Multilayer Substrate Integrated Waveguide Directional Coupler

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Abstract: - In this paper a new directional multilayer coupler based on SIW technology is presented. The proposed MSIW directional coupler work for the operation frequency 5.8 GHz. Ansoft HFSS simulation software is used. The tapered line is used as transition between MSIW and microstrip-line for easy integration. These structures present a good performance such a good isolation <-34 dB and coupling of -06.37 dB. He presents many advantages of convenient integration, compact size, low cost, mass-producibility and ease in fabrication. Simulated results are presented and discussed.

Key-Words: - Design, SIW, Multilayer SIW, Coupler, MSIW, Slot, Multilayer Coupler, Transitions.

1 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 [1-2].

The directional coupler is widely used in many microwave and millimeter wave system for generating desired power splitting with certain specification requirements such as frequencies; bandwidth and the size of structure [3]. The basic operation of directional coupler is when the input supplied to Port 1 is coupled to Port 3 (coupled) with the coupling factor, while the remains of the input power is delivered to Port 2 (through). There is no power deliver to the Port 4 (isolated) for the ideal condition [4].

Therefore, great interest and special effort have been directed to the development of different types of directional coupler for different applications [3]. Rectangular waveguide directional coupler was extensively investigated [5-10] and numbers of circuit configurations have been developed on the basis of various design principles that suitable for high performance, high power, low insertion loss and high quality (Q) factor. However, the manufacturing of the rectangular waveguide structure is rather expensive because of the bulky size and in a form of nonlinear. This contributes to the difficulty to integrate with other planar circuits. In order to overcome this problem, Substrate Integrated Waveguide (SIW) is used to overcome these problems.

Since the introduction of the SIW concept in 2001 [11], attention has been increased significantly towards using this technology in designing millimeter-wave coupler. Inheriting low radiation loss, acceptable Q-factor and high power handling capability from traditional rectangular waveguide structures, SIW also utilizes low cost, low profile and easy integration capabilities of planar structures [12].

The traditional SIW directional coupler is realized by two SIW's with a common broadside wall on which one or many small aperture are utilized to realize the coupling between two SIW's (Fig. 1).

Fig. 1 A traditional SIW Coupler.

For the goal to miniature microwave components and circuits, many technics are employed such FSIW, HMSIW and multilayer SIW [13-15].

To meet the increasing requirements of modern communication systems in terms of compact size and high selectivity, SIW components with multiple layer using the PCB or LTCC processes have been extensively studied in recent years [16-17].

The application of multilayer technology make the realization of coupler with compact size, light weight and high performance possible, due to its three dimensional integration characteristic, low-tolerance in manufacturing process [18].

This paper is organized as follows: Section I present an introduction to SIW coupler and the different miniaturization technics, Section II present the theory of the RWG Multilayer Directional Coupler, Section III present the design of the multilayer SIW coupler while the section IV discusses the simulation results.

2 Theory of RWG multilayer directional coupler

The directional property of all directional coupler is produced through the use of two separate waves or wave components, which add in phase at the coupled port and are canceled at the isolated port. The simplest ways of doing this is to couple one waveguide to another through a single small hole in the common broad wall between the two waveguides as showing in **Fig. 2**.

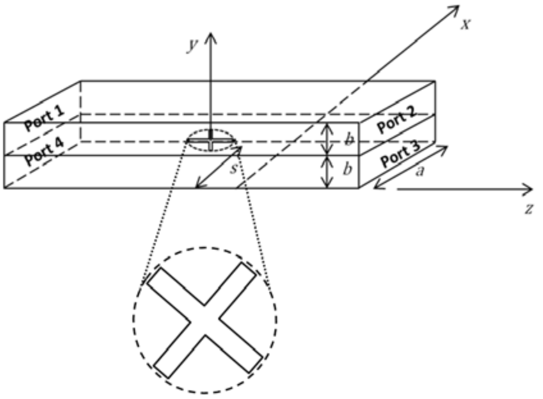


Fig. 2 A RWG multilayer directional coupler.

From [19] the aperture can be replaced with equivalent sources consisting of electric and magnetic dipole moments. The normal electric dipole moment and the axial magnetic dipole moment radiate with even symmetry in the coupled guide, while the transverse magnetic dipole moment radiates with odd symmetry. Thus, by adjusting the relative amplitudes of these two equivalent sources, we can cancel the radiation in the direction of the isolated port, while enhancing the radiation in the direction of the coupled port. The two waveguides are parallel and the coupling is controlled by s, the aperture offset from the sidewall of the waveguide.

Considering the configuration of the coupler, with an incident TE_{10} mode into port 1. These fields can be written as:

$$E_y = A \sin\frac{\pi x}{a} e^{-j\beta z} \quad \textbf{(1.a)}$$

$$H_x = \frac{-A}{Z_{10}} \sin\frac{\pi x}{a} e^{-j\beta z} \quad \textbf{(1.b)}$$

$$H_z = \frac{j\pi A}{\beta a Z_{10}} \cos\frac{\pi x}{a} e^{-j\beta z} \quad \textbf{(1.c)}$$

where $Z_{10} = k_0\eta_0/\beta$ is the wave impedance of the TE10 mode. This incident wave generates the following equivalent polarization currents at the aperture at x=s, y=b, z=0 [20]:

$$\bar{P}_e = \epsilon_0 \alpha_e \hat{y}\, A \sin\frac{\pi s}{a}\, \delta(x-s)\delta(y-b)\delta(z) \quad \textbf{(2.a)}$$

$$\bar{P}_m = -\alpha_m\, A\left[\frac{-\hat{x}}{Z_{10}} \sin\frac{\pi s}{a} + z\frac{j\pi}{\beta a Z_{10}} cos\frac{\pi s}{a}\right]\delta(x - s)\, \delta(y-b)\delta(z) \quad \textbf{(2.b)}$$

Relating $\bar{P}_e$ and $\bar{P}_m$ to the currents $\bar{J}$ and $\bar{M}$, and by using [20], the amplitude of the forward and reverse traveling waves in the top guide is given by:

$$A_{10}^{+} = \frac{-1}{P_{10}}\int_v \bar{E}_{10}^{-} . \bar{J} dv + \frac{1}{P_{10}}\int_v \bar{H}_{10}^{-} . \bar{M} dv$$

$$A_{10}^{+} = \frac{-j\omega A}{P_{10}}\left[\epsilon_0 \alpha_e sin^2\frac{\pi s}{a} - \frac{\mu_0 \alpha_m}{Z_{10}^2}\left(sin^2\frac{\pi s}{a} + \frac{\pi^2}{\beta^2 a^2} cos^2\frac{\pi s}{a}\right)\right] \quad \textbf{(3.a)}$$

$$A_{10}^{-} = \frac{-1}{P_{10}}\int_v \bar{E}_{10}^{+} . \bar{J} dv + \frac{1}{P_{10}}\int_v \bar{H}_{10}^{+} . \bar{M} dv$$

$$A_{10}^{-} = \frac{-j\omega A}{P_{10}}\left[\epsilon_0 \alpha_e sin^2\frac{\pi s}{a} + \frac{\mu_0 \alpha_m}{Z_{10}^2}\left(sin^2\frac{\pi s}{a} - \frac{\pi^2}{\beta^2 a^2} cos^2\frac{\pi s}{a}\right)\right] \quad \textbf{(3.b)}$$

where $P_{10} = ab/Z_{10}$ is the power normalization constant. Note from (3.a) and (3.b) that the amplitude of the wave excited toward port 4 (A_{10}^{+}) is generally different from that excited toward port 3 (A_{10}^{-}) because ($H_x^{+} = -H_x^{-}$), so we can cancel the power delivered to port 4 by setting $A_{10}^{+} = 0$. If we assume that the aperture is round, we can take the polarizabilities as $\alpha_e = 2r_0^3/3$ and $\alpha_m = 4r_0^3/3$. where r_0 is the radius of the aperture.

Then from (3.a) we obtain the following condition for $A_{10}^{+} = 0$:

$$\left(2\epsilon_0 - \frac{4\mu_0}{Z_{10}^2}\right) sin^2 \frac{\pi s}{a} - \frac{4\pi^2\mu_0}{\beta^2 a^2 Z_{10}^2} cos^2 \frac{\pi s}{a} = 0$$

$$\Rightarrow (k_0^2 - 2\beta^2) sin^2 \frac{\pi s}{a} = \frac{2\pi^2}{a^2} cos^2 \frac{\pi s}{a}$$

$$\Rightarrow \left(\frac{4\pi^2}{a^2} - k_0^2\right) sin^2 \frac{\pi s}{a} = \frac{2\pi^2}{a^2}$$

or

$$\sin \frac{\pi s}{a} = \pi \sqrt{\frac{2}{4\pi^2 - k_0^2 a^2}} = \frac{\lambda_0}{\sqrt{2(\lambda_0^2 - a^2)}} \quad \textbf{(4)}$$

The coupling factor is then given by:

$$C = 20 \log \left|\frac{A}{A_{10}^{-}}\right| dB \quad \textbf{(5.a)}$$

And the directivity by:

$$D = 20 \log \left|\frac{A_{10}^{-}}{A_{10}^{+}}\right| dB \quad \textbf{(5.b)}$$

Finally the directional coupler can be designed using (4) and (5.a) to determine the aperture position s and size r_0, to give the required coupling factor.

3 Multilayer SIW directional coupler design (MSIW)

2.1 Substrate Integrated Waveguide Design

The wave propagation inside of SIW structure is the same as the conventional waveguide [21]. If we assume a and b as the width and height of the conventional rectangular waveguide, the TE_{10} is propagation mode in the waveguide and cut off frequency is defined as shown in equation (6).

$$f_{cTE_{10}} = \frac{c}{2a\sqrt{\varepsilon_r}} \quad \textbf{(6)}$$

Fig. 3 show the structure of the SIW. Where W_{siw} and L_{siw} are the real width and length of SIW cavity. However d and p are the diameter and pitch respectively, are playing a main role to control the radiation losses, the diameter and pitch are given by [22] and [23]:

$$d < \frac{\lambda_g}{5} \quad \textbf{(7.a)}$$

$$p \leq 2 * d \quad \textbf{(7.b)}$$

with λ_g is the guided wave length of the dominant mode:

$$\lambda_g = \frac{2\pi}{\sqrt{\left(\frac{\varepsilon_r \omega}{c}\right)^2 + \left(\frac{\pi}{a}\right)^2}} \quad \textbf{(8)}$$

The SIW components can be initially designed by using the equivalent rectangular waveguide model in order to diminish design complexity. The effective width of SIW can be defined by [24]:

$$a_{eff} = W_{siw} - 1.08\left(\frac{d^2}{p}\right) + 0.1\left(\frac{d^2}{W_{siw}}\right) \quad \textbf{(9)}$$

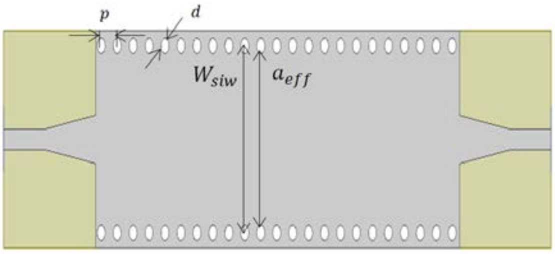
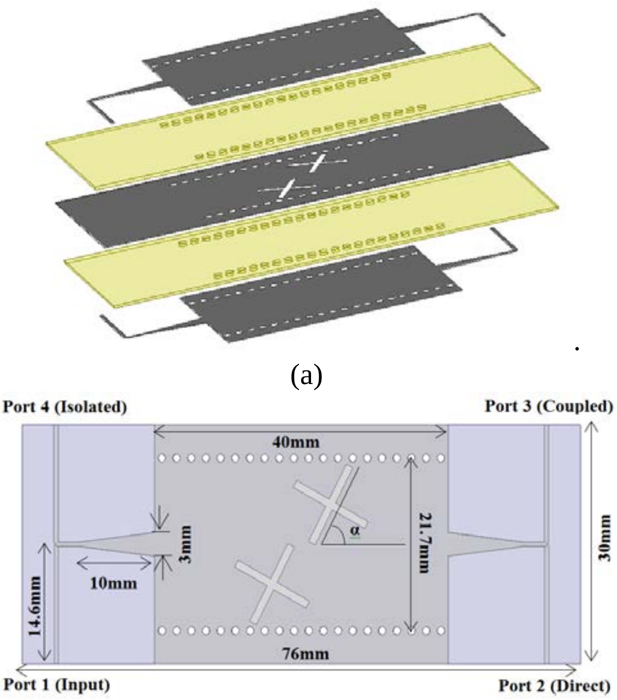


Fig. 3 Conventional Substrate Integrated Waveguide.

2.1 Multilayer SIW coupler Design

The geometry of the double-layered SIW coupler consist of two SIW's – one on the top of other coupled through two cross slots as shown in Fig. 4(a). The length, the angle and the distance of the 1mm thick slanted cross slot are optimized to achieve maximum coupling level at the operating frequency of 5.8 GHz.


(a)

(b)

Fig. 4 Geometry of the multilayer coupler.

4 Simulation and Results

The proposed multilayer coupler is simulated by using Ansoft HFSS. Basing on a substrate with a dielectric constant of $\varepsilon_r=3$, $\tan\delta=0.03$ and a height of h=0.254mm, the cut off frequency of the fundamental mode (f_0) was set to 4GHz.

The coupling level is basically controlled by the width of the slots and there inclination α.

The Coupling and Isolation are affected by the rotation of cross slot.

The following table show the variation of Coupling and Isolation by varying of inclination angle α value.

Table 1. Values of coupling and isolation by variation of angle α.

inclination angle α	Coupling at 5.8 GHz	Isolation at 5.8 GHz
20°	-7.09 dB	-13.59 dB
40°	-6.50 dB	-18.86 dB
60°	-6.25 dB	-21.22 dB
80°	-6.87 dB	-20.04 dB
90°	-6.91 dB	-15.23 dB

After optimization using HFSS, the best results in terms of coupling and low insertion losses is obtained for α = 62°.

Fig. 5 shows the simulated S-parameters versus frequency for this coupler with an angle α = 62°.

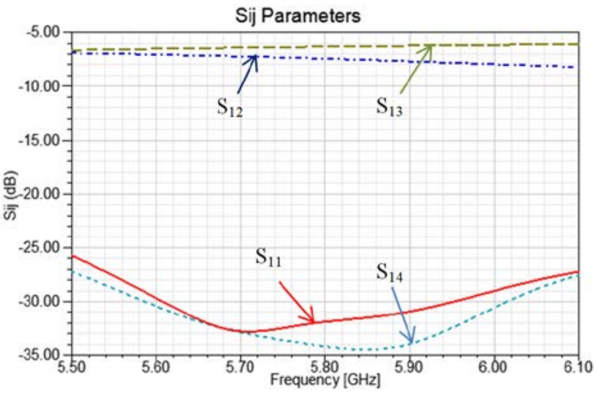


Fig. 5 Sij parameters of the proposed coupler.

The next table show the comparison between the results found in simulation with two cross and the one from [25].

Table 2. Comparison of the simulation results with the results of [25].

With Two Slot [24]		With Two Cross (Our work)	
S11 : Input S12 : Directivity S13 : Coupling S14 : Isolation	-22.22 dB -08.50 dB -08.68 dB -24.33 dB	S11 : Input S12 : Directivity S13 : Coupling S14 : Isolation	-31.87 dB -07.48 dB -06.37 dB -34.16 dB

From the results we obtained that the proposed coupler present a better performance than the one of the reference [25].

5 Conclusion

A directional coupler based on multilayer substrate integrated waveguide is designed, in this paper. A parametric study is presented by varying the inclination angle of cross slot coupler. After optimization, this study gives good matching conditions with coupling of -06.37 dB and good isolation below -34.17 dB over the 5.8 GHz frequency band. Transitions to microstrip-line are demonstrated allowing MSIW to be easily integrated with other planar circuits. The proposed multilayer SIW directional coupler is attractive for many applications.

References:

[1] L. Yong, X. H. Tang, and T. Wu. “SIW-Based W-Band Low Phase-Noise Injection-Locked Harmonic Oscillator.” *Journal of Infrared, Millimeter, and Terahertz Waves* 33, no. 9,pp. 943-952, 2012.

[2] Chen, X.P. and K. Wu, 2009. “Substrate integrated waveguide filter with improved stopband performance for satellite ground terminal”. *IEEE Trans. Microw. Theor. Tech.*, 57(3): 674-683.

[3] T. Djerafi, Ke Wu, “Super-Compact Substrate Integrated Waveguide Cruciform Directional Coupler,” *Microwave and Wireless Coponents Letters, IEEE*, vol.17, no. 11, pp.757-759, Nov. 2007.

[4] David M. Pozar, “*Microwave Engineering*”, *Third Edition*, John Wiley & Sons Inc, 2005.

[5] Binbin Kou, En Li, Zhuoyue Zhang, "A Ku Band High Power Rectangular Waveguide Directional Coupler's Design," *Engineering and Technology (S-CET), 2012 Spring Congress on*, pp. 1-4, 27-30 May 2012.

[6] F. Alessandri, M. Giordano, M. Guglielmi, G. Martirano, F. Vitulli, "A new multiple-tuned six-part Riblet-type directional coupler in rectangular waveguide," *Microwave Theory*

and Techniques, IEEE Transactions on , Vol. 51, no. 5, pp. 1441- 1448, May 2003.
Kishihara, M., Yamane, K.; Ohta, I., "Design of Cruciform Directional Couplers in E-Plane Rectangular Waveguide," *Microwave Symposium Digest, 2006. IEEE MTT-S International*, vol., no., pp. 1722-1725, 11-16 June 2006.

[7] Ohta, I.; Yumita, Y.; Toda, K.; Kishihara, M.; , "Cruciform directional couplers in H-plane rectangular waveguide," *Microwave Conference Proceedings, 2005. APMC 2005. Asia-Pacific Conference Proceedings* , Vol. 2, no., pp. 4 pp., 4-7 Dec. 2005.

[8] Perini, H.; Sferrazza, P.; , "Rectangular waveguide to strip-transmission-line directional couplers," *WESCON/57 Conference Record* , Vol. 1, no., pp. 16- 21, Aug 1957.

[9] Brodwin, M.E.; Ramaswamy, V.; , "Continuously Variable Directional Couplers in Rectangular Waveguide," *Microwave Theory and Techniques, IEEE Transactions on* , Vol. 11, no. 2, pp. 137- 142, Mar 1963.

[10] K. Wu, "Integration and interconnect techniques of planar and nonplanar structures for microwave and millimeter-wave circuits - Current status and future trend," *Proc. Asia-Pacific Microwave Conf.* pp. 411-416, Taipei, Taiwan, Dec. 2001.

[11] X.H. Wu and A.A. Kishk, “Analysis and Design of Substrate Integrated Waveguide Using Efficient 2D Hybrid Method”, vol. 5., *Morgan & Claypool Publishers Series, Synthesis Lectures on Computational Electromagnetics*, Lecture #26, Jan. 2010.

[12] N. Grigoropoulos, B. S. Izquierdo, and P. R. Young, “Substrate integrated folded waveguides (SIFW) and filters,” *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 12, pp. 829–831, Dec. 2005.

[13] W. Hong, B. Liu, Y. Q. Wang, Q. H. Lai, and K. Wu, “Half mode substrate integrated waveguide: a new guided wave structure for microwave and millimeter wave application,” *in Proc. Joint 31st Int. Conf. Infrared Millim. Waves 14th Int. Conf. Terahertz Electron.*, Shanghai, China, Sep. 18–22, 2006, p. 219.

[14] A. A. M. Ali, N. J. G. Fonseca, F. Coccetti and H. Aubert, "Design and Implementation of Two-Layer Compact Wideband Butler Matrices in SIW Technology for Ku-Band Applications," *IEEE Antennas Propag. Mag.*, vol.59, no.2, pp.503-512, Jan. 2010.

[15] J. X. Chen, W. Hong, X. P. Chen, P. P. Yan, Q. H. Lai, and K. Wu, “An LTCC X-band receiver front-end using embedded multilayer substrate integrated waveguide filter,” *Microw. Opt. Techn. Lett.*, vol. 51, no. 1, pp.71-73, Jan. 2009.

[16] D. S. Eom, J. Byun and H. Y. Lee, "Multilayer Substrate Intergated Waveguide Four-Way Out-of-Phase Power Divider," *IEEE Trans. on Microwave Theory and Tech.* , Vol. 57, no. 12, pp. 3469- 3476, Dec. 2009.

[17] J.-H. Lee, S. Pinel, J. Papapolymerou, J. Laskar, M. M. Tentzeris, H.-M. Lee, et al., “Low-loss LTCC cavity filters using system-onpackage technology at 60 GHz,” *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 12, pp. 3817–3824, Dec. 2005.

[18] C. G. Montgomery, R. H. Dicke, and E. M. Purcell, "Principles of Microwave Circuits", *MIT Radiation Laboratory Series*, vol. 8, McGraw-Hill, New York, 1948.

[19] David M. Pozar, “*Microwave Engineering*”, *Fourth Edition*, John Wiley & Sons Inc, 2012.

[20] J. E, R. Sanchez and V.Gutierrez-Ayala "A General EM-Based Design Procedure for Single-Layer Substrate Integrated Waveguide Interconnects with Microstrip Transitions" *Microwave Symposium Digest, IEEE MTT-S International.*

[21] Feng Xu; Yulin Zhang; Wei Hong; Ke Wu; Tie Jun Cui; , "Finite-difference frequency-domain algorithm for modeling guided-wave properties of substrate integrated waveguide,"*Microwave Theory and Techniques, IEEE Transactions on* , Vol. 51, no. 11, pp. 2221-2227, Nov. 2003.

[22] Yan, L.; Hong, W.; Wu, K.; Cui, T.J.; , "Investigations on the propagation characteristics of the substrate integrated waveguide based on the method of lines," *Microwaves, Antennas and Propagation, IEEE Proceedings* , Vol. 152, no. 1, pp. 35- 42, 19 Feb. 2005.

[23] M. Bozzi, A. Georgiadis, K. Wu "Review of substrate-integrated waveguide circuits and antennas," *IET Microw. Antennas Propag.* 2011.

[24] Sangkil Kim and Manos M. Tentzeris, " An Inkjet-printed Flexible Broadband Multilayer SIW Coupler for Antenna Array Systems," *IEEE Microw. Antennas Propag.* 2014.