Design of K-Band Substrate Integrated Waveguide Coupler, Circulator and Power Divider

Bouchra Rahali and Mohammed Feham

***Abstract*—Our study concerns the analysis of K-band passive devices using a new technology, substrate integrated waveguide (SIW), by the HFSS code. This technology has been applied successfully to the conception of planar compact components for the microwave and millimeter waves applications. This application focuses on three components: A coupler junction (-3dB) used for routing, dividing and combining the signals in the microwave system. The levels of reflection and isolation below -15dB occupy more than 26.43% of the bandwidth, the insertion loss S_{21} and coupling S_{31} fluctuate between -3.24dB and -3.78dB, respectively. The SIW ferrite junction circulator has potential applications in integrated communication and radar systems. Its frequency response shows reflection losses below -15 dB in more than 21.75% of the bandwidth, an insertion loss about -0.65 dB, while the maximum of the isolation is -38.11dB. The T-junction SIW power divider (-3dB) indicates that levels of reflection below -15dB occupy more than 26.32% of the bandwidth. The transmission coefficients S_{21} and S_{31} are around -3.54dB, showing equal division of the power injected into port 1. In this paper, design considerations and results are discussed and presented.**

***Index Terms*—Rectangular wave guide, substrate integrated waveguide, HFSS, coupler, circulator, power divider.**

I. Introduction

The rectangular waveguide is known for its characteristic properties of low loss and high power handling. However, due to its bulky structure, it is difficult to integrate and to manufacture at low cost in the planar structure. Recently, a new technology, called "substrate integrated waveguide (SIW)" [1], [2] has emerged. It responds to these constraints in the design of microwave components [3], integrating the rectangular waveguide in the microstrip substrate. The SIW technology is one of the most popular and developed until now because it is very easy to integrate the conventional rectangular waveguide in the standard printed circuit board (PCB). The rectangular waveguide, synthesized in the substrate integrated waveguide technology (RSIW) (Fig. 1), is built in a dielectric substrate by placing two discrete metal walls designed by metal rods, the ground plane of the substrate and the cover are also metal, preserving most of the benefits of conventional metallic rectangular waveguides. Indeed the geometry and the distribution of the electric field in (RSIW), illustrated in Fig. 2 and Fig. 3, are similar to those of the equivalent rectangular waveguide [4], [5]. In this paper, K-band RSIW components are proposed and optimized. They are building blocks of many microwave and millimeter waves integrated circuits and telecommunication systems.

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II. Design of RSIW

The concept of integrated rectangular waveguide substrate is based on electrical side walls synthesized by rows of metalized holes. The substrate of permittivity ε_r is sandwiched between two metal plates placed on top and bottom to allow propagation of all modes TE_{n0} [5]. If the RSIW is properly designed by optimal parameters (Fig. 1), a width W_{SIW}, a diameter d of the holes, and a spacing p between two consecutive holes, its electrical behavior is similar to that of a conventional rectangular waveguide filled with the same dielectric of width W_{eq} [4]. Indeed, the current lines along the side walls of the RSIW are vertical, the fundamental mode TE_{10} can propagate efficiently. This means that the propagation modes, the characteristic impedances and the dispersion characteristics are almost identical with negligible radiation losses.

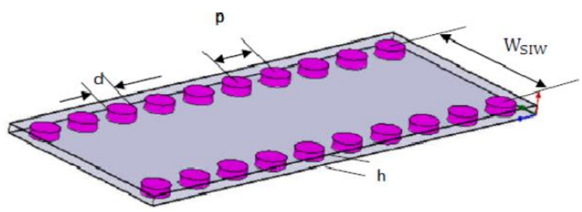


Fig. 1. Rectangular waveguide integrated into a substrate RSIW.

Based on the work of [3], empirical equations were derived:

$$W_{eq} = W_{SIW} - \frac{d^2}{0.95\,p} \quad (1)$$

$$p < \frac{\lambda_0}{2}\sqrt{\varepsilon_r} \quad (2)$$

$$p < 4\,d \quad (3)$$

$$\lambda_0 = \frac{c}{f}$$

where λ_0 is the space wavelength.

In this paper, the software HFSS [6], based on the finite element method (FEM), has been applied to analyze the RSIW devices. It should be noted that the formulas given by equations (1), (2) and (3) are commonly used to obtain initial values ofW_{SIW}, which is optimized later by HFSS. Following this approach, we deduce the parameters (Table I) of the RSIW, designed in K-band [18-26.5] GHz from a conventional waveguide WR42 [7] (Fig. 2)

Then we analyze this structure by using HFSS, which allows the electromagnetic field cartography of the TE_{10} mode and the scatter diagram. Fig. 3 shows the similarity of the electric field distribution of the TE_{10} mode guided in the RSIW and in its equivalent waveguide.

TABLE I: THE PARAMETERS OF THE RSIW

Classic wave guide	Equivalent wave guide	RSIW
WR42, a=10.668mm, b=4.318mm, ε_r =1	h=0.254mm, ε_r = 9.9 W_{eq}=3.39mm	h=0.254mm, ε_r =9.9, d=0.254mm, p= 0.5mm, W_{SIW}=3.52mm

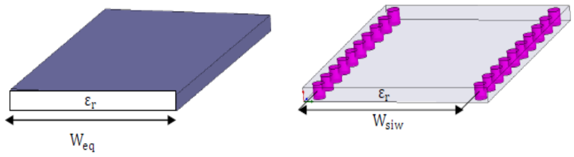
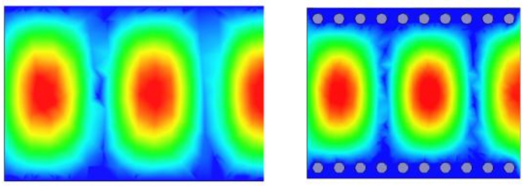


Fig. 2. Equivalent rectangular waveguide and RSIW.



(a) (b)

Fig. 3. Electric field distribution of the TE_{10} mode in the equivalent rectangular waveguide (a) and in the RSIW (b) respectively, at frequency f = 22GHz.

Fig. 4 shows the dispersion characteristics between these two equivalent waveguides. It should be noted that this similarity propagation is valid for all modes TE_{n0}.

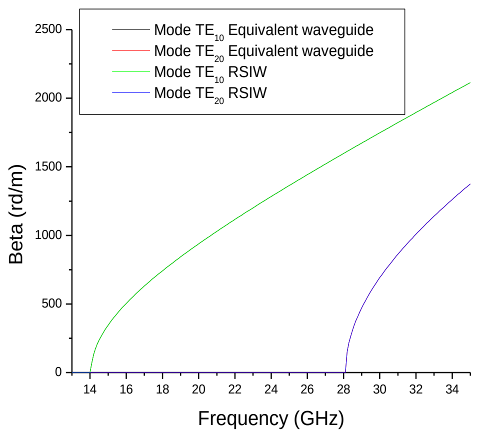


Fig. 4. Dispersion characteristics.

III. RSIW MATCHING

In this study, a microstrip transition (taper) [8] is used to interconnect RSIW to the planar transmission lines. There is a tapered section which is used to match the impedance between a 50 Ω microstrip line and the RSIW. The 50 Ω microstrip line, in which the dominant mode is quasi-TEM, can excite well the dominant mode TE_{10} of the RSIW, as their electric field distributions are approximate in the profile of the structure. Initial parameters W_T and L_T of the taper are determined from several formulas given in [9], following by an optimization using the HFSS [6]. The optimal parameters are presented in Table II. Fig. 5 shows the proposed configuration of two back-to-back transitions of microstrip line to RSIW. It allows the design of a completely integrated planar circuit of microstrip and waveguide on the same substrate without any mechanical assembly.

TABLE II: THE OPTIMAL PARAMETERS

L_T	5.5mm
W_T	1.44mm
W_{mst}	0.2mm
L	3.508mm

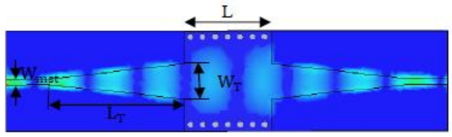


Fig. 5. Electric field distribution of TE_{10} mode at f = 22 GHzin the matched RSIW.

Fig. 6 and Fig. 7 show the results of the RSIW analysis without transition and with a coplanar taper of dimensions L_T and W_T, respectively.

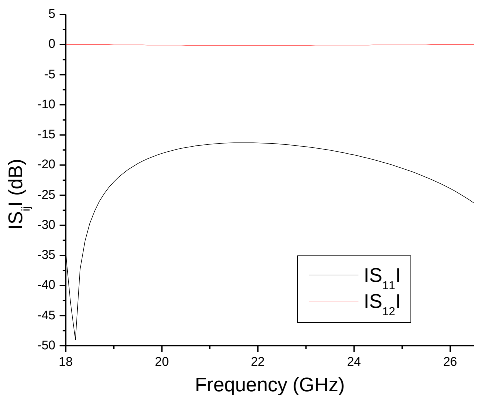


Fig. 6. Transmission coefficients S_{21} and reflection S_{11} of the RSIW.

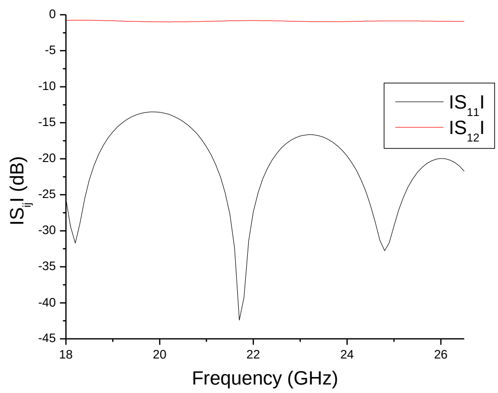


Fig. 7. Transmission coefficients S_{21} and reflection S_{11} of the matched RSIW with taper.

The results illustrated in Fig. 7, indicate that the reflection coefficient S_{11} remains below-15dB over 25.3% of the frequency band and the transmission coefficient S_{12} is around -0.93 dB across the entire band.

IV. DESIGN OF RSIW PASSIVE DEVICES

A. SIW Coupler

The development of modern communication systems, in microwave and millimeter waves domain, requires high quality and high density integration circuits. The size and cost are two essential requirements of these systems. This has stimulated the rapid development of many passive compact [10] and low cost components. Couplers [11] which have been widely used as key components in many systems have been intensively studied for decades. The directional couplers are passive devices used for routing, dividing and combining the signals in the microwave system. In the antenna beam-forming networks, the directional coupler is generally an important element in power dividing/combining networks, so great interest and effort have been directed to the development of different types of directional couplers [7]. The RSIW directional couplers [12] are extensively investigated. Coupler's configuration is illustrated in Figure 8. The RSIW directional coupler (-3*dB*) is realized by two RSIW with a common wall on which an aperture is used to realize the coupling between these two guides. The geometry of the coupler is determined [13] based on an even/odd mode analysis, where the even mode is the TE_{10} and the odd mode is the TE_{20}. The phase difference $\Delta\varphi$ between the two modes is expressed by

$$\Delta\varphi = (\beta_1 - \beta_2) W_{ap} \quad (4)$$

where β_1 and β_2 are the propagation constants of the TE_{10} and TE_{20} modes, respectively. In the band of operation, the condition $\Delta\varphi = \pi/2$ needs to be satisfied. Port 1 is the input port, port 2 is named as the through port, port 3 is the coupling port and port 4 is designed as the isolated port. The tapered transition between the 50Ω microstrip line and the RSIW is added to each port so that we can integrate this component directly into a microstrip circuit. The matrix $[S]$ of a symmetric coupler (-3 *dB*), adapted to its access, is given by equation (5).

$$[S] = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & j & 0 \\ 1 & 0 & 0 & j \\ j & 0 & 0 & 1 \\ 0 & j & 1 & 0 \end{bmatrix} \quad (5)$$

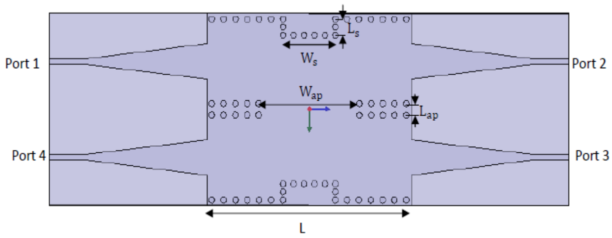


Fig. 8. RSIW coupler.

The coupler parameters are finely tuned using three-dimensional (3D) electromagnetic (EM) simulation under HFSS [6] to achieve wide-band performance. The final dimensions of the SIW coupler are presented in Table III.

TABLE III: THE FINAL DIMENSIONS OF THE SIW COUPLER

L	9.245mm
W_s	2.37mm
L_s	0.652mm
W_{ap}	4.55mm
L_{ap}	0.724mm

Fig. 9 and Fig. 10 present the electric field distribution of the TE_{10} mode in the *K*-band and the reflection coefficients S_{11}, the transmission coefficients S_{21}, the coupling coefficient S_{31} and the isolation coefficient S_{41}. The results of this analysis show clearly the directional coupler character in the band [18-26.5] GHz, where we have noted the levels of reflection and isolation below -15dB in more than 26.43% of the bandwidth, and the insertion loss S_{21} and coupling S_{31} fluctuate between-3.24dB and -3.78dB. These simulation results prove the good performance of this integrated structure.

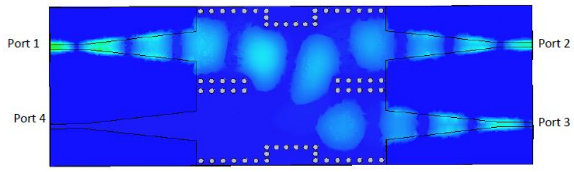


Fig. 9. Electric field distribution of TE_{10} mode for RSIW coupler at f=22 GHz.

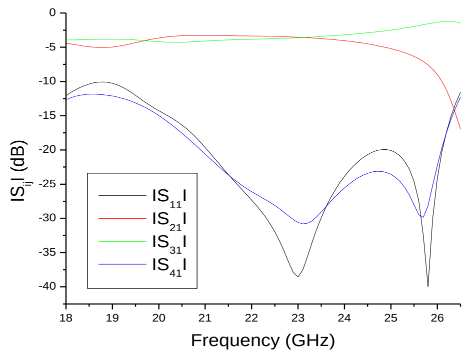


Fig. 10. Frequency response of the RSIW directional coupler.

B. *SIW Circulator*

Starting from a dielectric substrate between two metal planes, two rows of holes are drilled and metalized, making contact between the two metal planes of the substrate. Currently, instead of drilling, there is the possibility of using laser technology to achieve any form of reduced size hole on substrates of high permittivity [7]. The RSIW, whose vertical electric walls are synthesized by two rows of metalized square holes made using a laser, has proven to be a good choice in terms of insertion losses and bandwidth. This technology is less expensive than the use of engraving [7]. The side d of the square holes stems, p the spacing between the holes and W_{SIW} the spacing between the two rows of holes, are physical parameters necessary for designing RSIW (Fig. 11).

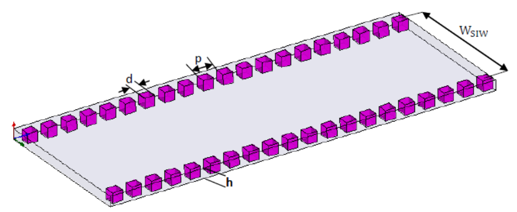


Fig. 11. Rectangular waveguide integrated into a substrate RSIW.

Based on the formulas given by equations (1), (2) and (3), design techniques for the rectangular waveguide can be applied to analyze and design, under HFSS, various components just by knowing W_{SIW} of the RSIW.

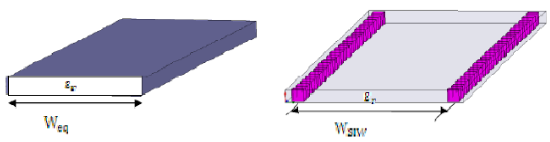
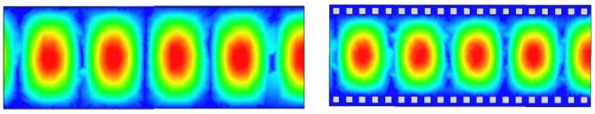


Fig. 12. Equivalent rectangular waveguide and RSIW.

This analysis allows the cartography of the electric field of the TE_{10} mode and the scatter diagram. The rows of holes, in contact with the metalized conductive planes of the substrate, define a region of electromagnetic waves propagation which is similar to that in a metallic rectangular waveguide. Fig. 13 shows the similarity of the electric field distribution of the TE_{10} mode in the RSIW and its equivalent waveguide.



(a) (b)

Fig. 13. Electric field distribution of the TE_{10} mode in the equivalent rectangular waveguide (a) and in the RSIW (b) respectively at f = 22GHz.

Fig. 14 also shows the dispersion characteristics of these two equivalent waveguides. Through various studies on the characteristics of SIW components [5] technology, it appears that only TE_{n0} modes are propagated. These components have a wide bandwidth for millimeter wave frequencies. The single mode band of the dominant TE_{10} mode extends from 1.25 $f_{c_{10}}$to 1.9$f_{c_{10}}$, $f_{c_{10}}$ is the cutoff frequency [1]

$$f_{c_{10}} = \frac{c}{2\, W_{eq}\sqrt{\varepsilon_r \mu_r}} \tag{6}$$

In these applications, the permeability μ_r is equal to 1.

It should be noted that this similarity propagation is valid for all modes TE_{n0}.

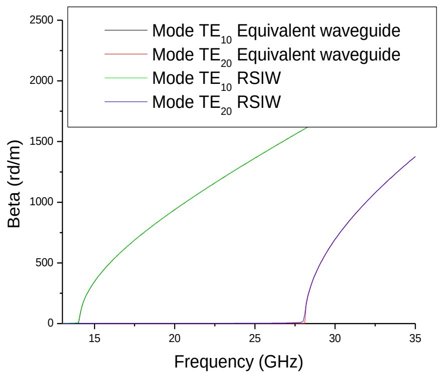


Fig. 14. Dispersion characteristics.

The protection of microwave sources is very common and recommended to increase the reliability of emitters in practice. Several types of solutions are used to provide this kind of function. However, in high power, the circulator waveguide technology [14] is still the best solution. Its topology of a hexapole (Fig. 15) having three access separate of 120 ° from each other, around a central body of ferrite (nickel materials and lithium ferrite) [5], [15] , to which is applied a vertical magnetic field conferring to the circulator the property of non-reciprocity. Indeed, when a transverse magnetic field is applied, it creates in its central part an internal field such that incoming wave from port 1, 2 or 3 cannot go out by the access 2, 3 or 1, respectively.

The two important variables for a circulator are insertion losses to be as low as possible (<1 dB) and good isolation (-30dB). The ideal circulator is a suitable hexapole that would be able to direct the energy to the next access, the third being isolated. Its ideal matrix [S] would be as follows:

$$[S] = \begin{bmatrix} 0 & 0 & e^{j\varphi} \\ e^{j\varphi} & 0 & 0 \\ 0 & e^{j\varphi} & 0 \end{bmatrix} \tag{7}$$

where φ is the phase shift associated with transmission of the access signal to the next access. The non-symmetry of the matrix reflects clearly the non-reciprocity of the component. This non-reciprocity is the whole point of the device and explains that this function can be used in many applications in telecommunications. This circulator was designed by using rods of square section, with the same parameters presented in Tables I and II, but L = 3.881mm.

In this study, the saturation magnetization of ferrite material is [15] $4\pi Ms$ = 5000 Gauss. Its relative dielectric constant is 13.7 and a radius R_f calculated by [14].

$$R_f = \frac{1.84\, c}{\omega_0 \sqrt{\varepsilon_f}} \tag{8}$$

where c and ω_0 are respectively the velocity of light in the free space and the operation frequency [14]. The ferrite height is equal to the RSIW thickness, R_f=1.1mm h_f=0.254mm.

The RSIW circulator, presented in Fig. 15, has been simulated by HFSS [6]. Fig.16 illustrates the distribution of the electric field of the TE_{10} mode in the band [18-26.5] GHz. The frequency response of this SIW circulator, the transmission coefficient S_{21}, the reflection coefficient S_{11} and the isolation coefficient S_{31} are reported through the figure 17. The analysis of these results shows that the reflection loss S_{11} below -15dB occupy more than 21.75% of the bandwidth, the insertion loss S_{21} is about -0.65 dB, while the maximum of the isolation S_{31} is -38.11dB. At frequency of 24 GHz, the Fig. 16 and Fig. 17 confirm the circulation property of this device [14].

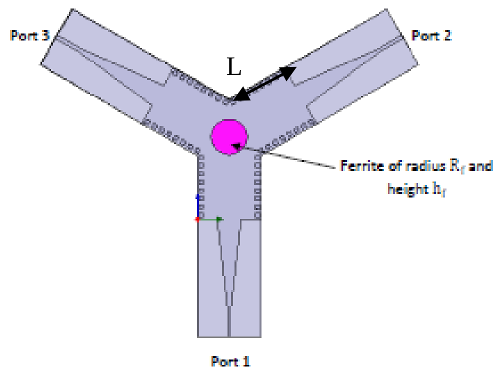


Fig. 15. RSIWcirculator.

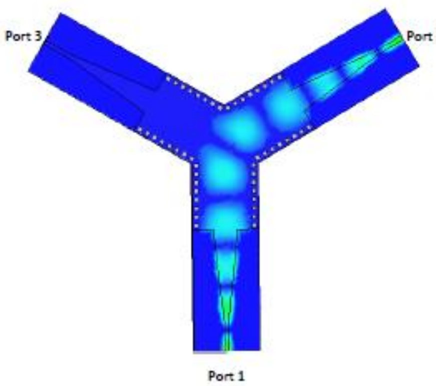


Fig. 16. Electric field distribution of the TE_{10} modeof the SIW circulator at f = 24 GHz.

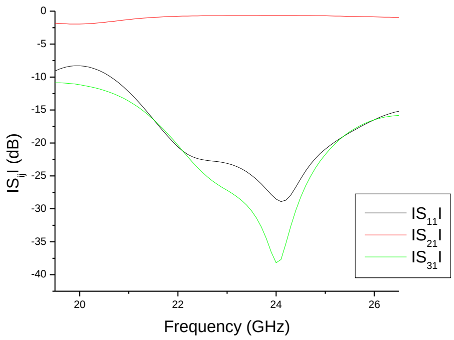


Fig. 17. Parameters S_{ij} of the SIW circulator.

C. SIW Power Divider

The power dividers [16] are passive microwave devices. There are mainly two types T and Y [5], [7], which are commonly used to deliver copies of a signal in a system. This application focuses on the three ports power dividers with equal power division ratio where the half power (-3dB) of an input signal is provided to each of the two output ports. The S matrix for a three ports network, is shown in equation (9)

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \tag{9}$$

The analyzed power divider (Fig. 18), designed in the *K*-band [18-26.5] GHz, is based on three identical RSIW with the characteristic parameters reported in Table I and Table II. Then three RSIW of length L=4mm are connected to form a *T*. An inductive metal cylinder of radius r and position xp is added to this junction in order to minimize reflection losses at the input port. To achieve this objective, an optimization of the radius r and the position xp of this disruptive element is required. For this purpose, it is generally useful to fix the radius r to the corresponding available practical value of diameter drills, and then change xp to reduce the reflection losses. This will be repeated until reflection losses reach acceptable limit, below -15dB, reach acceptable limit. Then, a microstrip transition is added to each port so that we can integrate this component directly into a microstrip circuit. The input wave (port 1) is divided into two parts which output to port 2 and port 3, respectively.

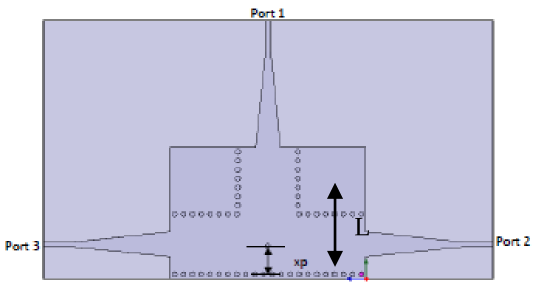


Fig. 18. RSIW power divider.

Fig. 19 and Fig. 20 illustrate the distribution of the electric field of the TE_{10} mode in the band [18-26.5] GHz and the transmission coefficients S_{21}, $S_{31}$and the reflection coefficient S_{11}, respectively. Fig. 20 indicates that S_{11} is less than -15 dB between 19.14 GHz and 25.02 GHz, which is more than 26.63 % of the bandwidth. The optimal values of the disruptive element are r=0.127mm, xp=1.66mm. The transmission coefficients S_{21} and S_{31} fluctuate between -3.45dB and - 4.02 dB, being very acceptable levels.

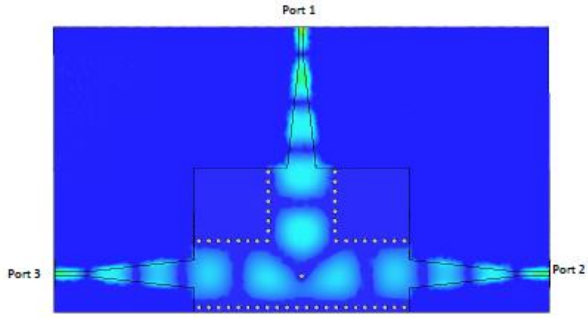


Fig. 19. Electric field distributionof theTE_{10} mode at f= 22GHz in the power divider with inductive cylinder.

Then, we changed the shape of the rods forming the side walls of the RSIW to analyze its influence. Fig. 21 and Fig. 22 illustrate the distribution of the electric field of the TE_{10} mode in the band [18-26.5] GHz and the transmission coefficients S_{21}, S_{31} and the reflection coefficient S_{11}, respectively. This power divider RSIW is designed by metal rods of square section with a side d equal to the diameter of the cylindrical rods used above. Fig. 22 indicates that S_{11} is less than -15 dB between 19.3 GHz and 25.02 GHz, which is more than 25.81% of the bandwidth. The optimal values of the disruptive element are r= 0.127mm and xp=1.66mm. The transmission coefficients S_{21} and S_{31} fluctuate between -3.58dB and -3.67dB, showing equal division of the power injected into port 1. Finally, we note that there is no significant change in the response of this power divider compared to the same device using cylindrical rods as sidewalls, provided that the spacing between rods is respected.

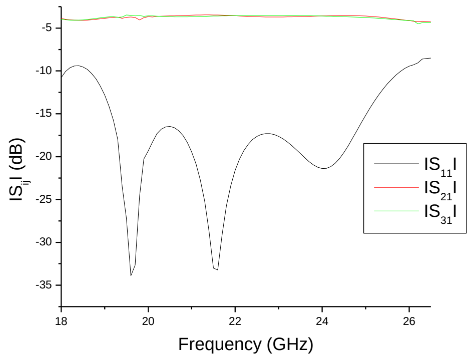


Fig. 20. Parameters S_{ij} in the power divider with inductive cylinder.

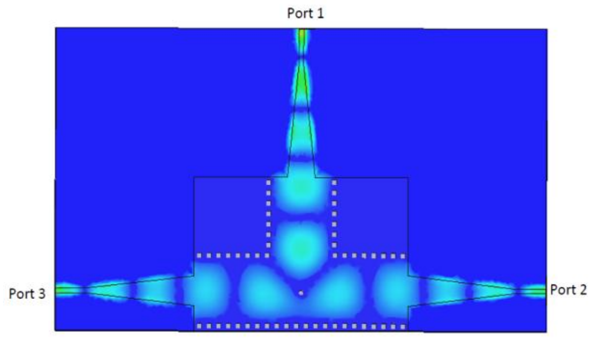


Fig. 21. Electric field distribution of theTE_{10} mode at f= 22GHz in the power divider with inductive post.

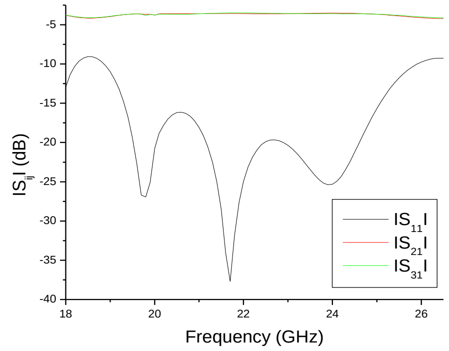


Fig. 22. Parameters S_{ij} in the power divider with square rods.

Fig. 23 and Fig. 24 illustrate the distribution of the electric field of the TE_{10} mode in the band [18-26.5] GHz, the transmission coefficients S_{21}, S_{31} and the reflection coefficient S_{11} of the power divider RSIW designed by metallic rods of rectangular section of width d and length 2d. Fig. 24 indicates that S_{11} is less than -15 dB between 19.6 GHz and 25.54 GHz, which is more than 26.32% of the bandwidth. The optimal values of the disruptive element are r = 0.127 mm and xp = 1.66 mm. The transmission coefficients S_{21} and S_{31} are around -3.54dB showing equal division of the power injected into port 1. We also note that there is no significant change in the response of the divider compared to using cylindrical rods as sidewalls. Using laser technology instead of drilling, allows achieving any form of reduced size hole on substrates of high permittivity [7] and less expensive costs.

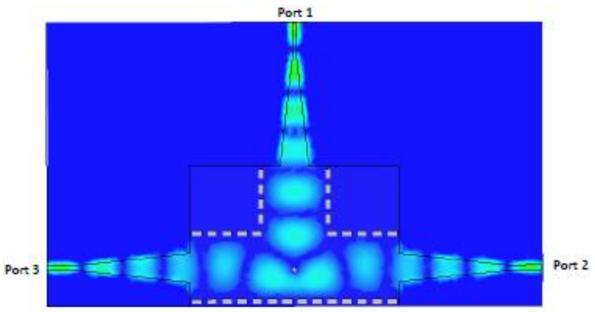


Fig. 23. Electric field distribution of the TE_{10} mode at f= 22GHz in the power divider with inductive cylinder.

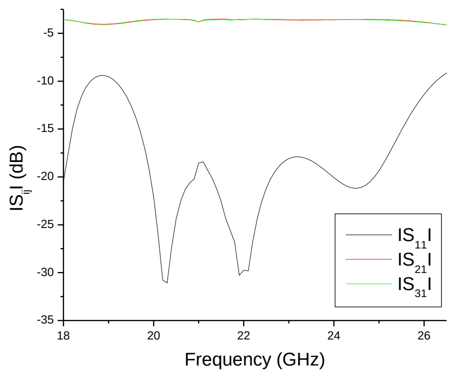


Fig. 24. Parameters S_{ij} in the power divider with rectangular rods.

V. Conclusion

Through this study, three passive components based on rectangular substrate integrated waveguide (RSIW) technology are analyzed in K-band. We have presented a simple and fast method to design RSIW devices using HFSS. Firstly, the coupler circuit, which is composed of two matched RSIW with a common wall on which an aperture is used to realize the coupling. Secondly, the K-band RSIW circulator, suitable for millimeter wave applications, has been designed; it can be integrated on the same substrate with microstrip and other planar circuit. The HFSS code has also been applied to the analysis of the K-band RSIW power divider. We focused on the design of RSIW power divider with cylindrical rods and then we changed the shape of the rods forming the RSIW sidewalls to analyze its influence. We noted that there is no significant influence on the response of the power divider when we change the shape of the sidewall rods; provided that the spacing between rods is respected. The developed RSIW coupler, circulator and power dividers can serve as building blocks in the design of complex microwave and millimeter wave circuits and systems. The simulation results have shown the good performance of these integrated structures.

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