Compact SIW Leaky Wave Antenna

Mohamad Khalil*†, Mahmoud Kamarei*, Jalal Jomaah†‡ and Hussam Ayad†‡
*School of Electrical and Computer Engineering, University of Tehran
Email: m.khalil@ut.ac.ir ; Kamarei@ut.ac.ir
†Physics department, Faculty of sciences, Lebanese University
Email: jjomaa@ul.edu.lb ; ayhuss@web.de
‡IMEP-LAHC,Grenoble INP, Grenoble-France

***Abstract*—A compact Substrate Integrated Waveguide (SIW) Leaky-Wave Antenna (LWA) is proposed. Internal vias are inserted in the SIW in order to have narrow walls, and so reducing the size of the SIW-LWA, the new structure is called Slow Wave - Substrate Integrated Waveguide - Leaky Wave Antenna (SW-SIW-LWA), since inserting the vias induce the SW effect. After designing the antenna and simulating with HFSS a reduction of 30% of the transverse side of the antenna is attained while maintaining an acceptable gain. Other parameters like the radiation efficiency, Gain, directivity, and radiation pattern are analyzed. Finally a Comparison of our miniaturization technique with Half-Mode Substrate Integrated Waveguide (HMSIW) technique realized in recent articles is done, shows that SW-SIW-LWA technique could be a good candidate for SIW miniaturization.**

***Index terms*— Leaky-wave antenna, SIW, Slow Wave, HMSIW.**

I. Introduction

Substrate Integrated Waveguide (SIW) is a very promising technique in that we can make use of the advantages of both waveguides and planar transmission lines. As a waveguide, we can get such advantages as low loss, high Q factor, high power capability and small radiation. And as a planar transmission line, we can fabricate it with Printed circuit Board (PCB) technique which is a relatively low cost [1]. This technique is becoming a new means of signal transmission, have been the basis for the design of many circuit components. Components such as power dividers, resonator cavities, and filters that have been developed using microstrip, stripline or milled-waveguides technologies are now redesigned using the SIW platform, also patch antennas and Leaky Wave Antennas are being redesigned now using SIW [2]–[7]. The concept of planar Leaky Wave Antennas (LWAs) due to their multiple advantages like narrow and high directive beams, inherently simple feeding network, and reduced unit cell length, make us interested on this kind of structures. The low profile and easy manufacturing make them ideally suited for modern communication systems since they give high-quality performance at low cost [8]. This type of antennas is on study these last years using SIW technique, and was analyzed by [5] and then the scanning angle and gain is optimized by [4], [7], [9], good results were obtained. The criticism that has been raised about these new interconnects and components is that they possess a relatively large footprint. Research works published in [2], [3], [10]–[15] have in particular focused on the development of miniaturized components using HMSIW, Quarter Mode SIW, high permittivity, multi-layer components, Folded SIW technique. In [6], [9], [16] they focused on the miniaturization of the LWA antenna using the Half Mode Substrate Integrated Waveguide technique (HMSIW). Here in this paper we try to minimize the LWA using a new technique, by inserting the vias inside the SIW-LWA, first introduced by [17] in order to realize a compact narrow wall coupler, and recently used by [15] in order to show the potential of this technique to reduce the transversal and longitudinal size of the SIW transmission lines. here we inspect the influence of internal vias on the lateral size reduction, also on the characteristics of the LWA (Gain, radiation efficiency, scanning angle).

This paper is organized as follow. In Section II, we give a short explanation of Slow Wave Substrate Integrated Waveguide (SW-SIW) concept. In section III we give a detailed explanation of antenna design, geometry of SW-SIW-LWA. In Section IV, comparison of S-parameters, Gain, size and radiation efficiency of proposed antenna with usual LWA is given, section V shows the radiation pattern of the antenna. In Section VI, the results have been discussed briefly and analyzed, finally in section VII a small conclusion is added.

II. SW-SIW Concept

The basis of the SW-SIW-LWA is to separate the TEM field into a TE and TM fields and thus having the effect of Slow Wave. When Internal metallized via-holes is inserted inside the SIW the electric field is concentrated in the upper substrate (Substrate 1), since the electric field lines are captured by the top of the metallic vias [see Fig.1a]. On the contrary, the magnetic field flows around the metallic vias and remains present in the whole volume [see Fig.1b]. This behavior is a typical phenomenon for slow-wave transmission lines, which require a separation of electric and magnetic fields. Also from a circuit point-of-view and compared to microstrip lines or CPWs, this is similar of having a capacitance between the vias from above and the upper metalic layer, and an inductance in the lower part (substrate 2), varying the number of vias their height or radius, means a variation of the capacitance and inductance. Also this phenomen induce the variation of both the cutoff frequency and the phase velocity in the presence of internal metallized via-holes which in turn will decrease or increase the transversal and longitudinal dimension of the SIW-LWA dependent on the number of vias and their size. EM simulations will be presented in order to show effect of

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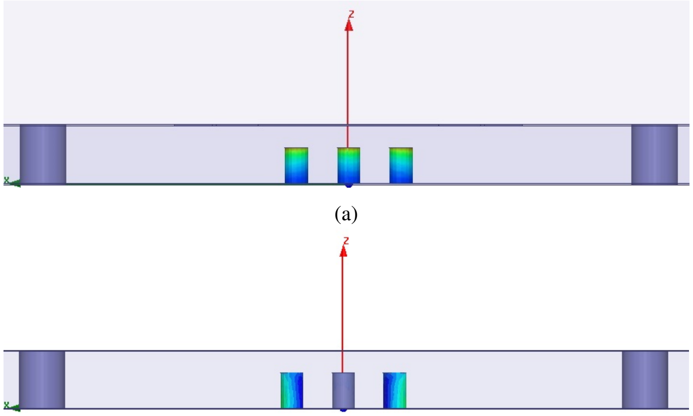

(a)

(b)

Fig. 1: Cross-section view of the SW-SIW-LWA in the middle of a transversal via-holes section for a via-diameter $400\mu m$. (a) Electric field magnitude (b) Magnetic field magnitude.

these internal vias on both the cutoff frequency and the phase velocity.

III. SW-SIW-LWA DESIGN

A top view of the proposed SW-SIW-LWA is shown in Fig.4a. This topology requires a double-layer substrate [see Fig.4b]. Lateral via-holes are connected between ground and top layer in order to define the waveguide lateral dimension, like a conventional rectangular waveguide structure, whereas internal metallized via-holes of height h_1 are connected to the Ground layer only. A detailed description of different part of our SW-SIW-LWA design will be discussed in this section.

A. SIW design

The SIW can be taken as a conventional dielectric-filled rectangular waveguide with an effective width w_{eff}, or the effective width can be approximately calculated from empirical formulas [18], the effective width of the SIW shown in Fig.4a is $w_{eff} = 10.54mm$, which is calculated from the empirical formulas in [18]. Also from [18] we calculate the diameter of the lateral vias $m = 0.8mm$ their periodicity $S = 1.6mm$, the height of the SIW is $h = 1mm$, the top metal layer and the bottom metal layer are of thickness $t = 0.017mm$, , the (substrate 1) and (substrate 2) are Rogers RT/duroid 5880 with relative dielectric constant $\epsilon = 2.2$, and dielectric loss tangent $tang(\delta) = 0.0009$. once the SIW is designed we move to the design of the LWA.

B. LWA design

The physical structure of a leaky-wave antenna consists of a leaky waveguide with a length L along which the leakage occurs. The propagation characteristics of the leaky mode in the longitudinal direction are given by phase constant β and leakage constant α , where α is a measure of the power leaked (and therefore radiated) per unit length [8] . The length of the non-tapered part of the antenna leading to 90% radiation is calculated by the formula introduced in [19] where l/λ is relatively large, and a value of 0.022 has been chosen for α/k_0 to agree well with [5]. From The formulas (1) introduced by [8] and the explanation given previously.

$$\frac{L}{\lambda_0} = \frac{0.018}{\alpha/k_0} \tag{1}$$

The value of the length of the LWA is L=220 mm at the center frequency of operation (11 GHz). In a leaky-wave antenna radiating from broad wall, leakage is obtained by periodic slots mounted on the top wall of the structure. The slot length is given by (2):

$$l = \frac{\lambda_0}{4\sqrt{\epsilon_r}} \tag{2}$$

where λ_0 is usually chosen as the wavelength at the center frequency of operation. The slot width is better to be chosen such that $w/l << 1$. The periodicity of the structure, p, is normally chosen about 1/10 of the guided wavelength to avoid multi-beam operation [4].

From what stated previously we have the slots length of a usual LWA $l = 4.45mm$ with a periodicity of $p = 2.5mm$.

Also uniform array antenna yields smallest half power beam width and also posses the largest directivity. As an improvement the side lobes power level has to be reduced and radiation efficiency has to be increased. The reduction of side lobes certainly improves the performance of antenna. Reduction in the side lobes power along with enhanced radiation efficiency and gain of the antenna is required. Non-uniform array usually posses the smallest side lobes [7] . It is desirable to compromise between side lobes and beam width. Hence, the dimensions of the slots are optimized by varying the slot length following the results obtained by [4], [5] and so we choose to have non-uniform slots one of a length $L_{s1} = 6mm$ and the other of a length $L_{s2} = 4.55mm$, L_{s1} and L_{s2} are distant one from the other with a distance p and repeated periodically on a distance of 220mm, the width of the slots is $w_s = 0.45mm$.

On the other hand our periodic LWA is designed to radiate (due to periodicity of the slots) in the forward region ($0 < \theta_0 < \frac{\pi}{2}$) so the fundamental space harmonic $\beta_0(\omega)$ is a slow wave, and $\beta_{-1} > 0$.

C. Transition design

The vias are also considered under the microstrip tapered sections Figure (2) in order to concentrate the main part of the electric field in the upper substrate which facilitate the propagation of the EM field into the SW-SIW. The microstrip line width was optimized to obtain a $50-\Omega$ characteristic impedance ($L_w = 3.1mm$). The tapered sections of length L_{tap} and W_{tap} width, were then optimized to improve the return loss ($L_{tap} = 15.37mm$ and $W_{tap} = 4.7mm$).

D. SW-SIW-LWA design

Finally in order to miniaturize our SIW-LWA we introduce vias inside the SIW, as stated previously and shown Figure (1-4) the vias have the role to separate the Electromagnetic wave into a TE and TM waves which induced the Slow-Wave effect, also a capacitance is formed between the top layer

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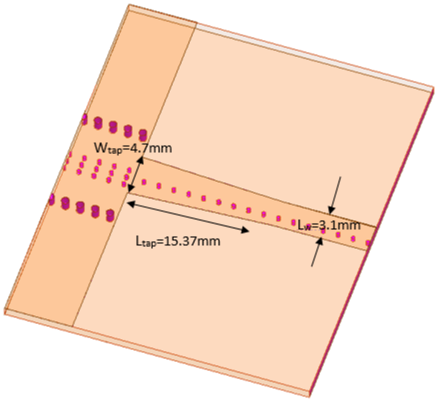

Fig. 2: Microstrip to SIW transition

and the top of the vias and an inductance around the vias where the variation of their dimensions lead to the variation of the capacitance and inductance and the variation of the cut-off frequency and wave velocity, the complete structure is shown Figure (3). Since the simulation take a considerable

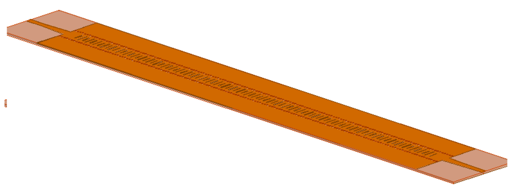

Fig. 3: Complete structure of SW-SIW-LWA

time (simulation for 3-vias with height $h_1 = 0.8mm$ the time consumed is one week with a computer of 32Gb RAM) and based on the results of [15], the diameter of the vias for the structure of three vias is fixed to $d = 0.4mm$ and the spacing between the vias is $v = 0.9mm$. The effect of slow wave is basically due to the height of the vias and their number so we only vary the height of the vias from 0.4mm to 0.8mm with a step of 0.2mm. Also the simulations are done for two different number of vias one with one row, and the other with three rows, each row contain 157 vias, with periodicity $v_p = 1.6mm$. For the structure of one row we inspect the variation of the diameter and the results are shown Figure (5).

IV. Simulations results

A. S-parameters

Full-wave EM simulations were carried out with a classical microwave computer-aided design (CAD) tool HFSS. The SW-SIW-LWA shown in Figure (4) was simulated. The transmission coefficient S_{21} and reflection coefficient S_{11} are shown in Figures [(5a) and (5b)] respectively . Reflection coefficient S_{11} lies below -10 dB in the band (from 7.8- 9.7 GHz for $h_1 = 80\%$ and 3-vias inserted). The lower cut-off frequency is approximately 7.8 GHz. S-parameters of proposed SW-SIW-LWA has been compared with LWA without internal vias whose cut-off frequency was 11GHz, so the cut-off frequency

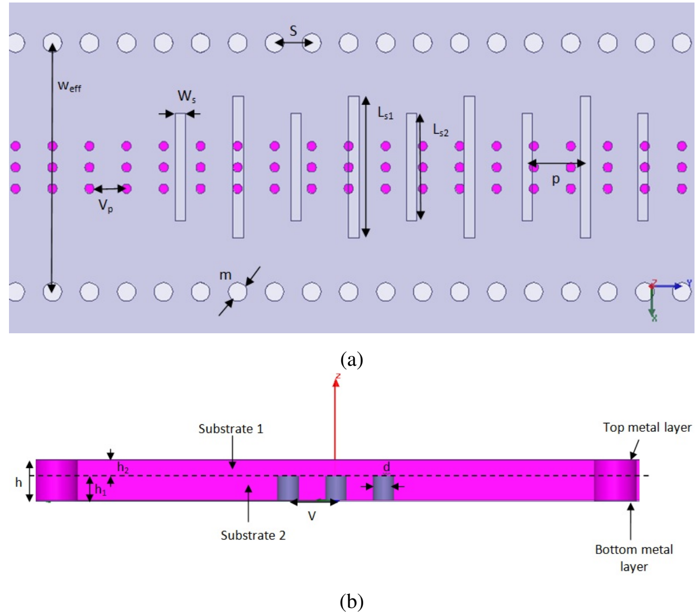

Fig. 4: Shematic view of the proposed SW-SIW-LWA (a) Top view (b) cross-sectional view (Example with 3 internal vias)

is reduced for 30%. Also the effect of the number of vias was observed as we can see from Figure (5b) for the same height of vias ($h = 80\%$) the SW-SIW-LWA with 3 rows internal vias have a cut-off frequency of 7.8GHz where as for the same antenna with one rows internal vias the cut-off frequency is 9.9GHz. The diameter of the vias for the structure of one row is increased from 0.2mm to 0.4mm, increasing the diameter, also give us a good miniaturizing factor see figure (6), the cut-off frequency decrease, and is almost near to that of the structure with 3 rows of vias.

B. Velocity

The phase velocity of an SIW could be the same of a regular rectangular waveguide (3).

$$v_\phi = \frac{\omega}{\beta} = \frac{c_0}{\sqrt{\epsilon_{eff}(1 - (\frac{f_c}{f})^2)}} \tag{3}$$

But our SIW is formed of 2 layers "substrate 1" with $\epsilon_r = 2.2$ and "substrate 2" having the same ϵ_r of the first but with the difference that vias are embedded inside. So we have to calculate ϵ_{eff} that correspond to the new SIW that have two layers. An empirical formula in [15] was derived but have a clear shift from the values obtained from HFSS. Here we only show the values of HFSS and see how the velocity is decreasing while introducing the vias. The method of calculating ϵ_{eff} is left for a latter paper.

As it was stated before our antenna is a periodic LWA, and the wave inside is a slow wave, that what we can see Figure (7). For an SIW-LWA where no vias inside v_ϕ/c_0 is already very small ($v_\phi/c_0 < 0.0216$), by introducing the vias inside, with the best case of height of vias $h_1 = 80\%$ (Since the larger the ratio (h_1/h), the smaller the phase velocity is, which is

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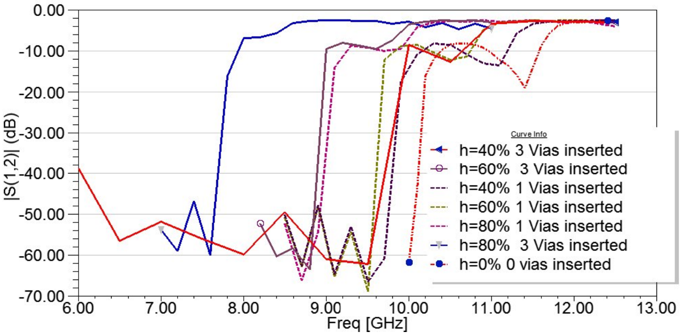
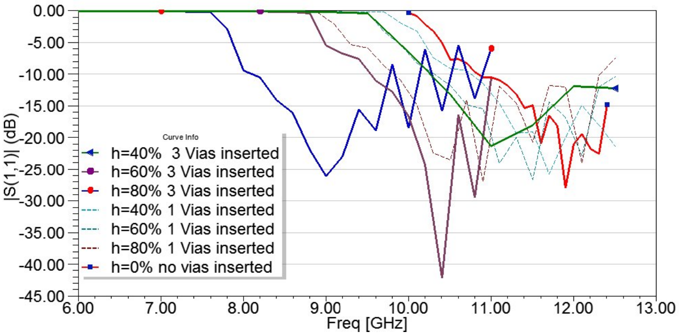


(a)



(b)

Fig. 5: S-parameters of SW-SIW-LWA (a) transmission coefficient (b) reflection coefficient (Example with 3 internal vias and 1 internal vias)

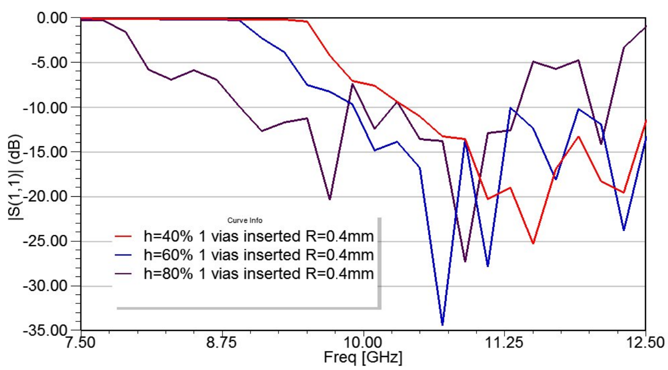


Fig. 6: Reflection coefficient S_{11} for SW-SIW-LWA with one vias inserted and radius of 0.4mm

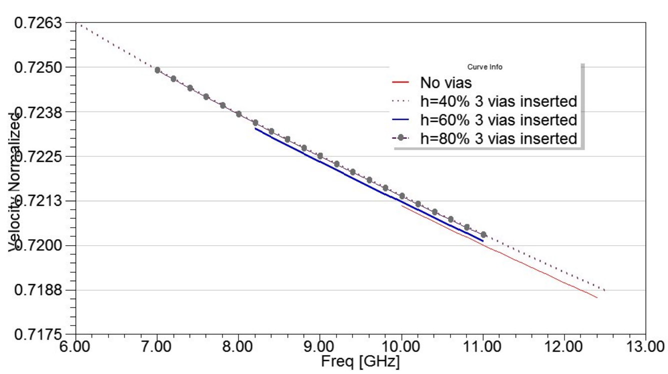


Fig. 7: velocity

due to an increase of the capacitive coupling between the top of the internal vias and the top metal layer [15]) and having 3-vias, the velocity is almost the same.

C. Radiation efficiency

Theoretically radiation efficiency e_r of slotted rectangular waveguide [5] can be calculated by .

$$e_r = \frac{\alpha_l}{\alpha_l + \alpha_d + \alpha_c} \tag{4}$$

where α_c is conductor loss of SIW, α_l is leakage loss and α_d is dielectric loss. Method of theoretical calculation of radiation efficiency (e_r) is explained in [5]. The plot for the radiation efficiency of proposed structure obtained from HFSS is shown and compared with Slow Wave Substrate integrated Waveguide leaky wave antenna in Figure (8). The radiation efficiency of SW-SIW-LWA antenna is obtained from HFSS by simulating the structure as shown in Figure (4). At a frequency that is close to cut-off frequency, the radiation efficiency is maximum. As frequency increases, radiation efficiency decreases and it continuously decreases till the beam scans near to end-fire. Comparison of radiation efficiency of proposed SW-SIW-LWA with SIW-LWA is shown in Figure (8). As the height of the vias inside the LWA increases, the efficiency decreases and that is caused by the concentrated electric field between the vias and the top metal layer, what induces more conduction and dielectric losses. Inside SIW without vias the losses are less because of the spread of the EM field inside the SIW.

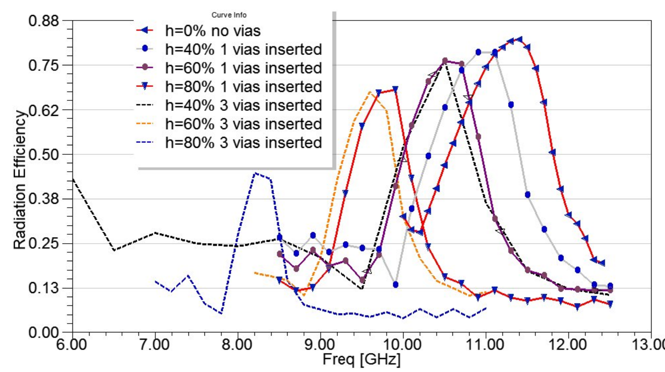


Fig. 8: Radiation efficency compared with the normal SIW-LWA

Also the effect of number of vias is shown Figure (8), the number of vias have a direct effect on the radiation efficiency. Comparing the structure of 3-vias with the one of 1-vias at a height of $h_1 = 40\%$, the 1-vias structure is more efficient but we must consider the reducing factor of the cut-off frequency that is larger for the one of 3-vias.

D. Gain and Directivity

The realized gain of the SW-SIW-LWA with 3 internal vias, with height $h_1 = 40\%, 60\%, 80\%$ is shown in Figure (9a) compared with the one that have no vias inserted, we can see that Realized gain of SW-SIW-LWA is decreasing while the height of vias is increased, we have a losses of 3dB between

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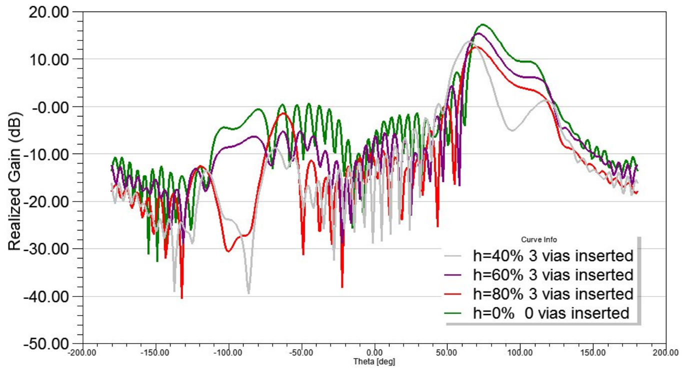
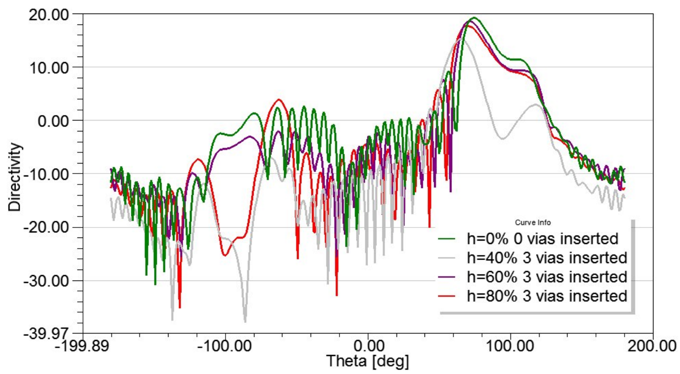


(a)



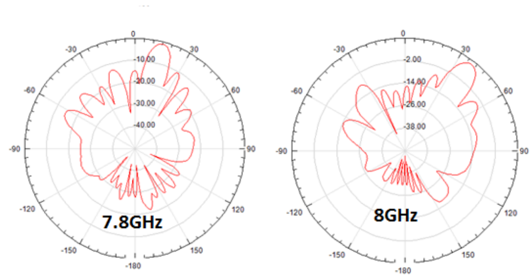
(b)

Fig. 9: (a) Realized Gain of the SW-SIW-LWA with 3 vias inserted with height of $40\%, 60\%, 80\%$ compared to usual SIW-LWA (no vias inserted) (b) directivity of the SW-SIW-LWA with 3 vias inserted with height of $40\%, 60\%, 80\%$ compared to usual SIW-LWA (no vias inserted)

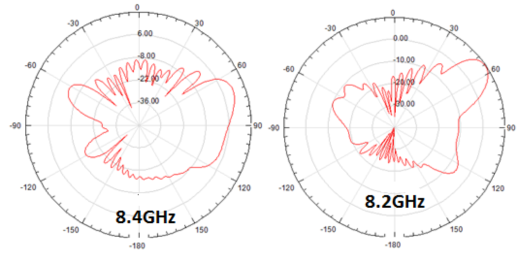
the SW-SIW-LWA with height of $h_1 = 80\%$ and that of usual SIW-LWA, and that's what was expected since the efficiency of the SW-SIW-LWA is decreased. The opposite is for the directivity, for SW-SIW-LWA with 3-vias of $h_1 = 80\%$ the directivity is increased and that's what we are expecting and was explained before section III.

V. Radiation Pattern

In Figures (10) the radiation patterns of the main beam has been shown. It is seen that the beam scans with frequency. The main beam scans from near broadside to near end-fire in frequency range 7.8-8.4 GHz. At the frequency 7.8 GHz beam starts scanning from near broadside. At 7.8 GHz near broadside, radiation efficiency is very poor that is very clear from Figure (8). As frequency increases beam scans in same quadrant and reaches near 40° shown in Figure (10a). When frequency increases up to 8.4 GHz beam scans near to end-fire. These results are simulated on HFSS. As frequency increases leaky mode scans very close to end-fire, the main beam of leaky mode turns into surface wave mode. The slow wave or surface wave does not participate in radiation when their is no periodic slots.



(a)



(b)

Fig. 10: Radiation pattern of our SW-SIW-LWA(a)Pattern near end-fire and Pattern at 60° (b) Pattern near broadside and Pattern at 40°

VI. Results

The simulations designed by inserting the vias inside the SIW-LWA have showed that the antenna could be miniaturized, but compromise must be done in order to maintain good radiation efficiency, also the reduction of size in the longitudinal dimension is not applicable for LWA , since the antenna in basics work in the slow wave range for forward radiation and must be in the fast wave mode for backward radiation and good efficiency. Comparison of the SW-SIW-LWA with different other LWA miniaturized using HMSIW technique is showed Table (I), shows that this technique have good a miniaturization factor, compared to [6], [16] but have a disadvantage, is that it isn't able to scan in the backward mode as in [9] since introducing the vias will transform the fast wave into a slow wave.

VII. Conclusion

Here in our paper we have designed a Slow Wave Substrate Integrated Waveguide Leaky wave Antenna (SW-SIW-LWA) and simulations where done with HFSS. We have demonstrated that by introducing vias inside the SIW-LWA we can miniaturize it's size in the lateral sides but no significant reduction in the longitudinal side since periodic LWA already works in the slow wave region. The percentage of miniaturizing is dependent on the number of the vias their height and diameter. A compromise must be done between the percentage of miniaturizing and radiation efficiency since while decreasing the cut-off frequency the losses are increasing, because the EM field is more confined.

Structure	Antenna type	Scanning type	FW-BW scanning/broadside	Bandwidth(GHz)	Gain(dB)	Lateral size(mm)
[9]	IDC-HMSIW	Freq. scanning	Yes/Yes	7.4-13	7.48-12	12
[16]	HMSIW	Freq. scanning	2^{nd}quadrant /No	8-9.2	13.2-16.32	23
[6]	HMSIW	Fixed freq.	No/Yes	5.6	9.4-12.23	27.6
This work	SW-SIW	Freq. scanning	2^{nd} quadrant /Yes	7.8-8.4	7$\sim$14	40

TABLE I: Comparison of miniaturized SW-SIW-LWA with HMSIW-LWA

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