Abstract—Recently, there has been a lot of interest in the substrate integrated waveguide (SIW) technology concept allowing the integration of waveguides in the substrate, replacing the rectangular metal waveguide sidewalls by two rows of metal rods. The electric field distribution in the rectangular waveguide SIW, denoted RSIW, is similar to that of a conventional rectangular waveguide. In this paper, a Ku-band substrate integrated waveguide phase shifter is conceived and optimized by Ansoft HFSS code.

Index Terms—Rectangular wave guide, microwave components, SIW, phase shifter, HFSS.

I. INTRODUCTION

The matching of planar components and rectangular waveguides on the same substrate is quite difficult and expensive. To obtain the benefits of rectangular waveguides while remaining in planar profiles, the SIW technology [1] is interesting. The waveguide in the technology SIW (RSIW) is indeed a compromise between the two; it has some interesting characteristics in terms of easy integration while offering components to a high quality factor. Most microwave components were modeled in SIW technology such as bends [2], filters [3], couplers [4], [5], duplexers [6], sixports junctions [7], [8], circulators [9], [10], phase shifters [11]. The phase shifter is a device which serves to change the phase of a signal with minimal attenuation. It is used to measure the phase shift introduced by the components. It is widely used in antenna arrays to change their radiation patterns. Many types of shifters in rectangular guides currently exist and are used in industry for many applications. A lossless, adapted and reciprocal phase shifter has the following scattering matrix S.

\[
[S] = \begin{bmatrix}
0 & -j \frac{\omega}{c} \frac{d}{p} \\
\frac{\omega}{c} \frac{d}{p} & 0
\end{bmatrix}
\]  

(1)

There are already some phase shifters SIW technology cited in the literature [11]. They are easy to manufacture by adding to the waveguide RSIW, metal or dielectric cylinders of radius \( r \) set at the entrance and/or at the exit of the guide.

II. DESIGN OF RSIW

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. The diameter \( d \) of 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 rectangular waveguide in technology SIW (Fig. 1).

Based on the work [12], empirical equations were derived for determining the width of the equivalent rectangular waveguide, giving the same characteristics of the fundamental mode propagating in the RSIW (Fig. 1) having the same height and the same dielectric.

\[
W_{eq} = W_{SIW} - \frac{d^2}{0.95 p}
\]  

(2)

where \( W_{SIW} \) and \( W_{eq} \) are respectively the width of the rectangular waveguide technology SIW and its equivalent waveguide (Fig. 2 and Fig. 3), \( d \) is the diameter of the metal cylinder and \( p \) is the distance between two adjacent cylinders, with:

\[
p < \frac{\lambda_0}{2} \sqrt{\frac{\varepsilon_r}{c}}
\]  

(3)

\[
p < 4 \frac{d}{c} \frac{\lambda_0}{f}
\]  

(4)

The period \( p \) should be kept low to reduce leakage losses between adjacent cylinders. The choice of subject is also the problem of losses. 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 a metallic rectangular waveguide, as illustrated in Fig. 3.

We analyzed the phase shifter designed in Ku-band [12]-[18] GHz from a conventional waveguide [2]. The
characteristic parameters of the waveguide RSIW synthesizing a waveguide WR62 with $a = 15.799\text{mm}$, $b = 7.898\text{mm}$, a filled dielectric permittivity $\varepsilon_r = 4.4$, $\tan \delta = 0.02$, height $h = 0.508\text{mm}$ and length $L = 25.4\text{mm}$. Following the same approach, cited above [13], to deduce the parameters of the RSIW and the equivalent waveguide (Fig. 4), we found $W_{eq} = 7.58\text{mm}$ and $W_{SIW} = 8.54\text{mm}$ for $p = 2.54\text{mm}$ and $d = 1.524\text{mm}$.

In this paper, the software HFSS [14], based on the finite element method (FEM), has been applied to analyze the SIW devices. It should be noted that the formulas given by equations (2), (3) and (4) are commonly used to obtain initial values $W_{SIW}$, optimized later by HFSS. This software allows the layout of the cartography of the electromagnetic field of the TE$_{10}$ mode and scatter diagram. Fig. 5 shows the similarity of the electromagnetic field distribution of TE$_{10}$ mode guided in the RSIW guide and its equivalent waveguide.

Fig. 6 also shows the consistency of the dispersion characteristics between these two equivalent waveguides. It should be noted that this similarity propagation is valid for all modes TE$_{n0}$.

### III. RSIW MATCHING

In our study, we are interested in transitions to interconnect RSIW to the planar transmission lines; we mention in particular the microstrip transition taper [15]. The transition between RSIW and microstrip can be designed on the same substrate, which has an excellent mechanical tolerance and does not have to be tuned [16]. There is a tapered section which is used to match the impedance between a 50 $\Omega$ microstrip line and the RSIW. The 50 $\Omega$ 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.

Fig. 7 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. Fig. 8 and Fig. 9 show the results of the RSIW analysis without transition and with a coplanar taper of dimensions \( L_T \) and \( W_T \).

They also show that \( S_{11} \) is less than -15dB over the whole band and the transmission coefficient \( S_{12} \) is around -0.458dB over the entire band.

### IV. DESIGN OF RSIW PHASE SHIFTING

One of the simplest approaches to design a phase shifter in technology SIW is to use a waveguide RSIW with variable length \( L \). The phase introduced by such device is equal to \( \beta_g L \). To vary this phase, it suffices to change the length \( L \) by changing the number of metal cylinders. Using this approach, we simulated three structures RSIW with lengths \( L, L1 \) and \( L2 \) respectively, and \( L1 < L < L2 \). Fig. 10 shows the mapping of the electric field of the TE\(_{10}\) mode, guided from the input to the output of the phase shifter at frequency of 15 GHz. Fig. 11 illustrates the phase of the transfer function \( S_{12} \) of this phase shifter with lengths \( L, L1 \) and \( L2 \) respectively, corresponding to 10, 9 and 11 metal cylinders (Vias). We deduce from this figure that the phase varies between -180° and 180° across the operating band.

![Fig. 10. The electric field distribution of the TE\(_{10}\) mode of the phase shifter SIW at \( f = 15 \) GHz.](image)

![Fig. 11. The phase of the transfer function \( S_{12} \) for different lengths of RSIW.](image)

Another way to introduce an additional phase shift in the guide RSIW, involves inserting disturbing rods. This phase shift depends on the position and size of the disturbing element. Fig. 12 shows the electric field map of the TE\(_{10}\) mode of this shifter at the frequency 15 GHz. The phase shift introduced by the component can be easily controlled by the addition of a disturbing rod of radius \( r \), placed at the input and/or the output of the RSIW, the change in its dimension \( r \) and/or its position \( x_p \) reflecting the distance between this rod and a row of the metallic rods. Fig. 13 illustrates the phase change of the transfer function \( S_{12} \) of this phase shifter depending on the position \( x_p \) and the radius \( r \) of the disturbing element reflecting an air hole at frequency of 15 GHz. We note that the phase increases with the radius \( r \) of the air hole for a given position \( x_p \). This phase is maximum for \( x_p = 4.27 \)mm corresponding to the middle of \( W_{SIW} \), position at which the disturbing element introduces a great influence.

![Fig. 12. Electric field distribution of TE\(_{10}\) mode SIW phase shifter for \( r = 0.5 \)mm at \( f = 15 \) GHz.](image)

![Fig. 13. Phase of \( S_{12} \) as a function of radius \( r \) and position \( x_p \) air hole at \( f = 15 \) GHz.](image)

Then, in the same waveguide RSIW, we inserted at two extremities, two identical metal rods with radius \( r \) and \( x_p \) position. Fig. 14 exposes the distribution of the electric field of the TE\(_{10}\) guided mode at the frequency \( f = 15 \) GHz. Fig. 15 represents the change of the phase of the transfer function \( S_{12} \) of this phase shifter depending on the position \( x_p \) and the radius \( r \) of the two disturbing elements position at the frequency \( f=15 \) GHz. We notice that the phase increases with radius \( r \) for a given position \( x_p \). This phase is maximum for \( x_p = 4.27 \)mm corresponding to the middle of \( W_{SIW} \), position at which the disturbing elements introduce a great influence.

![Fig. 14. Electric field distribution of TE\(_{10}\) mode SIW phase shifter at \( f = 15 \) GHz.](image)

![Fig. 15. Phase of \( S_{12} \) as a function of radius \( r \) and the position \( x_p \) of two disturbing elements at \( f = 15 \) GHz.](image)

In a conventional shifter, we try to get the best possible adaptation to minimize reflection losses. The structure must also provide a constant phase shift in the operating frequency band. A method that best applies to RSIW [12], consists in placing a dielectric rod at the center of the guide. Of course, this creates some disturbing reflection, but they are generally
less than those generated by metal rods. The additional phase shift is of course obtained by comparing the phase of the phase shifter with that of the same guide RSIW undisturbed at its center. Fig. 16 shows the structure of a phase shifter conceived by insertion in the middle of the waveguide RSIW, a dielectric rod formed of an air hole \((\varepsilon_p = \varepsilon_r = 1)\). We then analyzed a guide RSIW for different rod sections, cylinder (Fig. 16 (a)), rectangle (Figure 16 (b)) and rhombus (Fig. 16 (c)) with identical surface. The graph in Fig. 17 shows that the additional phase shifts induced by various forms of disturbing rods with similar surfaces are very close, as shown by their frequency response over the entire frequency band (Fig. 18).

![Image](image.png)

Fig. 16. The electric field distribution of the TE_{01} mode of the phase shifter SIW at \(f = 15\text{GHz}\), with: (a) cylinder rod, (b) rectangular rod, (c) rhombus rod.

![Image](image.png)

Fig. 17. Additional phase shift as a function of the disturbing shape.

![Image](image.png)

Fig. 18. Frequency responses of the guide RSIW for three different disturbing elements.

After all these analyses, we can conclude that the insertion of disturbing elements, of various shapes, in a RSIW guide generates phase shifts. Moreover, this phase depends on the permittivity and the size of the section of the disturbing rod and not on its shape [17].

V. CONCLUSION

In this paper, an analogue phase shifter in low cost SIW technology has been presented. The phase shift is determined by inserting rods of different diameters and placed at different locations in the RSIW or by inserting disturbing elements of various shapes. Moreover, this phase depends on the permittivity and the size of the section of the disturbing rod and not on its shape. To validate the proposed concept, a Ku-band phase shifter is designed and optimized. Feasibility of this phase shifter is validated by simulated results got from HFSS. The proposed phase shifter SIW is compact, easy for fabrication, and has an attractive application prospect for design of complex microwave and millimeter-wave circuits systems such array antenna.

REFERENCES

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