

# Design of a Compact X-Band Substrate Integrated Waveguide Directional Coupler

B. H. Ahmad<sup>#1</sup>, Siti Sabariah Sabri<sup>#2</sup>, A. R. Othman<sup>#3</sup>

<sup>#</sup>Centre for Telecommunication Research & Innovation (CeTRI), Faculty of Electronics and Computer Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

<sup>1</sup>badrulhisham@utem.edu.my

<sup>2</sup>Corresponding author: sitisabariahsabri@gmail.com

<sup>3</sup>rani@utem.edu.my

**Abstract**— This paper presented the design of four-port network directional coupler at X-band frequency (8.2-12.4 GHz) by using substrate integrated waveguide (SIW) technique. SIW appears few years back which provides an excellent platform in order to design millimeter-wave circuits such as filter, antenna, resonator, coupler and power divider. It offers great compensation for smaller size and can be easily integrated with other planar circuits. The fabrication process can simply be done by using standard Printed Circuit Board (PCB) process where the cost of the manufacturing process will be reduced compared to the conventional waveguide. The directional coupler basically implemented at radar, satellite and point-to-point radio. The simulations for this SIW directional coupler design shows good performances with low insertion loss, low return loss, broad operational bandwidth and have high isolation.

**Keyword**-Bandwidth, Coupling, Directional coupler, Four-port network, Isolation

## I. INTRODUCTION

The directional coupler mostly is used to operate on input so that two output signals are available. Coupler may be a three-port component or may be a four-port component [1]. It 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 the structure [2]. The compact coupler could save some space and reduce the metal loss. The wideband properties will bring a generalized usage of couplers [3, 4]. In antenna beam-forming networks, power dividing or combining networks are required and directional coupler is generally an important element in this application [5]. The basic operation of directional coupler is when the input or power 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. [1]. Microwave directional coupler has many different applications in most microwaves, RFs, radar, measurement systems and modern communication systems. Directional coupler is the four-port network which can be implemented in many different forms, including waveguide, hybrid junction and branch line coupler [6].

Therefore, great interest and special effort have been directed to the development of different types of directional coupler for different applications [2]. Rectangular waveguide directional coupler was extensively investigated [7-12] and a number of circuit configurations have been developed on the basis of various design principles that suitable for high performance and high power applications [2]. Besides, it also provides advantages such as low insertion loss and high quality factor. However, the manufacturing of the rectangular waveguide structure is rather expensive because of the bulky size and in a form of non-planar. This contributes to the difficulty to integrate with other planar circuits. In order to overcome this problem, new technique of designing millimeter-wave circuit has been introduced by Ke Wu [13] which is called SIW. SIW is a type of rectangular dielectric-filled waveguide that is synthesized in a planar substrate with arrays of metallic vias or slots in order to realize bilateral edge walls. Integrated transitions can be designed on the same substrate compatible with planar structures such as microstrip and coplanar waveguide [14, 15]. SIW structure can be fabricated by using any standard process including low-cost PCB techniques and have small and compact size circuit. SIW components are covered by metal surfaces on both sides of substrate which contribute to have low insertion loss, low radiation loss and insensitive to outside interference [16].

## II. CONFIGURATION OF SIW DIRECTIONAL COUPLER

The configuration of X-band SIW directional coupler is shown in Fig. 1 with the geometric parameters. The two arrays of via hole were placed on the side wall of the coupler in order to guide and inhibit signal from leakage. The coupling obtained by slots over the entire width of common broadside wall of two adjacent SIW's with a continuous coupling aperture [17]. In 2007, Tarek introduced SIW directional coupler by using cruciform that is realized by two perpendicular rectangular waveguide with a cross region in which two metal posts were set

symmetrically to control the signal flow. The two additional via posts placed in each port were used as a reflection cancelling element by varying sections of SIW.

In this paper, the idea of design come from [16] which have the simple configuration where the coupling is obtained by two narrow apertures in the common broadside wall of two adjacent SIWs. As shown in Fig. 1, Port 1 is defined as input port, Port 2 as through port, Port 3 as coupled port and Port 4 as the isolated port. The transition between SIWs and microstrip line is realized by using step impedance which is used to match physically for both electrical and magnetic field distributions between the two media as close as possible or in other words as impedance matching.

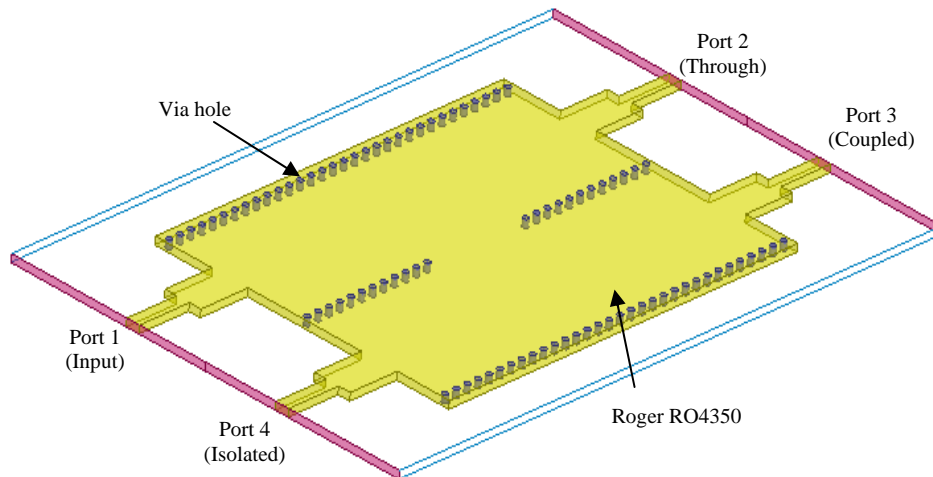


Fig. 1. Configuration of X-Band SIW directional coupler

### III. PARAMETER DESIGN OF SIW

The SIW was constructed from top and bottom metal planes of substrate and having two arrays of via holes in the both side walls as shown in Fig. 2. Via hole must be shorted to both planes in order to provide vertical current paths, otherwise the propagation characteristics of SIW will be significantly degraded. Since the vertical metal walls are replaced by via holes, propagating modes of SIW are very close to, but not exactly the same as in rectangular waveguide [18-19].

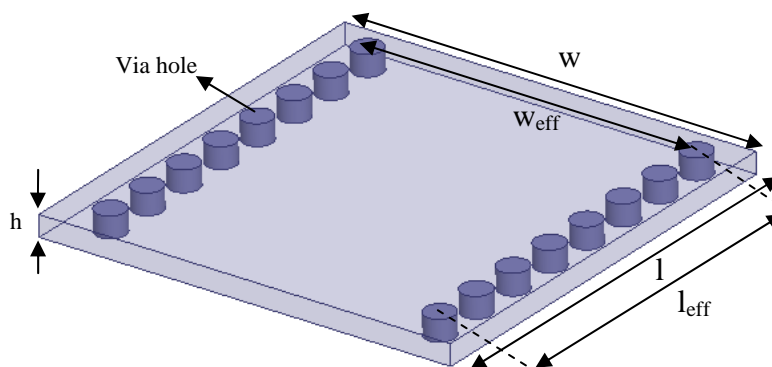


Fig. 2. Basic structure of SIW

By using equivalence resonance frequency, the size of SIW cavity is determined from [20]:

$$f_{101} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{\pi}{W_{eff}}\right)^2 + \left(\frac{\pi}{l_{eff}}\right)^2} \tag{1}$$

This is to ensure that the SIW coupler be able to support  $TE_{10}$  mode in the operating frequency range. The  $E$ -field distribution in SIW is just like in the conventional rectangular waveguide. The effective or equivalent width and length of SIW cavity can be determined from:

$$w_{eff} = w - \frac{d^2}{0.95p} \tag{2}$$

$$l_{eff} = l - \frac{d^2}{0.95p} \tag{3}$$

Where  $w$  and  $l$  are the real width and length of SIW cavity. However  $d$  is the diameter and  $p$  is the pitch, also known as distance between center to center of adjacent via hole shown in Fig. 3.

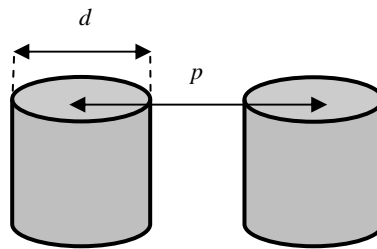


Fig. 3. Via hole

Via holes form a main part of SIW in order to realize the bilateral edge walls, the reduction and huge scale combination of electronic devices place a remarkable request on multilayer geometries and also important for discontinuities in multilayered circuits. The diameter and pitch is given by:

$$d < \frac{\lambda_g}{5} \tag{4}$$

$$p \leq 2d \tag{5}$$

In order to minimize the leakage loss between nearby hole, pitch needs to be kept as small as possible based on (4) and (5) above. The diameter of via hole also contributes to the losses. As consequences, the ratio  $d/p$  reflected to become more critical than pitch size of via hole. This is because the pitch and diameter are interconnected and it might distract the return loss of the waveguide section in view of its input port [21, 22]. 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:

$$w_{eff} = w_{siw} - 1.08 \left( \frac{D_{via}^2}{S_{vp}} \right) + 0.1 \left( \frac{D_{via}^2}{w_{siw}} \right) \tag{6}$$

The  $w_{eff}$  can be defined as the width of the conventional waveguide according to the dimension of the standard rectangular waveguide. When  $\left( \frac{S_{vp}}{D_{via}} \right)$  is less than 3 and  $\left( \frac{D_{via}}{w_{siw}} \right)$  is less than 0.2.

#### IV. PARAMETER DESIGN OF SIW DIRECTIONAL COUPLER

The diameter and pitch of via hole were determined from (4) and (5). From the reference value obtained, 0.5 mm is used for the diameter and the pitch or center to center of adjacent via holes is 1.1 mm. This coupler is designed by using a substrate of Roger RO4350 with dielectric substrate,  $\epsilon_r$  of 3.48 and a thickness of 0.508 mm. As shown in Figure 4,  $w_{aperture}$  can be optimized in order to control the coupling at Port 3 according to Hao [16]. After optimizing the value of  $w_{aperture}$ , 9.9 mm is the best result of output coupling. For X-band directional coupler, the width of SIW is chosen as 12.334 mm.

TABLE I  
The geometric parameters for SIW directional coupler

Parameter	Value (mm)	Step Impedance	Value (mm)
$d_{via}$	0.50	$W_{Z0}$	3.20
$p_{via}$	1.10	$L_{Z0}$	1.12
$w_{siw}$	12.33	$W_{Z1}$	4.73
$w_{aperture}$	9.90	$L_{Z1}$	5.03

Table 1 shows the summarized geometric parameters for the design coupler. It includes the diameter and pitch of the via hole. The width of SIW and aperture also denote in the table. The microstrip transition represent by using step impedance as shown in Fig. 4 with  $Z_0$  is given by  $50 \Omega$ .

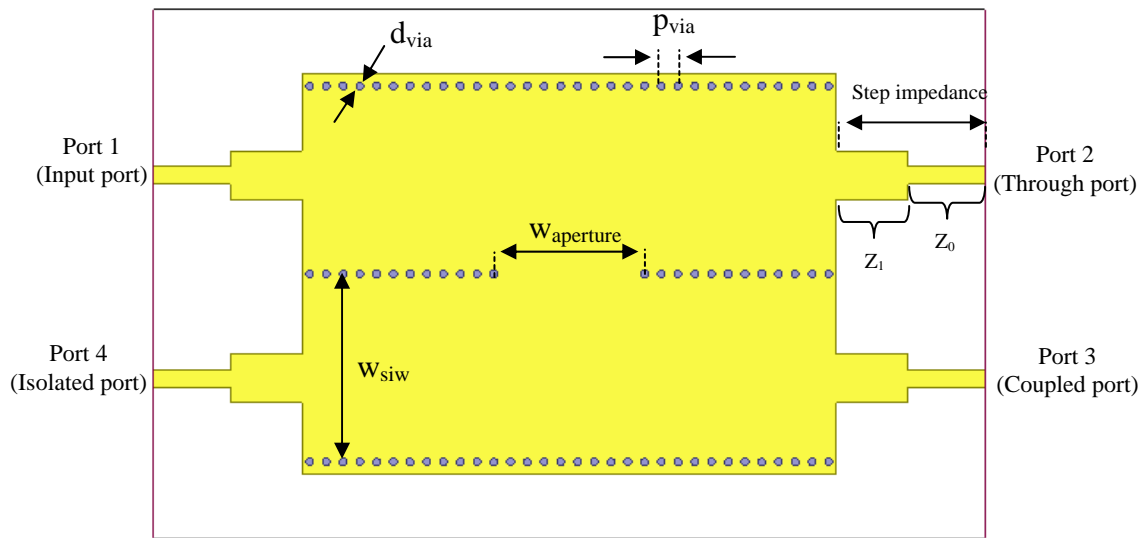


Fig. 4. Top view of the coupler

V. RESULT AND DISCUSSION

This section discusses the performance of directional coupler designed in terms of return loss, isolation, the phase difference between the coupled port and the bandwidth of the coupler. The X-band SIW directional coupler is simulated in Ansoft HFSS and obtained a series of S-parameter in frequency ranges from 8 GHz to 10 GHz. The  $S_{11}$  defines as the reflection of the input or return loss,  $S_{21}$  is the through port,  $S_{31}$  is coupling port and  $S_{41}$  is the isolated port. From the graph in Fig. 5, the simulation shows the return loss is less than -7.1 dB. The result has shown the isolation which is less than -11.1 dB at the center frequency of 9 GHz. The bandwidth of this coupler is approximately 1GHz when the return loss is less than 12 dB.

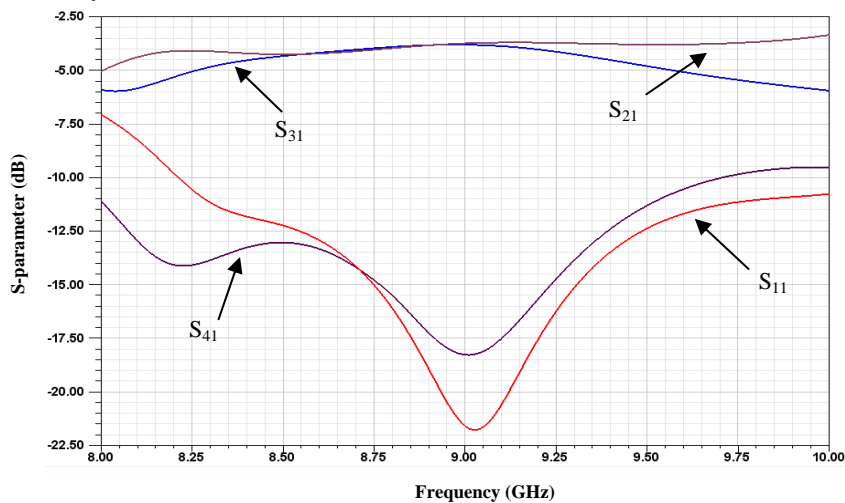


Fig. 5. S-parameter of X-band SIW directional coupler

By adjusting  $w_{aperture}$ , it can effectively control the output coupling at Port 3 which is the coupling port. From the experiment, coupling at Port 3 is reduced when  $w_{aperture}$  is decreased. The finest value obtained at  $w_{aperture}$  for this coupler is 9.9 mm. The magnitude or coupling flatness for  $S_{21}$  and  $S_{31}$  is approximately at -3.78 dB and -3.82 dB within the operating frequency as shown in Fig. 6.

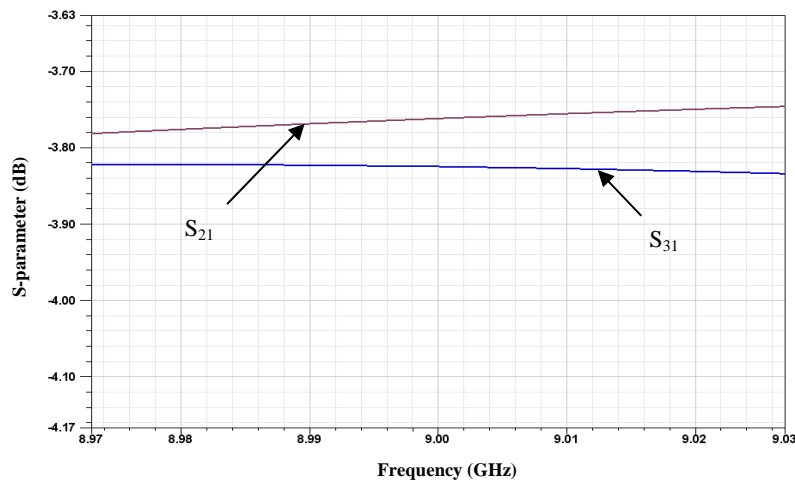


Fig. 6. The magnitude of  $S_{21}$  and  $S_{31}$

Fig. 7 shows the simulated phase of coupled wave between Port 2 (through port) and Port 3 (coupled port). From this graph, phase differences between these ports are calculated. As the results, phase difference obtained is  $90^\circ$  and observed at 9 GHz which is the center frequency of this coupler design as presented in Fig. 8.

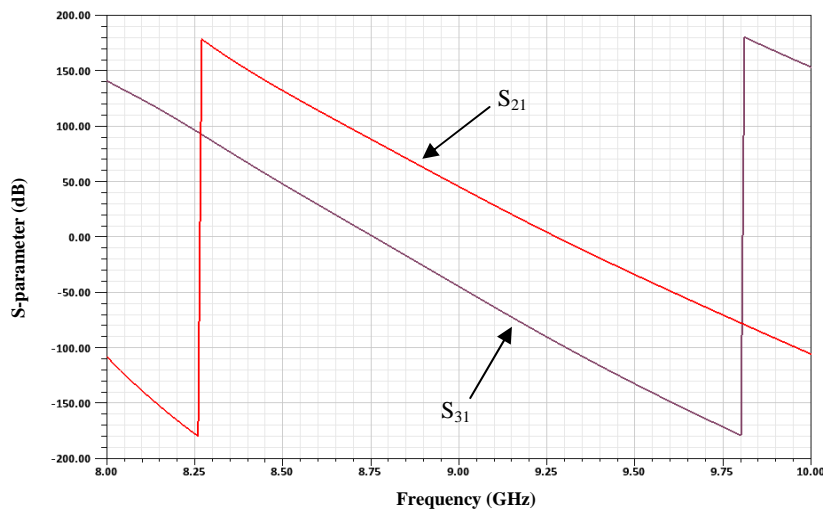


Fig. 7. Simulated phase of coupled wave in Port 2 and Port 3

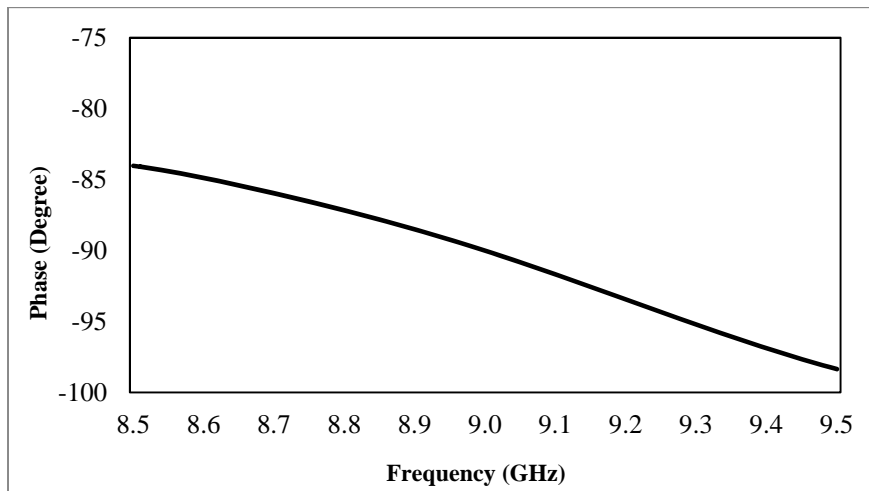


Fig. 8. The phase difference between two coupled ports

From the simulations of the SIW directional coupler by using HFSS, the magnetic  $E$ -field is observed as shown in Fig. 9. As the signal or power is supplied to the Port 1 (input) and it was coupled to the Port 3 (coupled). The rest of the input power is delivered to the Port 2 (through). Since the design coupler is not in ideal condition, there is a small amount of signal passing through the Port 4 (isolated).

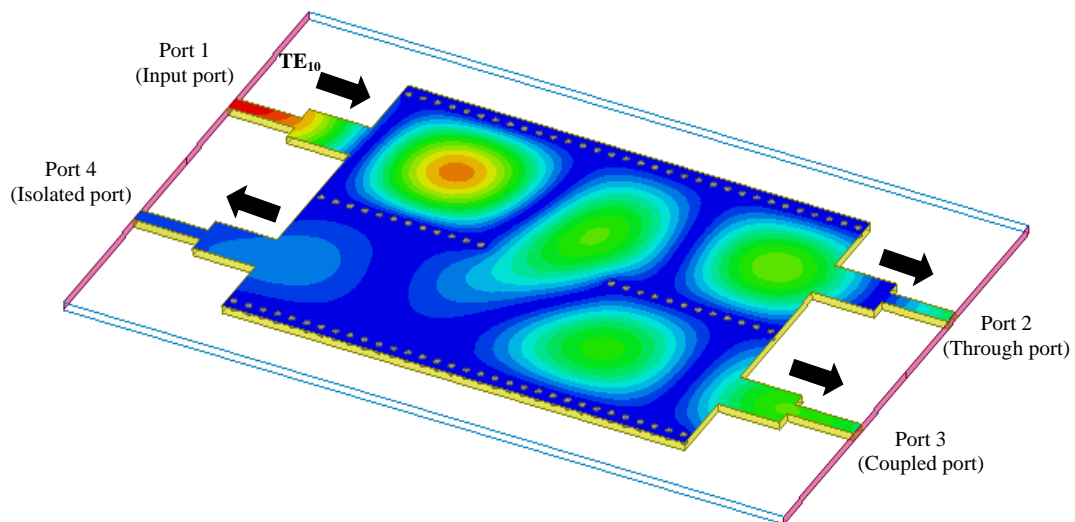


Fig. 9. Magnetic E-field of SIW directional coupler

## VI. CONCLUSION

In this paper, the SIW directional coupler based on coupling theory for X-band applications has been designed. The simulation process of the structure is done by using HFSS software. This type of coupler is suitable for high-density integrated microwave and millimeter wave applications. The design method is discussed; the effect of the aperture width of coupling and isolation is studied. By using SIW techniques, the compact size of the coupler is produced and easy to integrate with other planar circuit compared by using conventional waveguide.

## ACKNOWLEDGMENT

The research described in this paper was fully supported by Universiti Teknikal Malaysia Melaka (UTeM) Melaka. Therefore, we would like to thank the Ministry of Science, Technology and Innovation (MOSTI) for the Science Fund Grant (03-01-14-SF0043).

## REFERENCES

- [1] David M. Pozar, "Microwave Engineering", Third Edition, John Wiley & Sons Inc, 2005.
- [2] Djerafi, T.; Ke Wu; , "Super-Compact Substrate Integrated Waveguide Cruciform Directional Coupler," *Microwave and Wireless Component Letters*, IEEE, vol.17, no.11, pp.757-759, Nov. 2007.
- [3] Peng Chen; Guang Hua; De Ting Chen; Yuan Chun Wei; Wei Hong; , "A double layer crossed over Substrate Integrated Waveguide wideband directional coupler," *Microwave Conference, 2008. APMC 2008. Asia Pacific*, vol., no., pp. 1-4, 16-20 Dec. 2008.

- [4] Ke Wu; Deslandes, D.; Cassivi, Y.; , "The substrate integrated circuits – a new concept for high-frequency electronics and optoelectronics," Telecommunications in Modern Satellite, Cable and Broadcasting Service, 2003.
- [5] Ke-Jun Tan; Luan Xiu-Zhen; , " Compact directional coupler based on substrate integrated waveguide, " *Antenna Technology, 2009. iWAT 2009. IEEE International Workshop on* , vol., pp. 1-4, 2-4 March 2009.
- [6] Pourgholamhossein, Z.; Safian, R.; Pourghassem, H.; , "Wideband double layer Substrate Integrated Waveguide directional coupler, "Telecommunications (IST), 2010 5<sup>th</sup> International Symposium on, vol., no., pp. 328-331, 4-6 Dec. 2010.
- [7] 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* , vol., no., pp. 1-4, 27-30 May 2012.
- [8] Alessandri, F.; Giordano, M.; Guglielmi, M.; Martirano, G.; Vitulli, F.; , "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.
- [9] 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.
- [10] 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.
- [11] Perini, H.; Sferazza, P.; , "Rectangular waveguide to strip-transmission-line directional couplers," *WESCON/57 Conference Record* , Vol. 1, no., pp. 16- 21, Aug 1957.
- [12] 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.
- [13] Ke Wu; Deslandes, D.; Cassivi, Y.; , "The substrate integrated circuits – a new concept for high-frequency electronics and optoelectronics," Telecommunications in Modern Satellite, Cable and Broadcasting Service, 2003.
- [14] Wu, K.; , "Integration and interconnect techniques of planar and non-planar structures for microwave and millimeter-wave circuits - current status and future trend," *Microwave Conference, 2001. APMC 2001. 2001 Asia-Pacific* , Vol. 2, no., pp. 411-416 Vol. 2, 3-6 Dec. 2001.
- [15] Ahmad, B. H; Hunter, I. C.; , "Design and fabrication of a substrate integrated waveguide bandstop filter," *Microwave Conference, 2008. EuMC 2008. 38<sup>th</sup> European*, vol., no., pp.40-42, 27-31 Oct. 2008.
- [16] Hao, Z.C.; Hong, W.; Chen, J.X.; Zhou, H.X.; Wu, K.; , "Single-layer substrate integrated waveguide directional couplers," *Microwaves, Antennas and Propagation, IEE Proceedings* , Vol. 153, no. 5, pp. 426-431, Oct. 2006.
- [17] Chao Wang; Wenquan Che; Chao Li; Russer, P.; , "Multi-way microwave power dividing/combining network based on substrate-integrated waveguide (SIW) directional couplers," *Microwave and Millimeter Wave Technology, 2008. ICMMT 2008. International Conference on* , Vol. 1, no., pp. 18-21, 21-24 April 2008.
- [18] Hirokawa, J.; Ando, M.; , "Single-layer feed waveguide consisting of posts for plane TEM wave excitation in parallel plates," *Antennas and Propagation, IEEE Transactions on* , Vol. 46, no. 5, pp. 625-630, May 1998.
- [19] Uchimura, H.; Takenoshita, T.; Fujii, M.; , "Development of the "laminated waveguide"," *Microwave Symposium Digest, 1998 IEEE MTT-S International* , Vol. 3, no., pp. 1811-1814 Vol. 3, 7-12 Jun 1998.
- [20] Deslandes, Dominic; Wu, Ke; , "Design Consideration and Performance Analysis of Substrate Integrated Waveguide Components," *Microwave Conference, 2002. 32nd European* , vol., no., pp. 1-4, 23-26 Sept. 2002.
- [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, IEE Proceedings* , Vol. 152, no. 1, pp. 35- 42, 19 Feb. 2005.