, and easy fabrication are the advantages of SIWs [4-5]. In the last decade, in the process of redeveloping rectangular waveguide components in the form of substrate integrated waveguides, some cruciform couplers have been designed and implemented [6-9]. In the rectangular waveguide cruciform coupler [3], the wide cross junction technique for wide bandwidth has been introduced for the first time and 28% bandwidth has been achieved. The original cruciform coupler tends to give flat coupling property at high frequency region. The wide cross junction can shift the flat frequency characteristics to the lower frequency region. Wide cross junction techniques have been applied to the SIW cruciform couplers in different

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manners, such as bending the angel of cross junction [6] or changing the place of the vias in corners [7,8,9].

We need more compact and wider bandwidth couplers in some applications. A Half Mode SIW (HMSIW) cruciform coupler has been introduced by Wang, et al. [10]. In that structure, the size was reduced and a compact structure was achieved. But in that coupler, because of input/output arms bending for the impedance matching between HMSIW and cross region, a tradeoff exists between the width of cross junction and the bandwidth. If the size of cross region is decreased, the coupling factor will be improved, but the bandwidth will be reduced. Small size and low insertion loss are the advantages of the half mode SIW in comparison with SIW [11-12]. In recent years, some half mode SIW couplers have been designed. Size reduction is their common feature [13-14].

In this article, we propose a modified HMSIW cruciform coupler with smaller size and wide bandwidth .The size of coupler is reduced 24% in comparison to previous HMSIW cruciform couplers. Also, a fractional bandwidth is obtained about 35%. The half mode SIW is a modified structure of SIW to reduce its size. It is built by bisecting a SIW structure along the symmetrical center plane along the propagation direction. To this reason, when an SIW works only in dominant mode, TE_{10}, tangential E-field has maximum value and normal magnetic field is equal to zero in symmetrical plane along the propagation direction. Thus, we can assume the center symmetrical plane as a fictitious magnetic wall and bisect the SIW from this fictitious wall to two sections. Each half section has half of the field distribution, and the power leakage from open side is negligible because of its large width-to-height ratio (exceed 10).

II. CIRCUFORM COUPLER DESIGN

The cruciform coupler is a type of 90 degree hybrids. It originally consists of two rectangular waveguides which are crossing each other at right-angle. Two metallic posts in cross region are used to make the coupling factors. Also, metallic posts are placed in each input arm for better matching. The height of structure is less than wavelength; thus, the electromagnetic field is nearly constant in vertical direction. The wide cross junction technique leads to wider bandwidth in cruciform couplers [6-9].

A prototype 3-dB HMSIW cruciform coupler is designed by replacing the SIW waveguides by the half mode structures. Figure 1 shows the designed half mode cruciform coupler geometrical dimension at 24 GHz. The coupler is designed on a Rogers RT/duriod 5880 substrate. The height of substrate is 0.508 mm with $\varepsilon_r = 2.2$ (loss tangent 0.0009). r is the radius of vias, h is the thickness of substrate, a is the initial width of half mode SIW arms, d is the distance between two coupling via, c and m present coupling vias and matching vias, respectively. Width of the arms are shown by “a” in Fig. 1 and it is calculated by the formula presented in [11]. It is about λ/4 wavelength and gives the cutoff frequency of the HMSIW. Also, the diameter r and spaces s between the vias are calculated by equations in [5]. Two metallic posts are inserted in cross region to generate and control the coupling factors. Here, the placements of coupling vias in Fig. 1 is presented with 90 degree rotation to Wang’s half mode coupler design [10]. The Wang’s structure is classified to a kind of short-slot coupler. By this change, the cross junction will be large enough for wide bandwidth and we don’t need to sketch the arms of coupler similar to the pervious design by Wang, et al. Therefore, realization of a smaller coupler is expected. We also introduce the bending vias in corners and the tapering vias of input arms for better matching and apply widening technique for wide bandwidth (the vias are tapered with the rate of w=0.2 mm). Coupling factors and good matching state can be adjusted by changing the radius and place of coupling vias. Space ‘d’ between the coupling vias and radius Rc, affect the coupling factors and bandwidth. Small distance leads to disturbance to matching state and also decreases the S_{11} and S_{41}. Increasing this space causes weaker coupling factor. In addition, if the position (Uc, Wc) is adjusted individually, the coupling factor can be controlled more precisely. Therefore, it is possible to design a 6 dB or 9 dB coupler, if the coupling factor, namely, the position of the coupling vias are optimized. Matching vias are inserted in each input arms for better matching.

The size and place of coupling vias and the matching vias are optimized by full wave simulator software, HFSS 13. As a result, the dimensions of structure are determined as: εr=2.2, h=0.508 mm, r=0.5 mm, s=1.7 mm, a=4.5 mm, w=0.2, Rc=0.85 mm, Rm=0.35 mm, (Uc,Wc)=(3.5,-3.5), (Um,Wm)=(7,1.5).

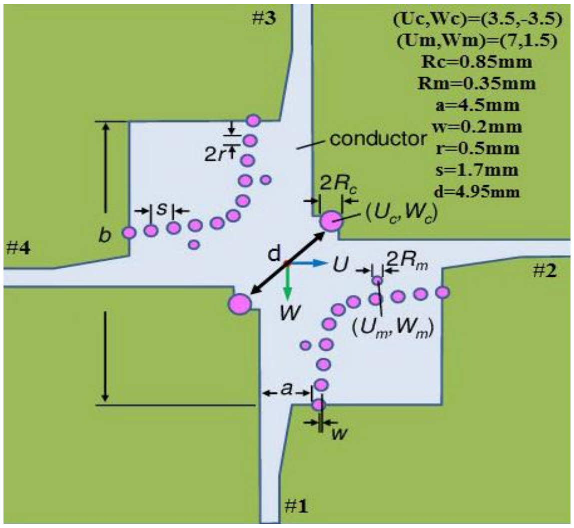


Fig. 1. Half mode cruciform coupler geometrical dimension.

III. SIMULATION AND EXPERIMENTAL RESULTS

The coupler is simulated by HFSS13 with full wave simulation. Then, the simulation results are compared with experimental results. Figure 2 shows the current distribution at 24 GHz on the surface of half mode prototype coupler. It is found that the input signal from port 1 interacts with metallic posts in the cross region, and is coupled equally to port 2 and port 3. The S-parameters of the coupler obtained by HFSS are shown in Fig. 3. In the simulation, the conductor, dielectric, and radiation losses are considered.

From 20.5 GHz up to 29 GHz, S_{21} and S_{31} are between range of 4-6 dB. The values of S_{11} and S_{41} in the frequency range of 21-29 GHz are below -15 dB, 35% bandwidth is achieved by -15 dB isolation. The following typical values are obtained for the center frequency at 24 GHz:

$$S_{11} = -33\text{dB} \quad S_{21} = -4\text{dB},$$

$$S_{31} = -4\text{dB} \quad S_{41} = -30\text{dB}.$$

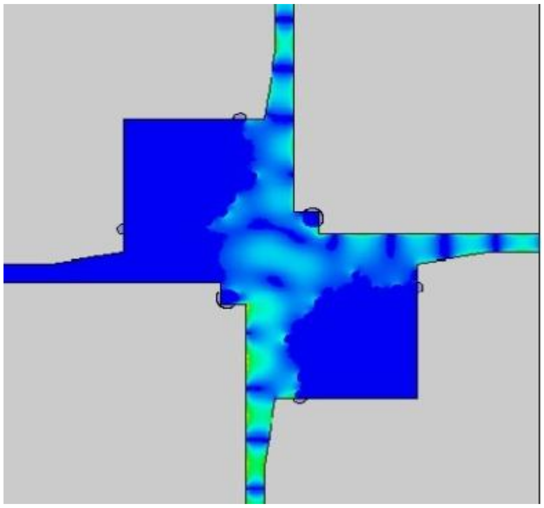


Fig. 2. Current distribution on the surface of half mode prototype coupler for 24 GHz.

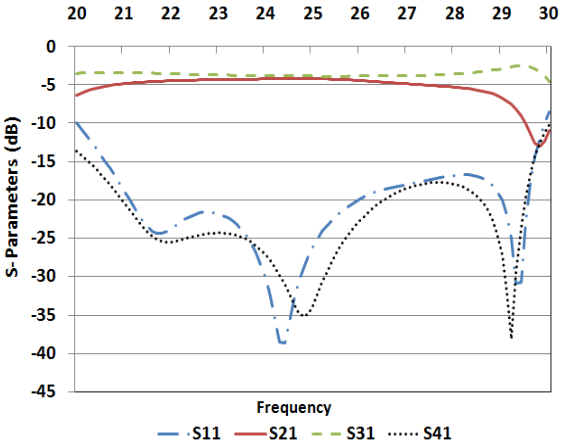


Fig. 3. S-parameters of half mode SIW cruciform coupler in HFSS.

Figure 4 shows the phase difference between ports 2 and 3 and it obviously shows 90-degree phase difference. The designed 3 dB coupler was fabricated and the S-parameters and phase difference were measured using Agilent's E8361C vector network analyzer. Figure 5 (a) shows the fabricated coupler. The measured magnitudes of the S-parameters and the output phase difference are presented in Figs. 5 (b), (c), and (d). A full 2-port 1.85 mm calibration was performed on the VNA electronically. The 1.85-3.5 mm adapters and the SMA connectors are necessary for the measurement. To exclude the insertion losses of microstrip lines, the SMA terminals and the adapters, a straight section of 2-port microstrip line was fabricated. The insertion losses including terminal connectors are calibrated by using the measurement results of the 2-port microstrip straight section. It is obvious that both the simulated results and the measured results are in good agreement. The size of our prototype coupler is 24.0×24.0 mm without tapered microstrip sections. Considering the fact that the width of HMSIW is a=4.5 mm (or about 1/4 wavelength), it is equal to about 6 times of the width (or 1.5 wavelengths) of HMSIW. It becomes 36.0×36.0 mm with tapered microstrip sections.

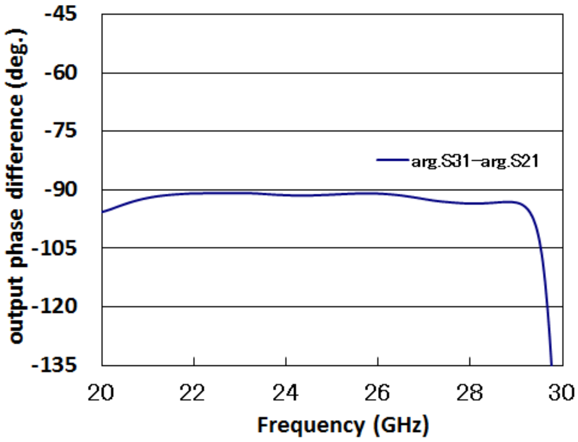
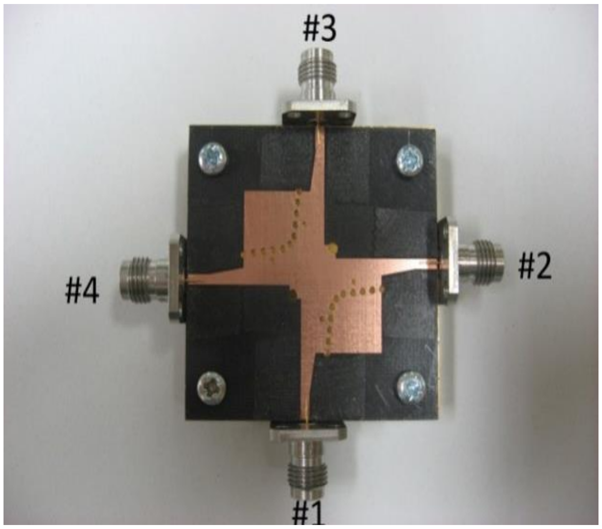
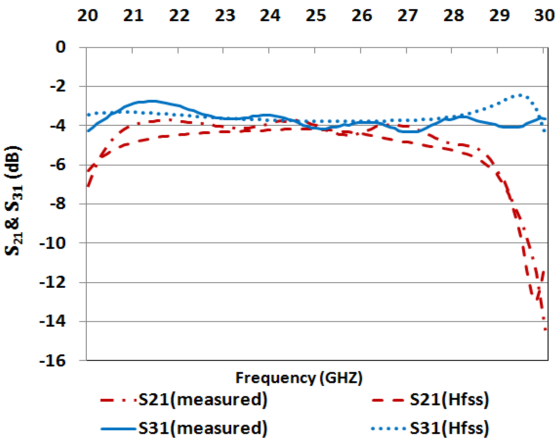


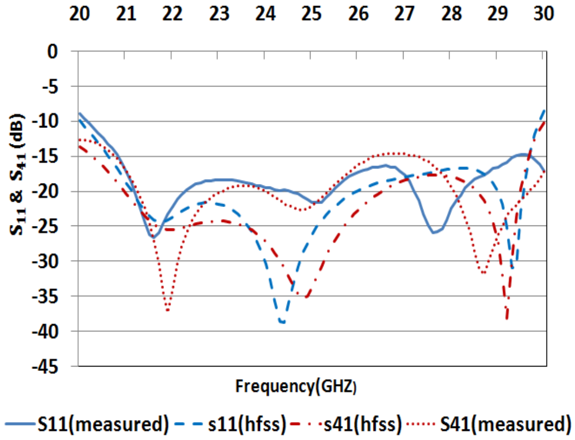
Fig. 4. Output phase difference between port 2 and 3 in HFSS.



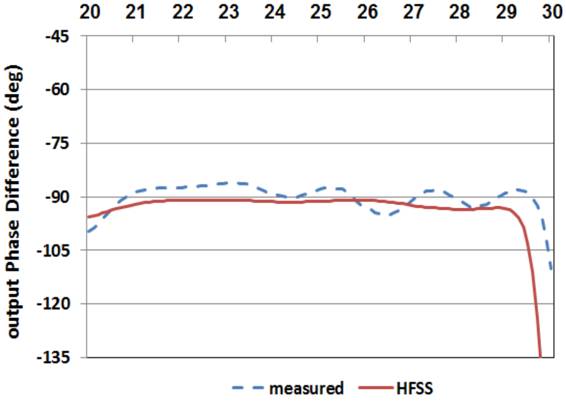
(a)



(b)



(c)



(d)

Fig. 5. Experimental results: (a) fabricated coupler, (b) measured and simulated S_{21} and S_{31}, (c) measured and simulated S_{11} and S_{41}, and (d) output phase difference.

First, the prototype coupler is compared with a broadband SIW cruciform coupler that is designed by Kishihara, et al. [6]. Their coupler has been designed for 21-28 GHz frequency and 30% bandwidth. The size of SIW cruciform coupler is 26.15×26.15 mm and it is equal to 3.89 widths or 1.95 wavelengths and with tapered microstrip sections it becomes 30.55×30.55 mm. One can conclude that the area of the present prototype is about 40% smaller and bandwidth of 35% is 5% broader than the one in [6]. Subsequently, another comparison is done with Wang's HMSIW cruciform coupler designed at 36 GHz [10]. The area of this HMSIW cruciform coupler is 15.5×15.5 mm without tapered sections it is equal to 6.89 widths or 1.72 wavelengths, because the width of the HMSIW is around 2.25 mm or 1/4 wavelength. This comparison indicates that our proposed structure is 24% smaller than previous research by Wang, et al. In addition, the modified model has more than 35% bandwidth while the previous one has achieved only 22% bandwidth. This comparison results are shown in Table 1. Due to using half mode SIW and optimum arrangement of vias, the phase difference between ports 2 and 3 is around -90° with tapered microstrip sections from simulation and experimental. We have achieved a coupler with 24% smaller size in compariosn to the HMSIW cruciform coupler and arround 40% smaller than the SIW cruciform coupler.

Table 1: Comparison between our coupler and two models of previous one

	Frequency	Bandwidth	Size (Without Taper Microstrip Section)
Ref [6]	21-28 GHz	30%	26.15×26.15 mm^2 (1.95 wavelength)
Ref [10]	32-40 GHz	22%	15.5×15.5 mm^2 (1.72 wavelength)
Our design	20.5-29 GHz	35%	(24×24 mm^2) (1.5 wavelength)

IV. CONCLUSION

In this paper, a modified cruciform type coupler with half mode SIW structure is presented for millimeter wave applications. The bandwidth of about 35% is obtained in full wave simulation and experimental. Small size and broad bandwidth are the obtained features of this coupler.

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