Design of Substrate Integrated Waveguide Multi-band Slots Array Antennas

Keltouma Nouri, Tayeb Habib Chawki Bouazza, Boubakar Seddik Bouazza, Mehdi Damou, Kada Becharef, and Salima Seghier

Abstract—**In this paper, the design of slots array antennas based on Substrate Integrated waveguide (SIW) has been analyzed and simulated. A waveguide slot antenna has a vertical row of slots along the length of a vertical waveguide, with the array of slots increasing the gain by flattening the vertical beam. The whole array antennas including two slots and feeding element is completely constructed at a single substrate by using substrate integrated waveguide technique and tapered micro-strip transition. These structures are simulated by the software HFSS on substrate of Duroid 5880. Simulated results on return loss and radiation pattern are presented and discussed.**

Index Terms—**Array, slot antenna, substrate integrated waveguide, transition.**

I. Introduction

Antenna is one of the important elements of the communications systems. Thus, antenna design has become one of the most active fields in the communication studies. However, there is a need for more focused radiation patterns (high gain), such as in point-to-point terrestrial links, satellite communications, and air-traffic radar. A more focused radiation pattern will also extend the communication range [1]. To create a more directive radiation pattern, the size of the antenna must be increased. This can be done with simple resonant antennas like the dipole and the loop, but it is usually difficult to control the side lobe levels of these antennas. A waveguide slot array antenna is mainly used for high gain flat antennas in millimeter-wave wireless communication systems due to their unique features such as lower loss in comparison with microstrip antennas, and simpler structure compared with reflector antennas [2].

One of the types of waveguide slot array antenna is the SIW slot array antenna. Substrate integrated waveguide (SIW) technique has been found to be a promising approach which provides a low-loss, low-cost and high-density integration in a hybrid design platform. It is well known that a waveguide-type circuit usually presents a much larger as compared with its microstrip line or stripline counterparts as the width of waveguide is fundamentally restricted by its cutoff frequency as well as its dispersion properties. Stripline and microstrip line circuits have obvious predominance in this aspect. However, a large number of waveguide-type circuits provides designer with benefits on excellent loss performance, especially when the loss on a fine or narrow microstrip line is more pronounced as working frequency gradually goes higher and higher into millimeter wave regime. Substrate integrated waveguide is constructed by metal filled via-hole arrays in substrate and grounded planes which can be easily interconnected with other elements of the system on a single substrate plat form without tuning [3]-[8], this system can be miniaturized into small package called the system in package SIP which has small size and low cost [5]. A schematic view of an integrated waveguide is shown in Fig. 1. The SIW is an excellent candidate for the integration of high density millimeter wave circuits which require a good quality factor. It benefits from the very low production cost of the PCB process and it is relatively compact.

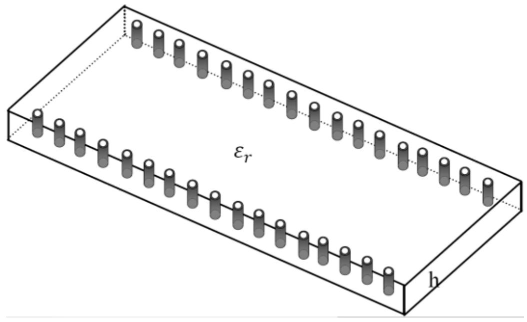

Fig. 1. Topology of the substrate integrated waveguide.

In this paper, we will propose, design of waveguide slots array antennas based on the SIW technology, the array consists of two longitudinal slots and it is match terminated. Firstly, we give the design equations for tapered microstrip-SIW transitions. Then we focus on the design of SIW slots array antennas with these transitions.

II. Feed Design

The proposed structure has been fed with a conventional microstrip line. The section of the microstrip line connecting the radiation surface has been tapered for proper impedance matching [9]. Tapered transition shows in Fig. 2 have been studied.

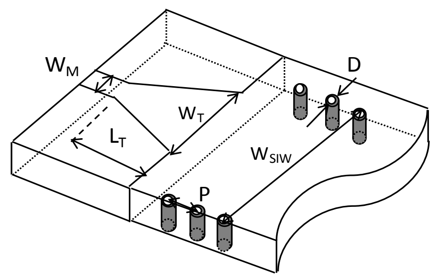

Fig. 2. Configuration of the microstrip to SIW transition.

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This transition consists of the tapered microstrip line and the step between the microstrip and the rectangular waveguide. The geometry of a microstrip line is shown in Fig. 3.

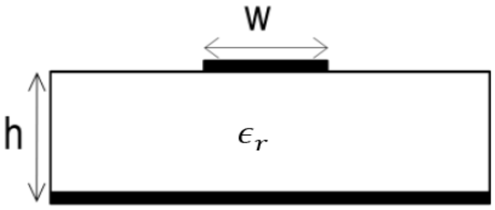


Fig. 3. Geometry of microstrip line.

When $W/h \geq 1$, the effective dielectric constant of a microstrip line is given approximately by [10]:

$$\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{w}\right)^{-\frac{1}{2}} \tag{1}$$

The effective dielectric constant can be interpreted as the dielectric constant of a homogeneous medium that replaces the air and dielectric regions of the microstrip, as shown in Fig. 4.

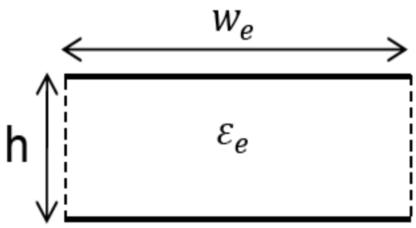


Fig. 4. Equivalent geometry of microstrip line.

The impedance of the waveguide model (Fig. 4) is given by:

$$Z_e = \sqrt{\frac{\mu}{\varepsilon_0 \varepsilon_e}}\frac{h}{w_e} \tag{2}$$

Combining with the equation for the impedance of microstrip line, we obtain:

$$Z_e = \begin{cases} \frac{60}{\sqrt{\varepsilon_e}} \ln\left(8\frac{h}{w}+\frac{w}{4h}\right) & w/h \leq 1 \\ \frac{120\pi}{\sqrt{\varepsilon_e}}\left[w/h + 1.393 + 0.667\ln\left(w/h + 1.444\right)\right]^{-1} & w/h > 1 \end{cases} \tag{3}$$

The taper is used to transform the quasi-TEM mode of the microstrip line into the TE_{10} mode in the waveguide. It is known that the propagation constant of the TE_{10} mode is only related to the width 'W_{SIW}'. Therefore, the scattering parameters are independent of the height or thickness 'h' of the waveguide. The scattering parameters are then only dependant of: W_{SIW}, We, ε_e and ε_r. These parameters, in the normalized frequency band, are related to the ratios: W_{SIW}/W_e and $\varepsilon_e/\varepsilon_r$. Curve fitting techniques have been used by Deslandes in [7] to find the relation between permittivity and width ratios. This relation is given by:

$$\frac{w_{SIW}}{w_e} = 4.38 e^{-0.627\frac{\varepsilon_r}{\varepsilon_e}} \tag{4}$$

Combining equations (1) and (4), we obtain:

$$\frac{1}{w_e} = \frac{4.38}{w_{SIW}} e^{-0.627\frac{\varepsilon_r}{\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{w}\right)^{-\frac{1}{2}}}} \tag{5}$$

Combining equations (2) and (3), we obtain:

$$\frac{1}{w_e} = \begin{cases} \sqrt{\frac{\varepsilon_0}{\mu}}\frac{60}{h}\ln\left(8\frac{h}{w}+0.25\frac{w}{h}\right) & w/h \leq 1 \\ \sqrt{\frac{\varepsilon_0}{\mu}}\frac{120\pi}{h\left[\frac{w}{h}+1.393+0.667\ln\left(\frac{w}{h}+1.444\right)\right]} & w/h > 1 \end{cases} \tag{6}$$

We can equate the equations (5) and (6) and solve it to obtain *w*, which is the optimum taper width.

III. The Design Equations of a Liner Sloted Waveguide Array

A slot cut out of a waveguide is one of the most fundamental types of aperture antennas. Fig. 5 shows a slot cut out of the broadside of a waveguide. If the waveguide is excited with TE_{10} mode wave traveling in the z-direction, the normalized field components are [11].

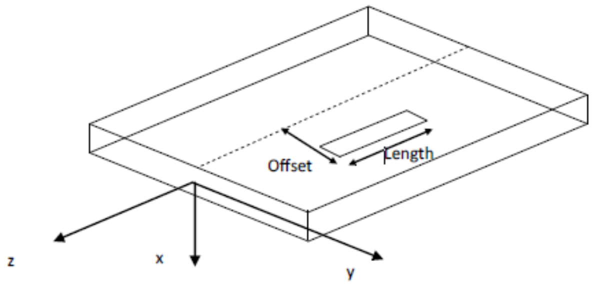


Fig. 5. Longitudinal slot cut out of a piece of waveguide.

If the waveguide is excited with TE_{10} mode wave traveling in the z-direction, the normalized field components are [11]

$$\begin{aligned} H_z &= j\cos\left(\frac{\pi x}{a}\right).e^{j(\omega t-\beta z)} \\ H_x &= -\frac{\beta}{\pi/a}\sin\left(\frac{\pi x}{a}\right).e^{j(\omega t-\beta z)} \\ E_y &= -\frac{\omega\mu_0}{\pi/a}\sin\left(\frac{\pi x}{a}\right).e^{j(\omega t-\beta z)} \end{aligned} \tag{7}$$

The electric field within the slot can be approximated with the following equation [9]:

$$E_x = \frac{V^s}{w}\cos\left(\frac{\pi z'}{l}\right) \tag{8}$$

where V^s is the voltage across the center of the slot, *w* is the width of the slot, l is the length of the slot and z' represents the position along the z-axis where the origin is taken to be the line that bisects the slot. The relation between the backscattered mode amplitude B_{10} and the forward-scattered mode amplitude C_{10} to the electric field induced in the slot when a TE_{10} mode wave is incident upon the slot.

$$B_{10} = C_{10} = \frac{\int_{slot}(E_1 \times H_2).dS}{2\int_{S_1}(E_{10}\times H_{10}).l_z dS_1} \tag{9}$$

where E_1 can be found in equation (8), and:

$$H_2 = l_z j cos\left(\frac{\pi x'}{a}\right). e^{-j\beta_{10} z}$$
$$E_{10} = l_y \frac{\omega\mu_0}{\pi/a} sin\left(\frac{\pi x\prime}{a}\right) \quad (10)$$
$$H_{10} = l_x \frac{\beta_{10}}{\pi/a} sin\left(\frac{\pi x'}{a}\right)$$

After integrating and simplifying equation (9) results in

$$B_{10} = -K \frac{(\pi/2kl).\cos(\beta_{10} l)}{(\pi/2kl)^2 - (\beta_{10}/k)^2} sin\left(\frac{\pi x}{a}\right) V_s \quad (11)$$

where:

$$K = \frac{2(\pi/a)^2}{j\omega\mu_0(\beta_{10}/k)(ka)(kb)}, k = \omega\sqrt{\mu_0 \varepsilon} \quad (12)$$

When designing an array of waveguide-fed slots the designer must be able to control the power radiated by each slot, ensure that all slots are resonating the design frequency and that the sum of all slot admittances equal the characteristic admittance of the waveguide. The power radiated by each slot is directly related to the amplitude of the electric field induced in the slot [12]-[15]. The symmetrical scattering off the shunt admittance modeling the nth slot in an array of N slots can be modeled in terms of its active admittance Y_n.

$$B = C = -\frac{1}{2}\frac{Y_n}{G_0} V_n \quad (13)$$

where G_o is the characteristic admittance of the waveguide and V_n is the mode voltage at the center of the slot. Equations (10) & (12) can be combined by requiring B_{10} and B to have the same phase at all points along the z-axis and that the backscattered power levels are the same [12], [13]. The result is a principle design equation that will be used in the design of antenna.

$$\frac{Y_n}{G_0} = K_1 f_n \frac{V_n^S}{V_n} \quad (14)$$

where:

$$K_1 = \frac{1}{j(a/\lambda)} \sqrt{\frac{2(k/k_0)}{\eta G_0 (\beta_{10}/k)(ka)(kb)}} \quad (15)$$

in which η is the free space impedance, and:

$$f_n = \frac{(\pi/2kl_n).\cos(\beta_{10} l_n)}{(\pi/2kl_n)^2 - (\beta_{10}/k)^2} \sin\left(\frac{\pi x_n}{a}\right) \quad (16)$$

V_n^S is the total slot voltage.

The equivalent transmission line circuit of this situation consists of the self-admittance of the slot in parallel with the characteristic admittance of the waveguide and can be represented with the following equation:

$$\frac{Y}{G_0} = \frac{2(B/A)}{1+(B/A)} \quad (17)$$

where A is the incident wave upon the slot and B is the backscattered wave caused by the discontinuity at the slot. This equation is still valid if A & B are replaced with A_{10} & B_{10} this substitution and rearranging this equation leads to:

$$B_{10}^n = \frac{\frac{Y}{G_0}(x_n, l_n)}{2 + \frac{Y}{G_0}(x_n, l_n)} \quad (18)$$

where x_n and l_n is the offset and length of the nth slot respectively. The equation (16) allows one to calculate the scattering matrix of the slot, which is characterized by a two-port microwave circuit as shunt admittance, if the normalized self-admittance of the slot as a function of the offset x_n and length l_n is known [13]. For this work, the design procedure was to design a slotted waveguide array antenna and using those results transform the waveguide into an equivalent substrate integrated waveguide. The conventional RWG slot array antenna is transferred to the SIW slot array antenna (Fig. 6).

Since the E field distribution in the SIW looks like that of a classic rectangular waveguide, the width w_{SIW} can be approximated as follows [14]:

$$w_{SIW} = w - \frac{D}{0.95P} \quad (19)$$

These relations allow for a preliminary dimensioning and design of SIW components, without any need of full-wave analysis tools. In this equation, w is the width of the dielectric waveguide. The parameters D and P are the wall post diameter and the period of vias respectively as shown in Fig. 6:

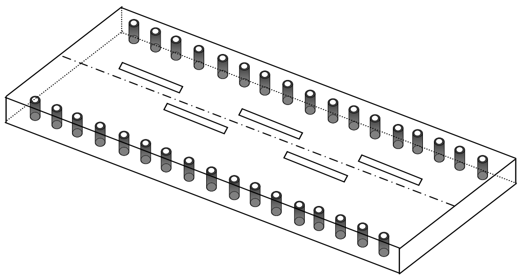


Fig. 6. Linear resonant SIW slots array antenna.

and the rule of design are:

$$b \le 2D \quad (20)$$

$$D < \lambda_g/5 \quad (21)$$

The electrical wavelength in waveguide is longer than in free space, so we must calculate the guide wavelength:

$$\lambda_g = 1 \Bigg/ \sqrt{\left(\frac{1}{\lambda_0}\right)^2 - \left(\frac{1}{\lambda_C}\right)^2} \quad (22)$$

where is the cutoff wavelength.

A. Multi-band Single Slot SIW Antenna

A SIW resonant single-slot antenna is shown in Fig. 7. This is a simple type of slot antenna. The coupling slot is cut on the top surface of the SIW.

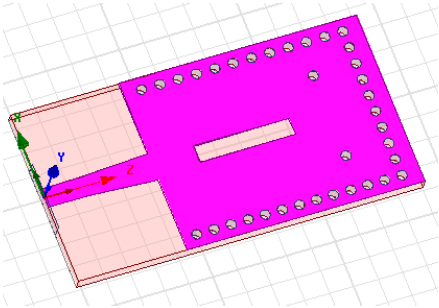
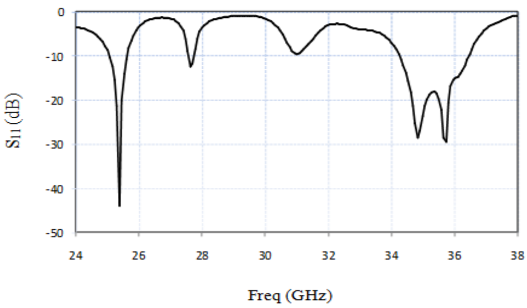


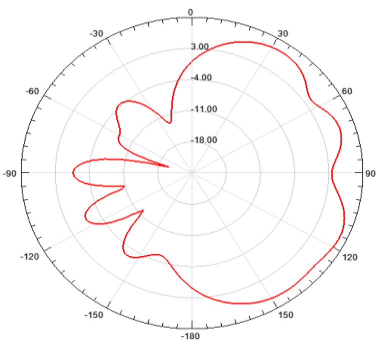
Fig. 7. SIW Single slot antenna.

The taper length L_T must be chosen as a multiple of a quarter of a wavelength in order to minimise the return loss.

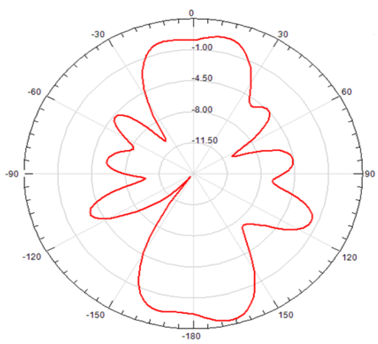
After Optimization, we can find $W_T = 2.286$ mm. The taper length is equal to L_T= 5.58 mm.

The SIW antenna is constructed into one substrate with height h = 0.508mm, dielectric constant $\varepsilon_r = 2.2$ and $tg\delta = 0.0009$, $w_{SIW} = 12.6$ mm is the width of SIW. The post diameter is D =0.8 mm and the P=1.5 mm is the cylinder spacing. The resonant length of the slot is approximately L=7.8 mm and the slot width is 1.4 mm. The SIW Slot Antenna is done with HFSS using the Finite Element Method (FEM). Simulated return losses and radiation patterns at frequency f = 25.36 GHz of the proposed antenna are shown in Fig. 8.





(a) Simulated radiation at frequency of 25.36 GHz for φ =90°.



(b) Simulated radiation at frequency of 25.36 GHz for φ =0°.

Fig. 8. Reflect ion coefficient and radiation Patterns of the SIW Single Slot Antenna.

The return losses are lower than 40 dB for 25.36 GHz and lower than 18 dB for frequency band [34.6 -35.9] GHz.

B. Two Slots SIW Array Antennas

Our next objective has been to increase the number of slots and the effect on the reflection coefficient which has been studied. The last structure with single slot has been modified to two slot array (Fig. 9). The slot lengths were to ensure good radiation, without causing end-to-end mutual coupling between adjacent slots. The distance between the two elements of the array has been chosen to be $\lambda/2$ [15]. To design the antenna array operating on the same frequencies, we used the same substrate: ROGERS RT/Duroid 5880.

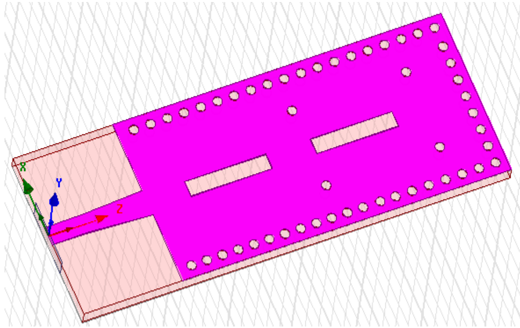
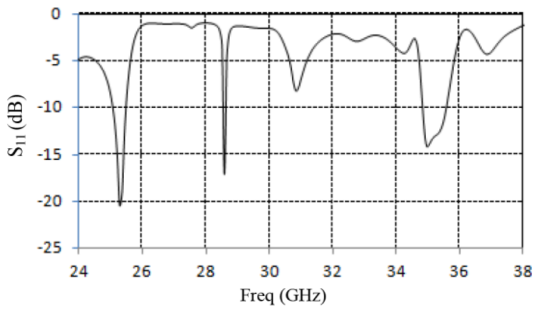
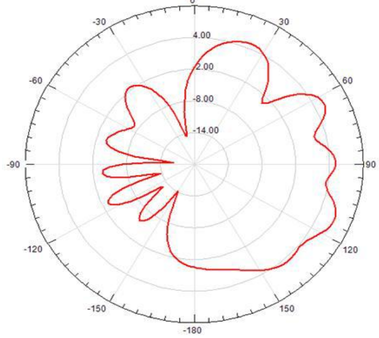
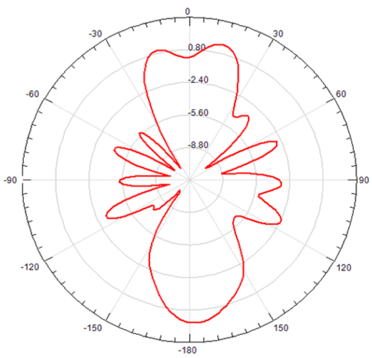


Fig. 9. Two slots SIW array antennas.





(a) Simulated radiation at frequency of 25.36 GHz for φ =90°.



(b) Simulated radiation at frequency of 25.36 GHz for φ =0°

Fig. 10. Reflection coefficient and radiation Patterns of the SIW two Slots array antennas.

The design was simulated and optimized using 3-D electromagnetic simulation software HFSS to obtain maximum radiation. The optimized dimension between two adjacent slots is 4 mm. Simulated return losses of the proposed array antennas are shown in Fig. 10.

The return losses are 20 dB for 25.4 GHz, lower than 15 dB for 29 GHz and lower than 15 dB for frequency band [34.8 -35.8] GHz.

V. Conclusion

Substrate Integrated Waveguide Multi-band Slot Array Antennas has been presented in this paper, which is integrated on a single substrate. The two slots SIW array antennas shows good performance in terms of return losses. The main characteristics of these kinds of SIW structures are low size, high power handling and easy to manufacture.

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