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Substrate Integrated Waveguide Directional Coupler in Ku and Ka Bands

Bouchra Rahali
STIC Laboratory, University of Tlemcen, 13000 Algeria
b_rahali@hotmail.fr

Mohammed Feham
STIC Laboratory, University of Tlemcen, 13000 Algeria
m_feham@mail.univ-tlemcen.dz

Junwu Tao
LAPLACE Laboratory, INP-ENSEEIHT Toulouse, France
junwu.tao@laplace.univ-tlse.fr

Temmar Khayreddine
Kheiro-89@outlook.fr

Hamdaoui Fayçal
hamdaoui.faycal@yahoo.fr

***Abstract* – *F*our port substrate integrated waveguide (SIW) directional couplers for Ku and Ka bands are conceived. Initial design directional coupler -3 db follow substrate integrated waveguide selection and aperture coupling theory as known from standard air-filled waveguide components. The simulation results using HFSS and CST software demonstrate that this design approach is satisfactory for many applications. Tapered microstrip ports are used as interfaces to the SIW couplers. Performances of design models of -3dB 90° SIW couplers described in this paper are analyzed.**

***Keywords* – Rectangular Waveguide, Microwave Components, SIW, Coupler, HFSS, CST.**

I. Introduction

By using a metalized arrays of vias or a metalized groove technique, both illustrated in Figure 1, the sidewalls of rectangular substrate integrated waveguide technology SIW [1][2][3][4] can be realized within the substrate. Bends [4][5], power divider [6], couplers [7], circulators [8] and phase shifter [2][3] were modeled in SIW technology. In this paper, we conceived, simulated, optimized and analyzed some couplers in microwave Ku and Ka bands, by using HFSS [9]and CST [10]Software.

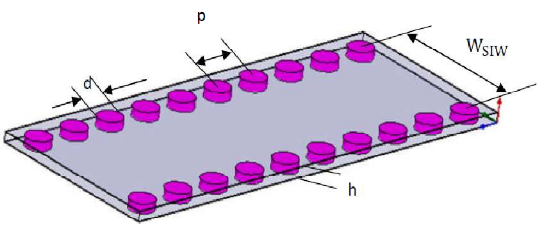

Fig. 1. Rectangular wave guide integrated into a substrate RSIW

II. Fundamental RSIW Characteristics

For designing rectangular wave guide in technology SIW (RSIW) seen in Figure 1, some physical parameters [1][2][3] are necessary. Two rows of holes are drilled and metalized establishing contact between the two metal planes of the dielectric substrate. This paper is organized as follows. Section III describes the structure and provides the basic theory. In Section IV Ku band coupler with another topology is given, followed by the simulation results. Another RSIW coupler have been designed and analyzed in Ka band. Finally, section VI presents our conclusions.

The RSIW have been designed in both bands from a rectangular waveguide equivalent based on dielectric substrate Arlon Diclad whose permittivity ε_r=2.2, tanδ=0.0009, height h = 0.508mm [2][3][4] by using arrays of cylindrical, cubic rods and metalized groove, where W_{eq} is the width of the corresponding rectangular waveguide equivalent (1), W_{SIW} is the width in RSIW, d is the diameter of vias and p is the space between vias [2].

To verify the accuracy of our method Figures 2 to 4 depict the similarity of the electromagnetic field distribution of TE_{10} mode and it is interesting to compare the dispersion curves of the first modes of the RSIW based on metalized groove, square vias on with those of an equivalent rectangular waveguide filled with the same dielectric material in ku band by using the finite element method (FEM) “HFSS” [9].

$$W_{eq} = W_{SIW}\left(\xi_1 + \frac{\xi_2}{\frac{p}{d}+\frac{\xi_1+\xi_2-\xi_3}{\xi_3-\xi_1}}\right) \quad (1)$$

$$\xi_1 = 1.0198 + \frac{0.3465}{\frac{W_{SIW}}{p}-1.0684}$$

$$\xi_2 = -0.1183 - \frac{1.2729}{\frac{W_{SIW}}{p}-1.2010}$$

$$\xi_3 = 1.0082 - \frac{0.9163}{\frac{W_{SIW}}{p}+0.2052}$$

With p ≤ 2d

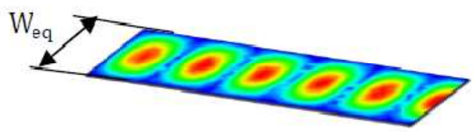

Fig. 2. Electric field distribution of the TE_{10} mode in rectangular waveguide equivalent at the frequency f=15GHz

Fig. 3. Electric field distribution of the TE_{10} mode in different RSIW at the frequency f=15GHz

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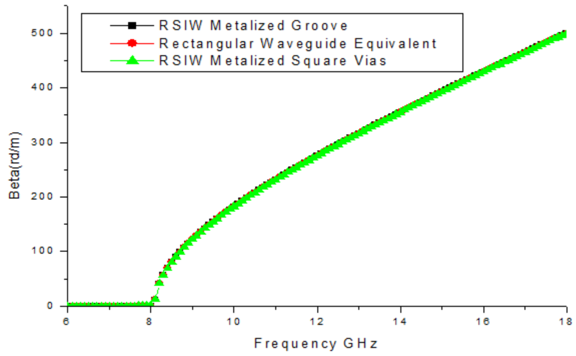

Fig. 4. Dispersion characteristics

III. Design Procedure of RSIW Coupler

As shown in Figure. 2 and 3, the RSIW is equivalent to a conventional rectangular waveguide filled with dielectric and therefore the coupler topology [11] illustrated in Figure 5 is conceived and optimized just by using the width of the equivalent waveguide.

In a schematic representation of the geometry of this coupler [11], Figure 6 shows the input, coupled, output and isolated ports, and the associated port numbering convention. The coupling section consists of one continuous aperture, and waveguide steps are used to achieve the matching of the input ports.

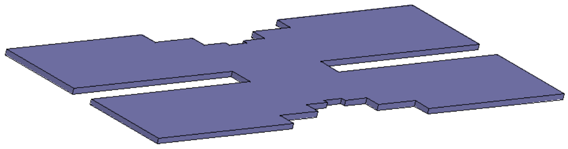

Fig. 5. Hybrid directional coupler equivalent.

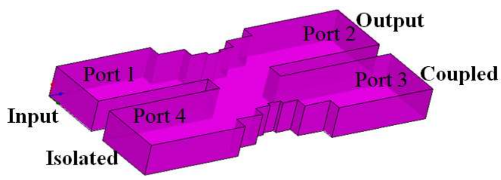

Fig. 6. Schematic representation of the proposed coupler geometry [5]

Figures 5 and 6 shows [11] a full-height slot in the common narrow-wall between two adjacent rectangular waveguides. H-plane steps are employed to achieve impedance match. The number of steps employed determines the bandwidth performance of the coupler.

Using the results presented in [11], initial values (1) have been calculated in Ku and Ka bands for the equivalent model of the hybrids realized by rectangular dielectric-filled waveguides and based on previous analysis [1][2] about the determination of the final SIW configuration (1), that is optimized with electromagnetic simulator[9][10].

IV. Ku Band RSIW Coupler

In this section firstly we analyzed hybrid directional coupler designed in Ku band [2][3].Through Figures 7 and 8 illustrating respectively electric field distribution of TE_{10} mode for dielectric-filled coupler and simulated S parameters, it can be seen the output at ports 2 and 3 are -2.69 dB to -3.38dB, respectively, the return loss and isolation are lower than -15dB from 13.19GHz to 17.04GHz.

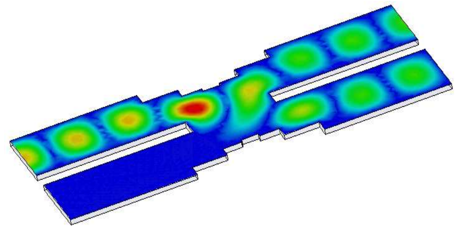

Fig. 7. Electric field distribution of the TE_{10} mode in hybride coupler equivalent at the frequency f=14.5GHz

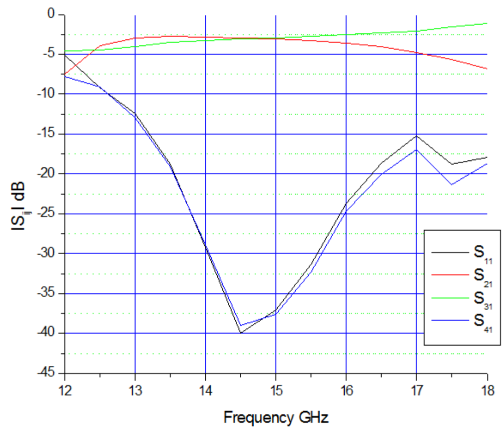

Fig. 8. Frequency response of the hybride directional coupler

In recent years, the concept of substrate integrated waveguide (SIW) has been introduced; it consists in a type of rectangular waveguide that can be synthesized in a planar substrate with arrangements of metalized posts to build the lateral walls.

The SIW directional coupler is realized by two RSIW [2][3] which are mainly working with TE_{10} modes with a common wall on which an aperture is utilized to realize the coupling between them.The distribution of the electric field of the TE_{10} mode at 14.5GHz, the reflection coefficients S_{11}, the transmission coefficients S_{21}, the coupling coefficient $S_{31}$and the isolation coefficient S_{41} of RSIW directional coupler built by concept of metalized groove are related through Figures 9 and 10 respectively.

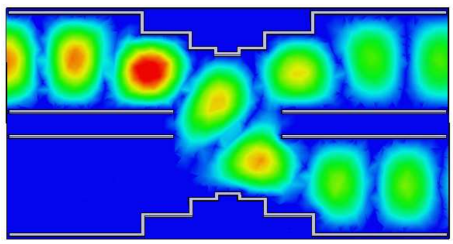

Fig. 9. Electric field distribution of the TE_{10} mode in RSIW directional coupler at the frequency f=14.5GHz.

In Figure 10 the levels of reflection and isolation are below -15 dB with more than 20.34% of the bandwidth,

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and which the insertion loss S_{21} and coupling S_{31} are around -3.09±0.7 dB. These results show clearly the -3dB directional coupler character in the [13.28-16.24] GHz band.

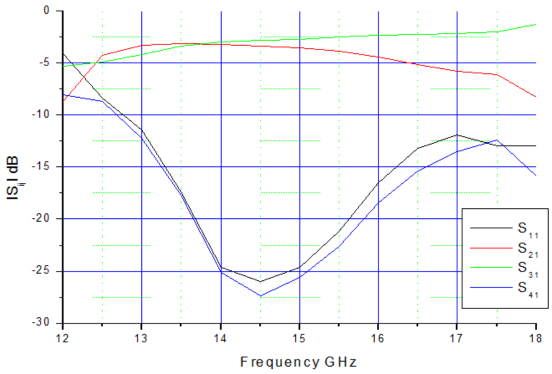

Fig. 10. Frequency response of the hybrid directional coupler

Through Figures 11 and 12 illustrating electric field distribution of the TE_{10} mode at the frequency f=14.5GHz and simulated parameters in RSIW directional coupler conceived by metal rods of square section with the same parameters presented in [2],the similarity is seen with figures 9 and 10 respectively.

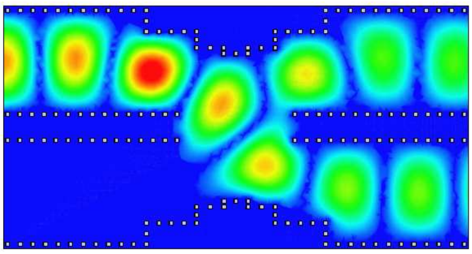

Fig. 11. Electric field distribution of the TE_{10} mode in RSIW directional coupler at the frequency f=14.5GHz

The coupling section consists of one continuous aperture, and waveguide steps used to achieve the matching of the input ports [2][3], are applied in the design of RSIW-based couplers. The aperture length, step width, and step length [7][11] are then optimized employing the FEM software [9]to achieve the coupling isolation and input specifications as required, the basic goal of the development to be presented in this paper.

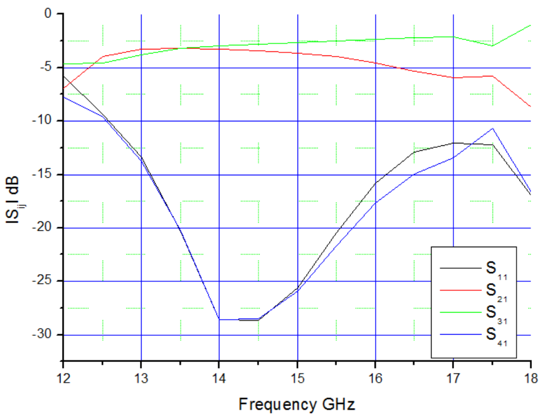

Fig. 12. Frequency response of -3 dB RSIW directional coupler simulated [9]

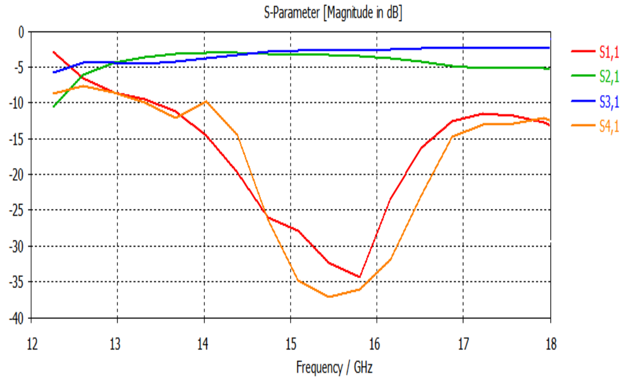

Fig. 13. Frequency response of -3 dB RSIW directional coupler simulated [10]

It can be clearly seen from simulation results of -3dB RSIW directional coupler illustrated in Figure 11, using HFSS and CST software through Figure 12 and 13 respectively, that Sij parameters are similar.

Software's HFSS [9] and CST [10] are two most widely used for design simulations. Both software's shows almost same result for the simulation of RSIW directional coupler in terms of accuracy. However HFSS is better in terms of time. Reason for this is its frequency domain solver while CST used time domain transient solver.

The connection between the waveguide and the planar circuits is provided via transitions formed with a simple matching geometry between both structures, thus providing a compact and low cost platform. The microstrip transition taper [12][13][14] is employed in the same substrate as illustrated in Figure 14 for the purpose of measurement. A substrate with a 2.2 relative permittivity, 0.5mm thickness and a loss tangent 0.0009 was used in simulation.

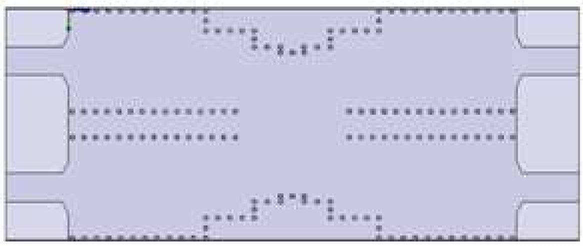

Fig.14. RSIW directional coupler (metalized vias) with transition taper

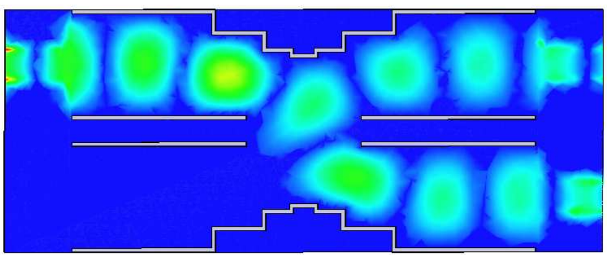

Fig. 15. Electric field distribution of the TE_{10} mode in the matched RSIW directional coupler (metalized groove) at the frequency f=14.5GHz

Figures 15 and 16 reflect electric field distribution of the TE_{10} mode in both matched RSIW directional coupler

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(metalized groove)and (metalized vias) at the frequency f=14.5GHz.

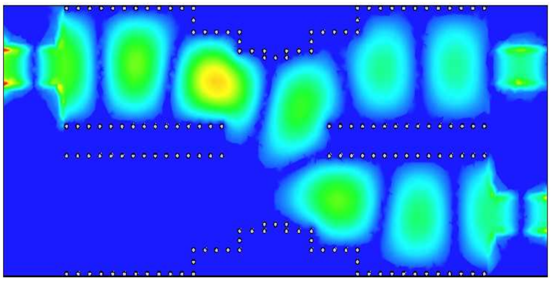

Fig. 16. Electric field distribution of the TE_{10} mode in the matched RSIW directional coupler (metalized vias) at the frequency f=14.5GHz

A-3 dB RSIW directional coupler with the configuration shown in Figures 15 and 16 have similar simulated results[9] presented in Figure 17 which shows these directional couplers can be operated from 13GHz to 16 GHz with return loss less than -12.5 dB. Both of the magnitudes of S_{21} and S_{31} are approximately -4.0 dB, and the isolation of port 4 is less than -15dB within the operating frequency range. In simulation, four SIW-microstrip transitions tapers are introduced, which will cause the extra insertion loss to the coupler.

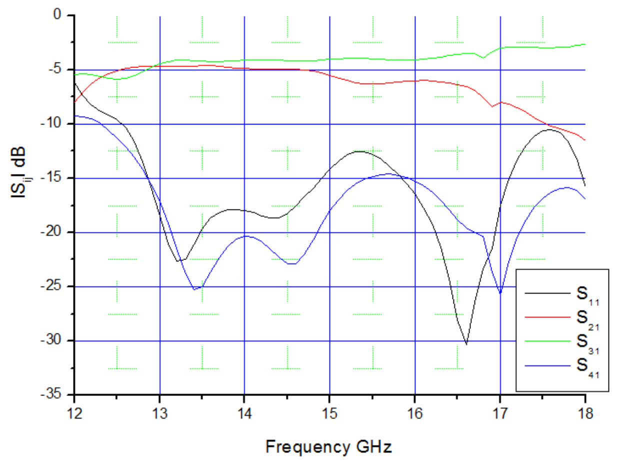

Fig. 17. Frequency response of matched RSIW directional coupler simulated [9]

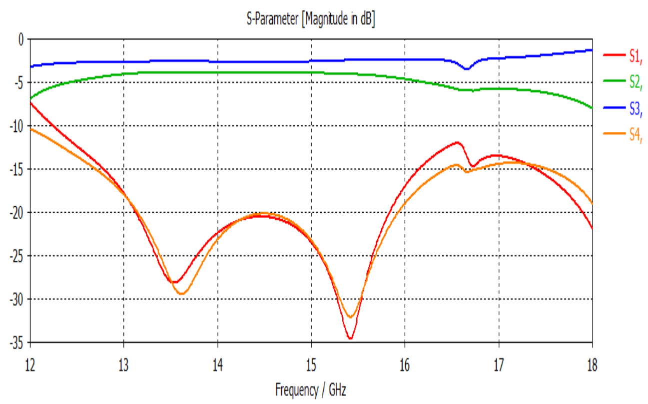

Fig. 18. Frequency response of matched RSIW directional coupler simulated [10]

From the simulations of the RSIW directional coupler using CST [10], the frequency response as observed in Figure 18, better than 15 dB isolation and return loss is achieved for the bands at 12.8-16.2 GHz and which the insertion loss S_{21} and coupling S_{31} are around -3.73 ± 0.85 dB. Good agreement is observed between the results of the two commercial software packages, thus verifying the design approach. The taper transition usually operating properly in most of the frequency range for SIW components degrade optimized coupler performance and are recommended only for measuring purposes.

Figure 19 shows the simulated phase difference of 90° RSIW directional coupler between two output ports. It can be seen the phase difference is distributed in the range of 89.22° to 93.09° within the frequency band of 12.73 to 15.28 GHz. It is clear that these simulation results demonstrate the good performance of this integrated structure.

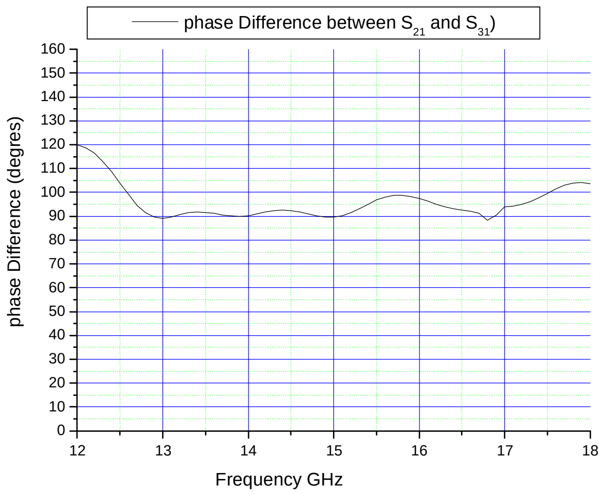

Fig. 19. The phase difference between two coupled ports

As being mentioned earlier in [2][5], we design several bends in RSIW, through Figures 20 and 21 the topology of the matched RSIW coupler use a circular bend connected with taper transition.

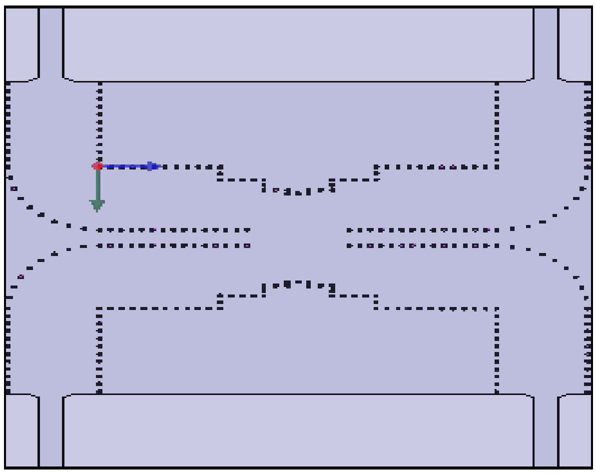

Fig. 20. Topology of matched RSIW coupler

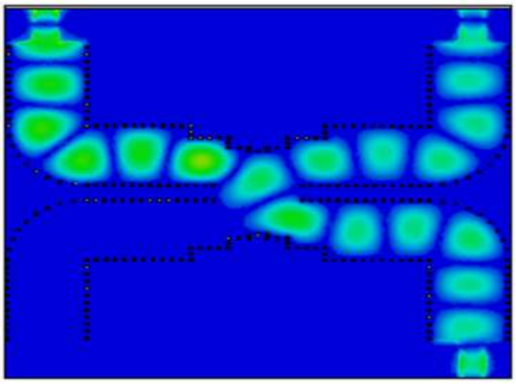

Fig. 21. Electric field distribution of the TE_{10} mode in the matched RSIW directional coupler at the frequency f=14.5GHz

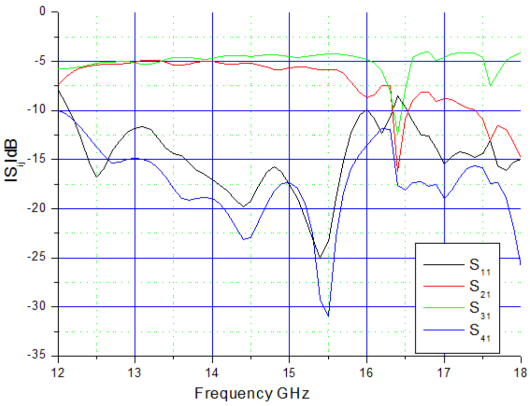

Fig. 22. Frequency response of the RSIW directional coupler

The parameters are finely tuned using three-dimensional electromagnetic simulation software [9] to achieve wide-band performance. The simulated results for the Ku-band directional coupler using circular bends are shown in Figure 22, in which the magnitude of S_{11} is lower than -15dB in the whole frequency range [13.69-15.70]; S_{41} is lower than -15dB from 12.67GHz to 15.84GHz also, it can be observed that S_{21} and S_{31} parameters are about -5.05 dB and -4.67dB respectively at 14.5GHz.

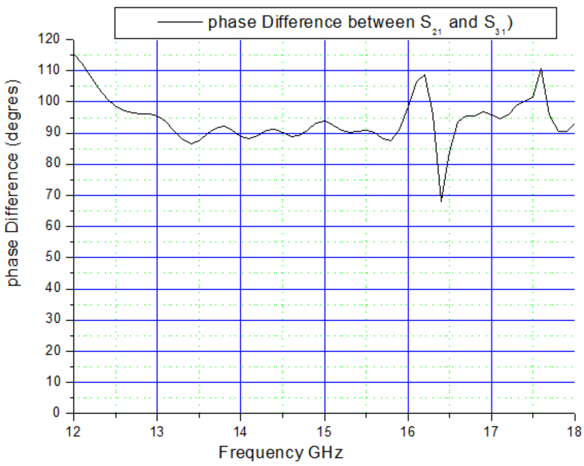

Fig. 23. The phase difference between two coupled ports

It is noticeable that the 90° coupler characterizes with good phase difference is distributed in the range of 86.36° to 93.85° in the frequency band of 13.08 to 15.93 GHz in Figure 23. The configuration of the SIW 90° coupler is obtained after gradual optimization with HFSS [9].

V. Ka Band RSIW Coupler

Our analysis in Ka band shows that the RSIW [2][4] basically has the same guided-wave characteristics as the conventional rectangular waveguide. The design parameters for the vias with respect to the equivalent waveguide width are obtained in close-form expressions from [2][4].Indeed, in order to verify the accuracy of our method, it is interesting to compare the dispersion curves of the first mode of the SIRW as depicted in Figure 24,with those of an equivalent rectangular waveguide filled with the same dielectric material whose ε_r=2.2, tanδ=0.0009 and height h = 0.508mm [1][2][4].

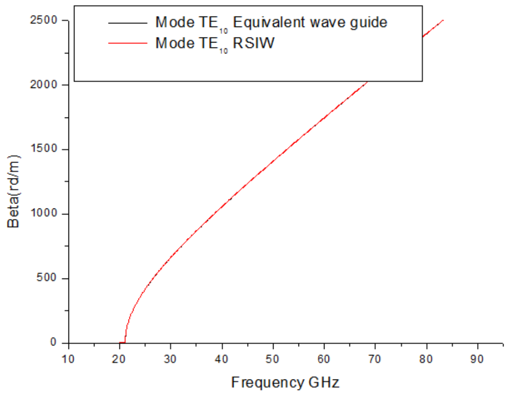

Fig. 24. Dispersion characteristics

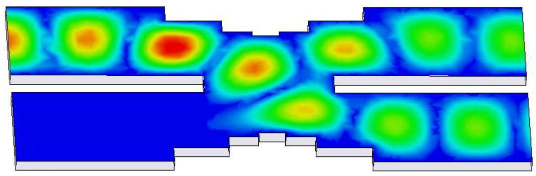

Fig. 25. Electric field distribution of the TE_{10} mode in hybrid coupler equivalent at the frequency f=33GHz

The configuration of Ka-band SIW directional coupler [11] is shown in Figure 25 with the continuous aperture coupling design [2][4].The physical parameters are optimized in HFSS simulator used here to further validate the correctness of this design.

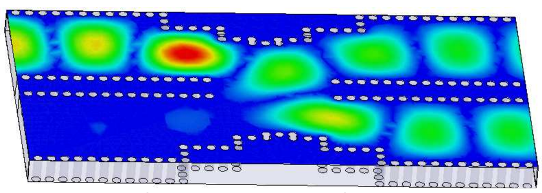

Fig. 26. Electric field distribution of the TE_{10} mode in the RSIW directional coupler (metalized vias) at the frequency f=33GHz

RSIW is a type of rectangular dielectric-filled [2][4] waveguide that is synthesized in a planar substrate with arrays of metallic vias or slots in order to realize bilateral edge walls. The coupling in Figure 26 obtained by slots over the entire width of common broadside wall of two adjacent RSIW with a continuous coupling aperture [11].

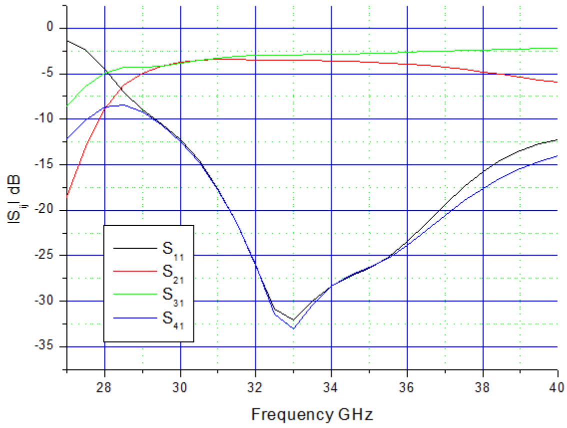

Fig. 27. Frequency response of the RSIW directional coupler

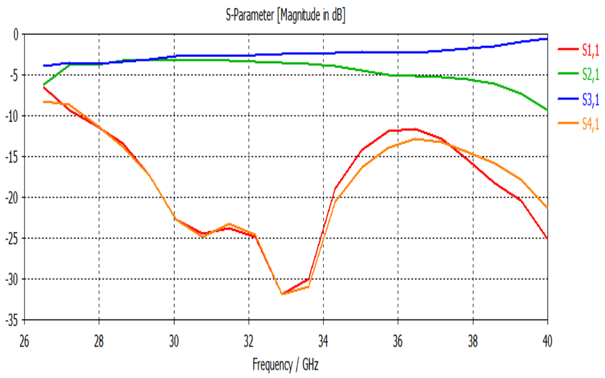

Fig. 28. Frequency response of the RSIW directional coupler

Both software's [9][10] show in Figures 27-28 almost same result for the simulation of RSIW directional coupler. However HFSS is better in terms of time. Reason for this is its frequency domain solver while CST used time domain transient solver.

The electric field distribution of the TE_{10} mode through Figures 25 and 26, the reflection coefficients S_{11}, the transmission coefficients S_{21}, the coupling coefficient S_{31} as well as the isolation coefficient S_{41} presented in Figures 27-28, indicate clearly that these simulation results demonstrate the good performance of these integrated structure. A bandwidth of more than 26.80% is obtained here for 15 dB return loss from 29.21 to 38.25 GHz.

A linearly tapered microstrip [13][14] is used, and this transition ensures a field matching between microstrip and rectangular waveguide as depicted in [2][4] over a broad bandwidth. Parameters [2] [13][14] of the taper have been modeled and optimized over the desired frequency bandwidth. In our work a commercial simulator [9] is used to carry out the transition design [4] as illustrated in Figure 29.Naturally, this will increase the insert loss of SIW components.

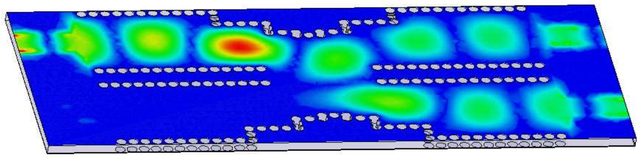

Fig. 29. Electric field distribution of the TE_{10} mode in the matched RSIW directional coupler at the frequency f=33GHz

The electric field distribution of the TE_{10} mode, the reflection coefficients S_{11}, the transmission coefficients S_{21}, the coupling coefficient S_{31} as well as the isolation coefficient S_{41} are presented in Figures 29-30, respectively.

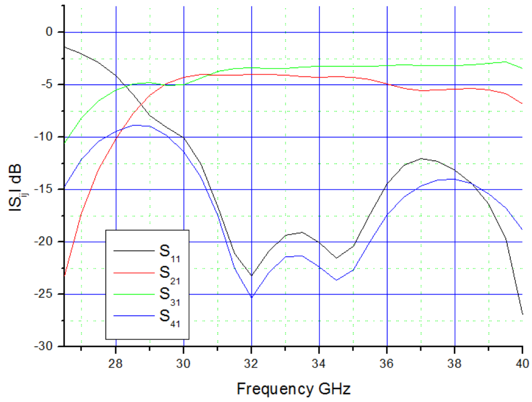

Fig. 30. Frequency response of the matched RSIW directional coupler [9]

Simulated results presented in Figure 30 which shows this matched 90°directional coupler can be operated from 30.5GHz to 36.0GHz with return loss less than -12.5 dB. Both of the magnitudes of S_{21} and S_{31} are approximately are -4.07 dB to -3.4 dB, respectively,, and the isolation of port 4 is less than -15dB within the operating frequency range.

Another simulation tool CST [10] is used here to further validate the correctness of this design, and the results are shown in Figure 31. It can be seen from comparison between results obtained by Ansoft HFSS and CST Microwave Studio presented respectively in Figure 30 and 31 good agreements, thus verifying the design approach.

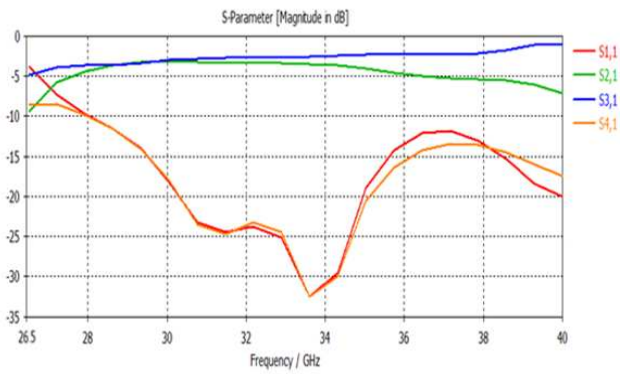

Fig. 31. Frequency response of the matched RSIW directional coupler [10]

Figure 32 shows the simulated phase difference between two output ports. It can be seen the phase difference is distributed in the range of 88.09° to 90.47° within the frequency band of 30.5 to 36.4 GHz.

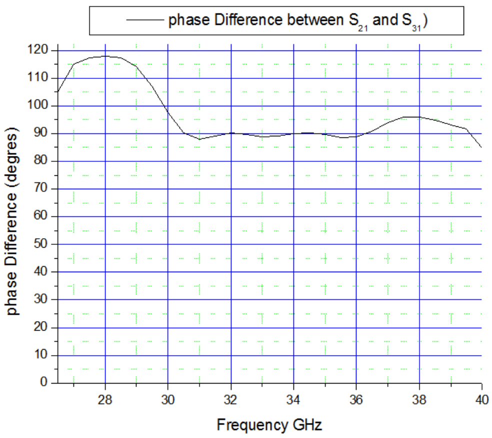

Fig. 32. The phase difference between two coupled ports

VI. Conclusion

The developed RSIW couplers are used in complex microwave and millimeter wave circuits. In this paper two -3dB of RSIW 90° directional couplers are designed in Ku and Ka bands. Using a simple and fast method An soft HFSS code, the optimized value was found and the corresponding performance was simulated and shown. Indeed prototypes of these directional couplers with different topologies have very good performances in terms of a good performance in broad operating bandwidths and achievable phase variation.

The HFSS-based design approach is shown to work well and is verified by comparison with results obtained by CST. Microwave Studio.

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Author's Profile

HAMDAOUI Fayçal received his Licence degree in 2014 from the Faculty of Technology, Department of Telecommunication, Tlemcen , Algeria. He is currently working toward his Master degree at the Faculty of Technology, Department of Telecommunication, Tlemcen, Algeria. His research interests Modeling and characterization of emerging technology in sensors SIW (Substrate integrated wave guide) for high frequency applications in telecommunications (wireless systems).

TEMMAR Khayreddine received his Licence degree in 2014 from the Faculty of Technology, Department of Telecommunication, Tlemcen , Algeria. He is currently working toward his Master degree at the Faculty of Technology, Department of Telecommunication, Tlemcen, Algeria. His research interests Modeling and characterization of emerging technology in sensors SIW (Substrate integrated wave guide) for high frequency applications in telecommunications (wireless systems).