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 structure is presented. The prototype coupler consists of four half mode SIW structures crossing each other in right angle and two metallic posts are inserted in free section of junction in order to reach the coupling properties. Compact size and broadband operation are the features of this coupler. The size of coupler is reduced about 24% compared to previous HMSIW cruciform coupler and around 40% smaller than the SIW cruciform coupler. A fractional bandwidth of about 35 percent is obtained. The coupler has been designed and simulated with HFSS13 and CST microwave studio for full wave simulation. Here, the simulation results have been compared with experimental results.

Keywords: half mode SIW, substrate integrated waveguide, cruciform coupler, directional coupler, millimeter wave

I. INTRODUCTION

In recent years by development of communication and radar systems at high frequency range, new structures should be designed for wave transfer at these frequencies. Low loss and small size should be considered in millimeter frequency range [1] 90 degree hybrids are 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 different conventional types for 90 degree hybrids [2]. The cruciform couplers are attractive due to some advantages such as compactness, simplicity, planar structure, right-angled input/output ports, high handling power, flat coupling and broadband quality [3, 4]. So many researches have been done on design and improvement of these couplers. Wide bandwidth and small size are 2 goals in designing of these couplers.

Substrate integrated waveguide is a new structure for using in high frequency applications. It is a new type of rectangular waveguide in which sidewalls are replaced by a row of metallic posts. Low loss, high Q factor, high power quality and easy fabrication are the advantages of SIWs. [5, 6] In the last decade, by developing rectangular waveguide
in form of substrate integrated waveguides, some cruciform couplers have been designed and implemented [7]-[10].

In [4], a cruciform coupler in common rectangular waveguide have been designed. In this article, for the first time, the wide cross junction technique for wide bandwidth is introduced and 28% bandwidth is achieved. Wide cross junction technique has been done in a different manner such as bending the angel of cross junction [7] or changing the place of the Vias in corners [8]-[10].

In some applications we need to have more compact and wider bandwidth couplers. A half mode SIW (HMSIW) cruciform coupler was introduced in [11] by Wang et al. In that structure, the size was reduced and a compact structure was achieved, but as the bending input/output arms are employed for the impedance matching between HMSIW and cross region, there is a tradeoff between the width of cross junction and bandwidth. By decreasing the size of cross region, coupling factor will be improved, but bandwidth will be reduced.

In this article, we propose a modified HMSIW cruciform coupler with small size and wide bandwidth. The size of coupler is reduced to 24% compared to previous HMSIW cruciform couplers. Moreover a fractional bandwidth about 35 percent is obtained.

The half mode SIW is a modified structure of SIW for reducing its size. It is built by bisecting an SIW structure along the symmetrical center plane along the propagation direction. It is because of this reason that’s why 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. So 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). Small size and low insertion loss are the advantages of the half mode SIW compared with SIW [12]-[13]. During last years, some half mode SIW couplers have been designed [14]-[15] and size reduction is a common feature in these designs.

II. Cruciform couplers design

A substrate integrated waveguide is shown in Fig. 1. The wave propagation inside of SIW structure is the same as the conventional waveguide [16]. As shows in Fig. 1, W is the width of SIW, d is Via's diameter and h is the substrate thickness. If we assume a and b as the width and height of the conventional rectangular waveguide, then $TE_{10}$ is propagation mode in the waveguide and cut off frequency is defined as shows in (1).

$$ a = \frac{c}{2f_{c,10} \sqrt{\varepsilon}}. $$

If the distance between the vias (S) is increased, the radiation losses will be created because of the leakage field in SIW structure.

$$ S \leq 2d $$

$$ d \leq \frac{\lambda_0}{5} $$

The guided wavelength for the dominant mode is as shows in (4):

$$ \lambda_{g,10} = \frac{2\pi}{\sqrt{\left(\frac{E_0 \omega}{c}\right)^2 + \left(\frac{\pi}{a}\right)^2}}. $$

If the $TE_{\omega0}$ is first propagation mode in SIW then we can calculate the maximum size of diameter as shows in (5):

$$ d \leq \frac{2a}{5\sqrt{m^2 - 1}} $$

Where (a) is the waveguide width as shows in (6):

$$ a = W - 1.08 \frac{d^2}{s} + 0.1 \frac{d^2}{W}. $$

![Fig. 1](conventional substrate integrated waveguide)
The cruciform coupler is one of 90 degree hybrids. It originally consists of two rectangular waveguides which are crossing each other with right-angle. Two metallic posts in cross region are used to make the coupling factors. Also metallic posts are placed in each input arms for better matching. The height of structure is less than the wavelength so the electromagnetic field is nearly constant in vertical direction. A wide cross junction technique leads to wider bandwidth in cruciform couplers [7]–[10].

A prototype HMSIW cruciform coupler is designed by replacing the SIW waveguides by the half mode structures. Fig. 2 shows the half mode cruciform coupler geometrical dimension designed at 24 GHz.

A Rogers RT/duriod 5880 with height of 0.508 mm and $\varepsilon_r=2.2$ (loss tangent 0.0009) is used as substrate in design. Two metallic posts are inserted in cross region for generating the coupling factors. Here the placements of coupling Vias has been presented with 90 degree rotation to Wang’s half mode coupler design. By this change, the cross junction will be large enough for wide bandwidth and we don’t need to sketch the arms of coupler like pervious design by Wang et al. So a smaller coupler is expected. We also have introduced the bending Vias in corners and the tapering Vias of input arms for better matching and applied widening technique for wide bandwidth. Coupling factors and good matching state can be adjusted by changing the radius and place of coupling Vias. A matching Via is inserted in each input arms for better matching.

The size and place of coupling and matching Vias are optimized by full wave simulator software, HFSS 13. The dimensions of structure is determined as $\varepsilon_r=2.2$, $h=0.508\text{mm}$, $r=0.5\text{mm}$, $s=1.7\text{mm}$, $a=4.5\text{mm}$, $w=0.2\text{mm}$, $R_c=0.85\text{mm}$, $R_m=0.35\text{mm}$, $(U_c,W_c)=(3.5,3.5)$, $(U_m,W_m)=(7,1.5)$. $r$ is the radius of Vias, $h$ is the thickness of substrate, $a$ is the initial width of half mode SIW arms, $c$ and $m$ present coupling Vias and matching Vias respectively.

III. Simulation and Experimental Results

The coupler has been simulated with HFSS13 for Full wave simulation. Then the simulation results have been compared with experimental results. In experimental, The S-parameters and phase difference were measured using Agilent’s E8361C vector network analyzer.

Fig. 2 Half mode cruciform coupler geometrical

Fig. 3 Current distribution on the surface of half mode prototype coupler for 24 GHz

Fig.3 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 output equally to port 2 and port 3. The S-parameters of the coupler obtained by simulation and experimental are shown in Fig. 4. In the simulation, the conductor, dielectric, and radiation losses are considered for HFSS.

In simulation result From 20.5 GHz up to 29 GHz, $S_{22}$ and $S_{33}$ are in range of 4-6dB. The values of $S_{11}$ and $S_{31}$ in frequency range of 21-
29GHz are below -15dB. By -15dB isolation, 35% bandwidth is achieved. The following typical values are obtained for the center frequency at 24 GHz.

\[ S_{11} = -33dB \quad S_{31} = -4dB \]
\[ S_{13} = -4dB \quad S_{41} = -30dB \]

As it showed in Fig.4 a good agreement exist between simulation and experimental results. Fig.5 shows the phase difference between ports 2 and 3 by simulation and experimental test and it obviously shows 90-degree phase difference. Fig.5 shows the fabricated coupler. The effects of terminal connectors are subtracted by using the measurement results of a 2-port microstrip straight section. It is found that both the simulated results and the measured results are in good agreement. The size of our prototype coupler is 24.0mm × 24.0mm without tapered microstrip sections. Considering the fact that the width of HMSIW is \( a = 4.5mm \) (or about 1/4 wavelength), it about 6 times of the HSIW width (or 1.5 wavelengths). With tapered microstrip sections it becomes 36.0mm × 36.0mm.

First, the prototype coupler is compared with a broadband SIW cruciform coupler that is designed by Kishihara et al. [5]. Their coupler is designed for 21-28 GHz and has achieved 30% bandwidth. The size of the SIW cruciform coupler is 26.15mm × 26.15mm and it is equal to 3.89 widths or 1.95 wavelengths and with tapered microstrip sections it becomes 30.55mm × 30.55mm. It is obvious that the area of the present prototype is about 40% smaller and bandwidth 35% is 5% broader than in [5].

Subsequently, another comparison has been done with Wang’s HMSIW cruciform coupler designed at 36 GHz. The area of this HMSIW cruciform coupler is 15.5mm × 15.5mm without tapered sections, and it is equal to 6.89 widths or 1.72 wavelengths, because the width of the HMSIW is around 2.25mm or 1/4 wavelength. This comparison indicates that our suggested structure is 24% smaller than previous research by Wang et al. in addition, the modified model has more than 35% bandwidth while the previous work has achieved only 22% bandwidth.

**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 percent is obtained with full wave simulation and experimental. Small size and broad bandwidth are the features of this coupler obtained due to using half mode SIW and optimum arrangement of Vias. The phase difference between ports 2 and 3 is around $90^\circ$ achieved from simulation and experimental. We achieved a coupler with 24% smaller in size comparing with the HMSIW cruciform coupler and around 40% smaller than the SIW cruciform coupler.

REFERENCES


