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Improved design of a SIW long slot leaky wave antenna with low SLL

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Amin Mahmoodi Malekshah[1], Mohammad Saeed Majedi[2] ✉, Amir Reza Attari[2]
[1]*Computer and Communications Research Center, Ferdowsi University of Mashhad, Mashhad, Iran*
[2]*Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran*
✉ *E-mail: majedi@um.ac.ir*

Abstract: This study presents a new design for the substrate integrated waveguide (SIW) long slot leaky wave antenna (LWA) with narrow beam, low side lobe level (SLL) and low cross-polarisation. To meet these specifications, the changes of phase constant, β, along the structure are compensated, the required leakage constant, α_r, is determined more accurately by considering the loss and a straight slot along the antenna is used. In order to calculate the leakage constant of the leaky-mode more accurately, thru-reflect-line method along with HFSS simulations is used. By properly determining the shape of SIW walls, the amount of leakage along the slot and the phase constant can be controlled. This results in a desired aperture amplitude and phase distribution. The presented LWA realises a Taylor distribution with a predefined SLL of −25 dB. Such a design also leads to a low cross-polarisation level and narrow beam at centre frequency of 17 GHz. The measurement results are consistent with the simulation results.

1 Introduction

Longitudinal long slot leaky wave antennas (LWAs) present many interesting properties in microwave and millimetre wave applications due to their narrow beamwidth, low profile, simple configuration and easy fabrication [1–3].

The most significant drawback of conventional long slot LWAs is their high side lobe level (SLL). By properly tapering the aperture field distribution, a lower SLL can be achieved. This tapering can be realised by meandering or changing the width of the slot [1]. However, changing the slot curvature or width generates two orthogonal field components in the slot aperture which leads to a higher cross-polarisation level. By meandering the substrate integrated waveguide (SIW) wall and using a straight slot, a low cross-polarisation far field pattern is obtained [4]. The measured SLL and cross-polarisation level of the antenna presented in [4] are −29.3 and −30 dB, respectively. In [5], low SLL and cross-polarisation are achieved by using a straight slot and a meandered ridge in the waveguide. Changing the distance of the slot from the sidewalls in [4] or the distance of the ridge from the slot in [5] changes both the leakage rate and phase constant along the structure. Since the leaky-mode phase constant determines the radiation angle, hence its variation along the antenna causes different sections of the antenna radiate at different angles and this broadens the antenna main lobe. Therefore it is important to find the geometrical parameters of the antenna in such a way that control not only the leakage rate, but also the phase constant along the structure. The authors in [6–8] establish a design procedure to modify the leakage constant of the excited leaky wave mode, while keeping its phase constant unchanged. This design procedure realises the desired distributions for α_r and β by changing the offset and width of the slot. Similar procedure is used in [9, 10] to simultaneously control the leakage and phase constants of the recently proposed LWA [11, 12]. The structure of the proposed antenna is based on SIW with one of its electric walls replaced with a partially reflected wall. The leakage and phase constants are controlled by properly changing the SIW width and separation between vias. In [13] asymmetrical ridged SIW LWA with a straight slot is designed. The ridge position is transversally varied to make a desired α_r and β distributions. It realises a Taylor pattern with a SLL of <−28 dB. Since the presented antenna in [13] needs different heights for ridges and SIW sidewalls, hence a double layer or multilayer SIW structure is used.

Several types of SIW LWAs have been investigated recently due to their advantages including simple structure, low profile, low cost and ease of fabrication and integration with planar circuits. Long slot SIW LWAs with the single layer and double layer are investigated in [4, 13]. Lossy properties of the SIW structure have a significant effect on the antenna performance. In the lossless case, the required leakage constant along the antenna can be obtained through a relation which is the function of the desired amplitude distribution and the fraction of absorbed power by the load [3]. This relation is also approximately true for low loss antennas; however, for the structures with higher loss, a modified relation should be used [14].

The main goal of this paper is to improve the design procedure for uniform LWAs. This improvement is obtained by determining the required α_r along the slot more accurately by considering the loss, calculating the α_r of the slotted structure more precisely by the thru-reflect-line (TRL) method [15] and compensating β along the slot. To verify the presented design procedure, a single layer SIW low SLL LWA is designed with a Taylor aperture distribution and compensated phase profile. This antenna consists of a straight long slot at the broad wall of the waveguide. By properly changing the offset of the slot and width of the SIW along the structure, a fixed phase constant and a desired leakage rate can be achieved to make the desired radiation pattern. These changes in the offset and width are realised only by changing the shape of SIW walls.

The theory of designing a long slot LWA with specified propagation constant parameters for lossless and lossy cases is expressed in Section 2. Section 3 describes the design procedure of a LWA with Taylor amplitude and linear phase distribution. Section 4 presents the simulated and measured results of this antenna. It is shown that the theoretical, simulation and measurement results are consistent with each other.

2 Theory

2.1 LWA theory

The propagation mechanism of the leaky-mode in a LWA is determined by the amplitude and phase of this mode in the longitudinal direction which are represented by the leakage

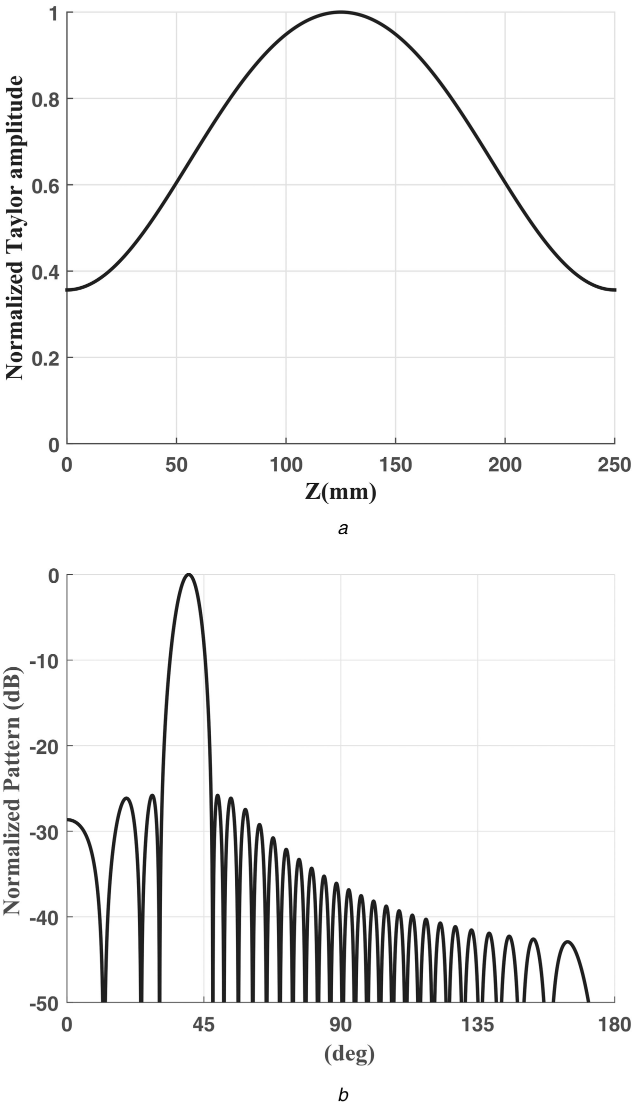


Fig. 1 *−25 dB Taylor distribution*
(a) Normalized amplitude and
(b) Corresponding normalised radiation pattern

constant, α_r, and the phase constant, β. The phase constant is related to the pointing angle of the radiation pattern from the endfire, θ_m, as [3]

$$\cos\theta_m = \frac{\beta}{k_0} \tag{1}$$

and HPBW, $\Delta\theta$, of the antenna radiation pattern can be obtained as [3]

$$\Delta\theta \simeq \frac{1}{(L/\lambda_0)\times\sin\theta_m} \tag{2}$$

in which λ_0 is the free-space wavelength and L is the length of the LWA. The aperture amplitude distribution plays the most important role in controlling the SLL of the radiation pattern. This aperture illumination is achieved by adjusting the leakage constant along the antenna length. The power distribution along the antenna for a travelling wave is in the form of

$$P(z) = P(0)\exp\left[-2\times\int_0^z \alpha(\zeta)\,\mathrm{d}\zeta\right] \tag{3}$$

in which $P(0)$ is the input power at $z = 0$. The attenuation constant of α is equal to the leakage constant of α_r in the lossless case. Using this formula a relationship between $\alpha_r(z)$ and the desired amplitude distribution, $A(z)$, can be obtained as [3]

$$\alpha(z) = \alpha_r(z) = \frac{(1/2)|A(z)|^2}{(1/(1-R))\int_0^L |A(\zeta)|^2\,\mathrm{d}\zeta - \int_0^z |A(\zeta)|^2\,\mathrm{d}\zeta} \tag{4}$$

where $R = P(L)/P(0)$ is the fraction of power that is absorbed by the load at $z = L$. The effects of ohmic losses on the radiation properties are studied in [3]. In this case, the power distribution along the antenna can be written as (3), but unlike lossless case, the attenuation constant is sum of the leakage constant, α_r, and the loss constant, α_l. A different closed-form expression for the required leakage rate distribution is obtained as [14]

$$\alpha_r(z) = \frac{(1/2)|A(z)|^2 e^{2\alpha_l z}}{(1/\eta)\int_0^L |A(\zeta)|^2\,\mathrm{d}\zeta - \int_0^z |A(\zeta)|^2 e^{2\alpha_l z}\,\mathrm{d}\zeta} \tag{5}$$

where η is the radiation efficiency. After determining the required $\alpha_r(z)$ along the antenna, it should be applied to the LWA. For this purpose, calculation of the leakage constant of a uniform LWA is needed. In the next subsection this will be explained.

2.2 Calculation of leakage constant of a LWA

Assuming very small $|S_{11}|$, the leakage constant of a lossless uniform LWA with the length of L can be achieved by the following expression [16]:

$$\alpha_r \simeq -\frac{\ln|S_{21}|}{L} \tag{6}$$

To obtain α_r from the above equation, we use the HFSS full-wave simulator and set the dielectric and conductor losses equal to zero. It should be noted that due to the effect of discontinuity at the beginning and the end of the slot, which is increased for a larger offset, the assumption of small $|S_{11}|$ is not fulfilled. To reduce the effect of the discontinuities and realise the condition of small $|S_{11}|$ for calculating leakage constant, we add a tapering transition part at the beginning and end of the slot. These added parts make an error in calculation of leakage constant. Hence to eliminate the effect of them, the TRL method is used. In this method the scattering parameters of the Thru and Line connections (in our case, the structure with different lengths of l_1 and l_2) are denoted by [T] and [L] matrices, respectively. Then $e^{\gamma\Delta L}$ (where $\gamma = \alpha + j\beta$ and $\Delta L = l_2 - l_1$) can be calculated by (7) [15]

$$e^{\gamma\Delta L} = \frac{L_{21}^2 + T_{21}^2 - (T_{11} - L_{11})^2 \pm \sqrt{\left[L_{21}^2 + T_{21}^2 - (T_{11} - L_{11})^2\right]^2 - 4L_{21}^2 T_{21}^2}}{2L_{21}T_{21}} \tag{7}$$

Since $|S_{11}|$ is very small, then (7) is simplified into L_{21}/T_{21} or T_{21}/L_{21}, depending on choice of sign. If $|T_{21}| > |L_{21}|$, the solution for α in terms of L_{21}, T_{21} and ΔL is as follows:

$$\alpha = \frac{1}{\Delta L}\times\ln\left(\frac{|T_{21}|}{|L_{21}|}\right) \tag{8}$$

3 Design procedure

Our goal is to design a SIW long slot LWA with Taylor amplitude distribution for −25 dB SLL which has a fixed phase constant along the slot. The beam pointing angle of this antenna should be $\theta_m = 40^\circ$ at the centre frequency of 17 GHz. The length of slot is set to $l_s = 250$ mm. The substrate which is used is RO4003 with $\varepsilon_r = 3.55$, $\tan\delta = 0.0027$ and $h = 0.813$ mm. The required amplitude distribution along the slot and its corresponding radiation pattern are shown in Fig. 1.

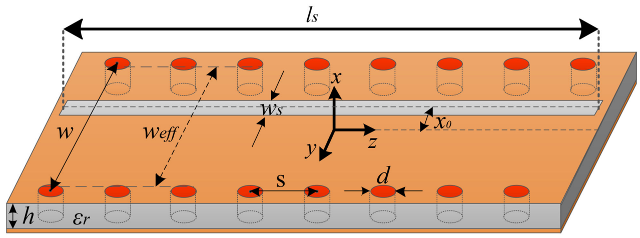


Fig. 2 *Geometry of straight long slot LWA based on the SIW structure*

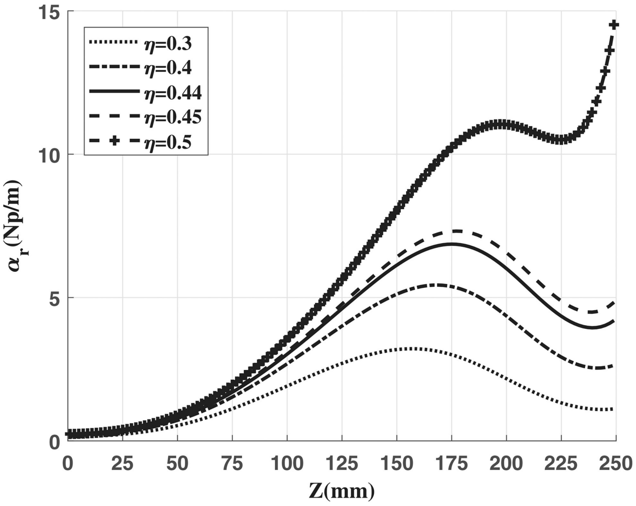
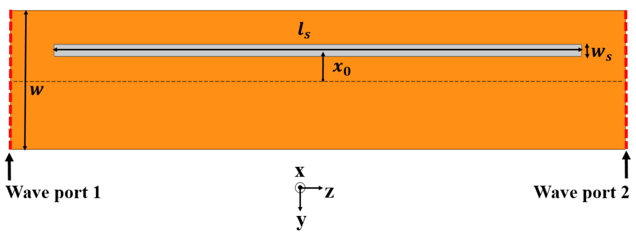
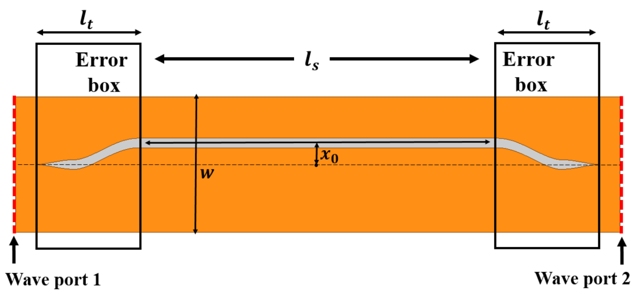


Fig. 3 *Required leakage constant along the slot for different values of antenna efficiency to achieve Taylor distribution with −25 dB SLL*



a



b

Fig. 4 *Prototype of the long slot LWA for calculating*
(a) β and
(b) α_r

As is explained in Section 2.1, using (5) along with the required amplitude distribution, $\alpha_r(z)$ along the antenna length can be determined. However for using (5), we need to obtain α_l. For this purpose first we must determine the structure of the antenna. The general structure of a SIW with a long slot on its top plane is shown in Fig. 2. The SIW parameters are $s = 2$ mm and $d = 1$ mm. In this SIW structure, α_l results from dielectric loss, α_d, and conductor loss, α_c. These parameters can be approximately obtained by theoretical relations in [15] for a closed rectangular waveguide. In this paper, for better accuracy we simulate a SIW

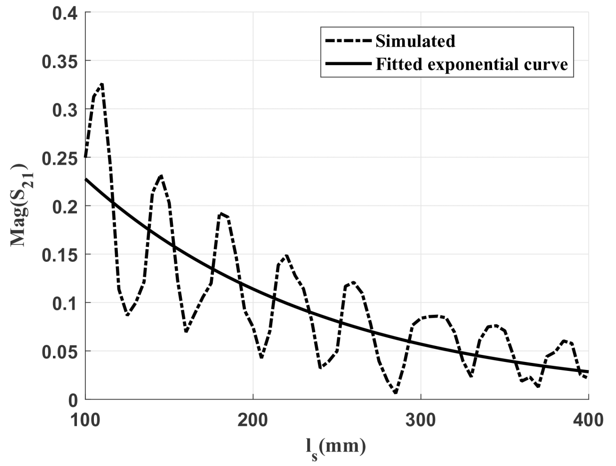


Fig. 5 *Magnitude of S_{21} as a function of and its exponentially fitted curve for $w = 5.6$ mm and $x_0 = 0.4$ mm*

structure without the slot to obtain α_l. To do so, the width of this waveguide is set to the mean value of widths which are required for the realisation of α and β. As it will be seen later this mean width is equal to 5.4 mm and hence the calculated α_l is 2.42 Np/m. Using this value in (5), Fig. 3 shows a comparison between the required $\alpha_r(z)$ distribution for lossy waveguides with different values of antenna efficiency. As it will be shown later, the maximum calculated leakage constant of the structure for $\theta_m = 40^{\circ}$ is about 7 Np/m. Regarding to this value and according to Fig. 3, the maximum efficiency that can be achieved is about $\eta = 0.44$.

Now the geometrical parameters of the structure should be tuned to realise the required amplitude and phase distributions. In this structure the offset, x_0, width of the waveguide, w, and width of the slot, w_s, are our choices to adjust the amplitude and phase distribution along the slot. In order to have a low cross-polarisation, we do not change w_s along the slot and set it to 0.6 mm. To choose suitable values for x_0 and w, accurate behaviour of α_r and β versus these parameters are needed. The dispersion characteristics of a SIW is approximately the same as that of a rectangular waveguide with an equivalent width of [17]

$$w_{\text{eff}} = w - \frac{d^2}{0.95 \times s} \tag{9}$$

So we use the equivalent rectangular waveguide to study α_r and β behaviour. The phase constant is simply obtained by using the simulated radiation pattern of the straight slot antenna of Fig. 4*a* along with (1). The leakage constant is achieved by the method explained in Section 2.2 and the antenna of Fig. 4*b* which has two small tapering transition parts of length l_t at the beginning and the end of the slot. For example, Fig. 5 shows the simulated $|S_{21}|$ as a function of l_s for $w = 5.6$ mm and $x_0 = 0.4$ mm. As can be seen, by changing l_s, the $|S_{21}|$ does not change exponentially and has an oscillating behaviour. In fact there is an unwanted mode in addition to the main leaky mode [5]. These modes have constructive/destructive effects on each other along the antenna which causes this oscillating behaviour. Hence using (8) leads to different values of α_r for different values of ΔL. To omit the oscillating behaviour of $|S_{21}|$ and obtaining an exponential curve, we simply use a curve fitting tool of MATLAB. This exponentially fitted curve is shown by the solid line in Fig. 5. Now α_r can be calculated by putting two arbitrary lengths of l_1, l_2 and their corresponding values of $|S_{21}|$ into (8).

Fig. 6 shows α_r and β/k_0 for different values of x_0 and w. As is seen, for a fixed width, the offset variation can provide an appropriate α_r distribution for our design; however, it makes a considerable change in β along the antenna. It is not appropriate for the phase constant to change along the antenna, because different sections of the slot radiate at different pointing angles and hence it broadens the beamwidth of the antenna. With regard to the

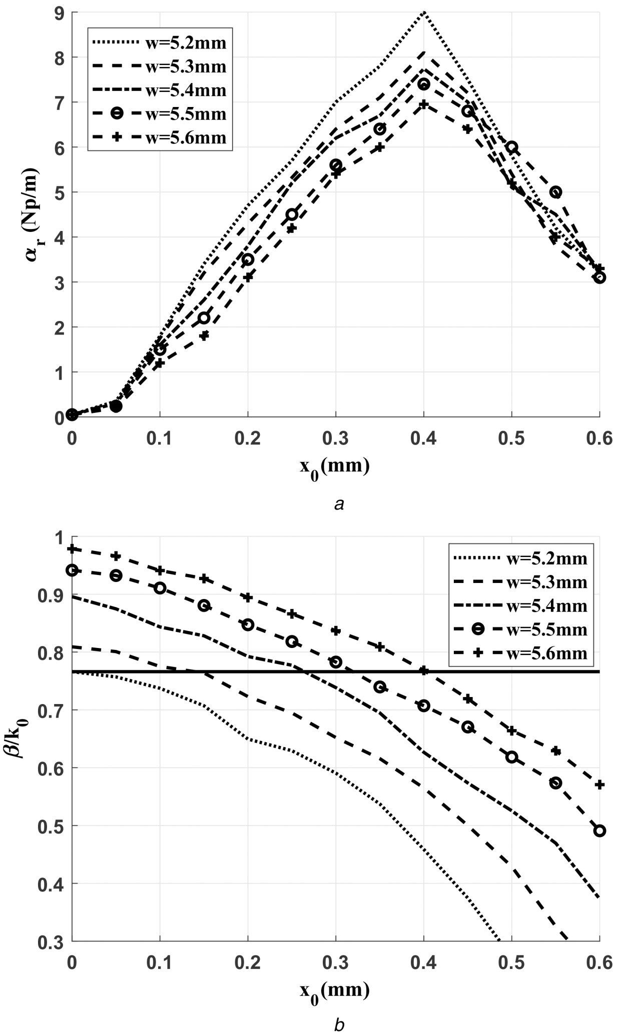


Fig. 6 *Propagation constant for different values of x_0 and w*
(a) Leakage constant and
(b) Phase constant

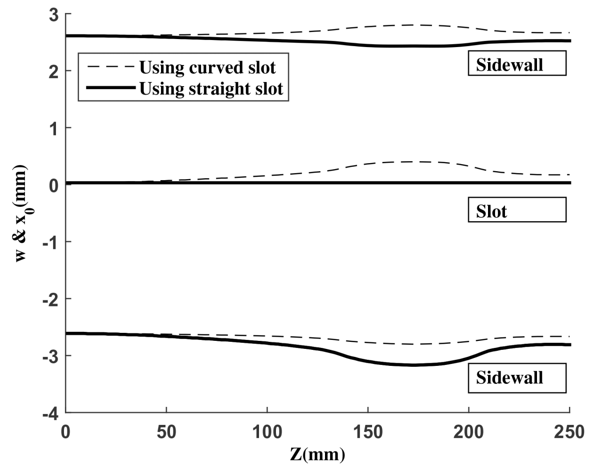


Fig. 7 *LWA walls and slot curves*

predefined main beam angle and by using (1), the required β/k_0 will be about 0.77. Also with the aid of Fig. 3, the required $\alpha_r(z)$ along the slot is determined. Hence Fig. 6 can be used to specify the proper values for x_0 and w along the slot in such a manner to achieve the required amplitude distribution and appropriate fixed phase constant.

In Fig. 7 the place of SIW walls and the slot of the designed antenna are shown as dashed curves. Two upper and lower lines are the wall curves and the middle line represents the slot. After flatten

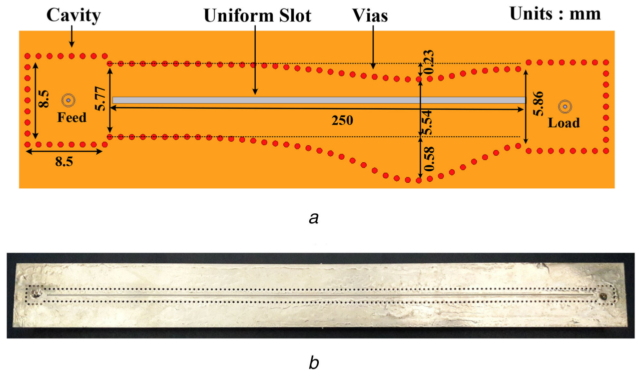


Fig. 8 *Geometry of the SIW long slot LWA*
(a) Schematic geometry (not to scale) and
(b) Fabricated antenna

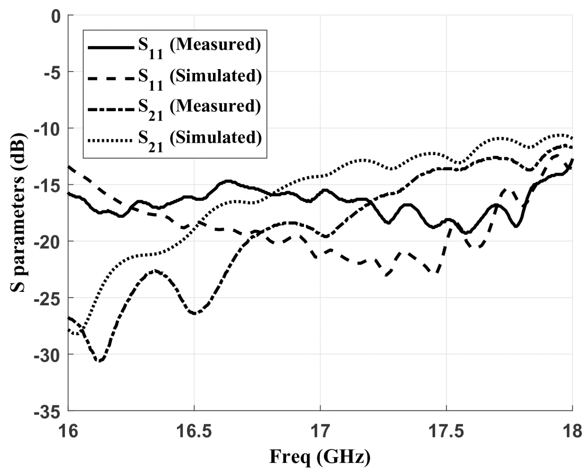


Fig. 9 *Measured and simulated scattering parameters*

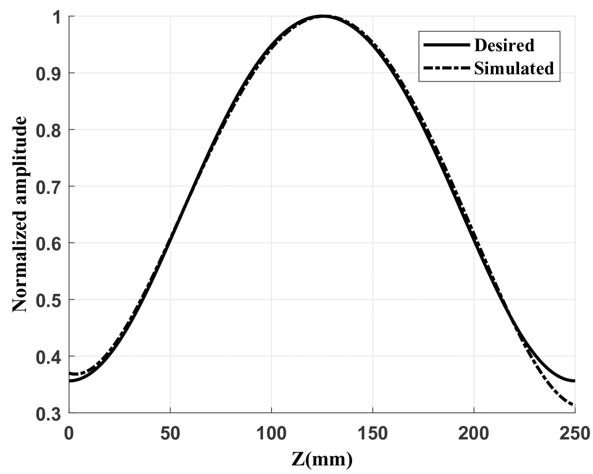


Fig. 10 *Normalised aperture amplitude distribution*

out the slot, the final antenna wall and slot curves are formed which are shown as solid lines in Fig. 7.

4 Simulated and measured results

Based on the design procedure described in the previous section, a SIW straight long slot LWA is designed, simulated in HFSS and fabricated. Geometry of this antenna with dimensions along with the fabricated prototype is shown in Fig. 8. As can be seen a SIW cavity structure is used for feeding and terminating the antenna. Fig. 9 shows the simulated and measured results of S_{11} and S_{21} parameters. There is a good agreement between the simulation and measured results. Figs. 10 and 11 compare the desired amplitude and phase distribution with the full-wave simulation results at 17 GHz, respectively.

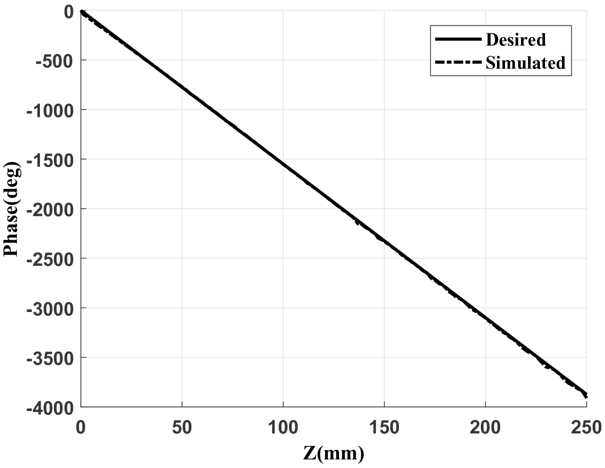


Fig. 11 *Aperture phase distribution*

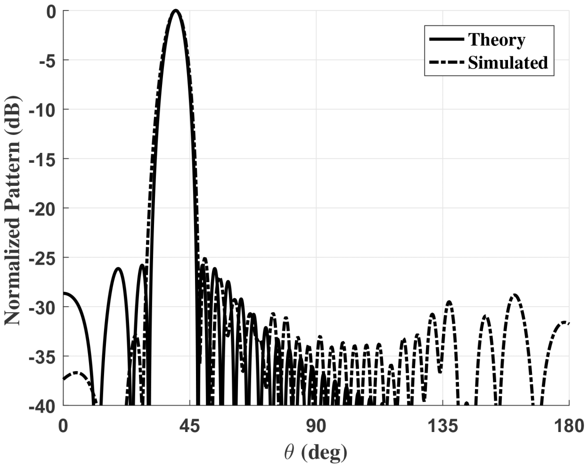


Fig. 12 *Comparison of theoretical and simulated normalised radiation patterns*

Table 1 Theoretical and simulated characteristics of the antenna at 17 GHz

	Theory	Simulated
SLL, dB	−25	−25.1
beam direction, deg.	40	39.8
HPBW, deg.	6.86	7.3
efficiency	0.44	0.43

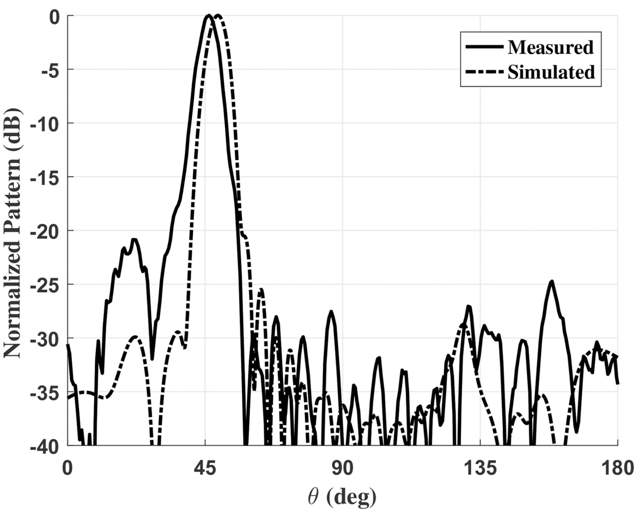


Fig. 13 *Normalised radiation pattern at 16.5 GHz*

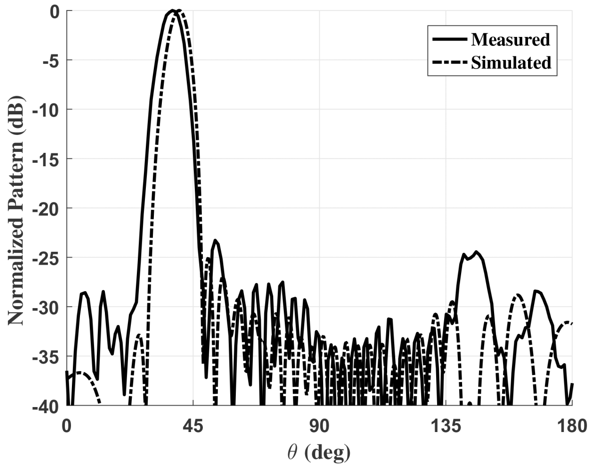


Fig. 14 *Normalised radiation pattern at 17 GHz*

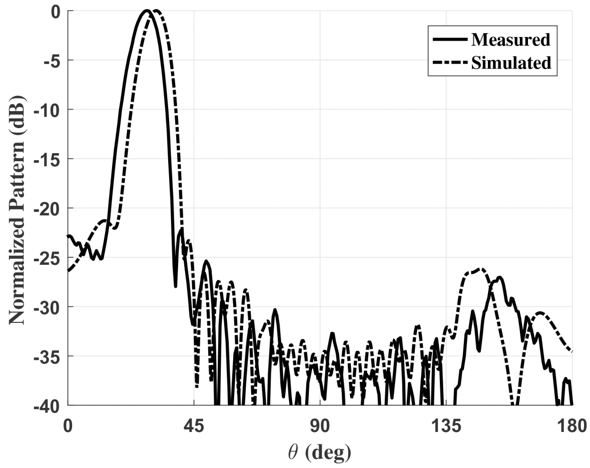


Fig. 15 *Normalised radiation pattern at 17.5 GHz*

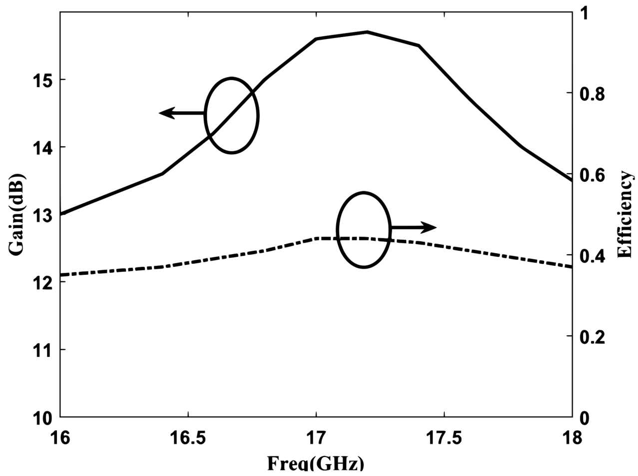


Fig. 16 *Simulated gain and radiation efficiency of the antenna*

Fig. 12 compares the theoretical and simulated normalised radiation pattern of the antenna at 17 GHz. Comparison between the theoretical and simulated results of the SLL, beam direction and HPBW at 17 GHz is listed in Table 1. Theoretical pattern characteristics presented in Fig. 12 and Table 1 are obtained based on the desired Taylor distribution. As can be seen, the simulated results are in good agreement with the theoretical characteristics. Figs. 13–15 compare the results of measured and simulated normalised radiation patterns at 16.5, 17 and 17.5 GHz. Fig. 16 shows the simulated gain and radiation efficiency of the antenna. Table 2 compares the measured and simulated SLL, beam direction, gain and HPBW for three frequencies of 16.5, 17 and 17.5 GHz. Good agreements are obtained between the measured

Table 2 SLL, beam direction, gain and HPBW of simulated and measured radiation patterns of the antenna at 16.5, 17 and 17.5 GHz

	16.5 GHz		17 GHz		17.5 GHz	
	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.
SLL, dB	−25.5	−20.8	−25.1	−23.2	−21.3	−22.3
beam direction, deg.	49.2	46.3	39.8	37.6	31.6	28.5
gain dB	13.8	14.4	15.6	15.3	15.5	15.7
HPBW, deg.	6.9	6.3	7.3	8.4	9	9.2

Table 3 Theoretical and simulated radiation pattern characteristics of the presented antenna and some other antennas

	Slot length	SLL, dB		HPBW, deg.	
		Theory	Sim.	Theory	Sim.
[1]	$20 \times \lambda$	−31.5	−40	4	6
[4]	$13.4 \times \lambda$	−35	−29.3	9.5	13.9
[6]	$10 \times \lambda$	−23	−20	9.5	9.5
[7]	$10 \times \lambda$	−26.5	−20	8.8	N/A
[12]	$13 \times \lambda$	−35	−28	9.85	N/A
this paper	$14.2 \times \lambda$	−25	−25.1	6.86	7.3

N/A = not available.

and simulated results. However, there is a small shift in the beam direction of radiation patterns at the above frequencies. This is probably due to inaccuracy in the fabrication process or difference between the dielectric constant of the fabricated antenna and the value considered in the simulation. Table 3 shows the comparison between theoretical and simulated radiation pattern characteristics in the presented antenna and some other antennas. As can be seen the proposed procedure leads to a better agreement between theoretical and simulated radiation pattern characteristics. It should be noted that the theoretical values that are not mentioned in the reference papers are calculated based on their amplitude distributions.

5 Conclusion

In this paper a new design method for the SIW straight long slot LWA is presented. The resulting antenna based on this method has a simple structure, low predefined SLL and narrow beamwidth. A modified formula is used to calculate the required leakage constant in the presence of loss. In order to calculate the accurate value of leakage constant, the TRL method along with HFSS simulations is used. To avoid broadening of the beamwidth, the changes of phase constant along the antenna is compensated. The shape of SIW walls is determined in such a manner to realise the required leakage constant and a fixed phase constant along the slot. Based on the proposed method a LWA at the centre frequency of 17 GHz and the beam direction of 40° is designed, simulated and fabricated. The measured SLL, HPBW and gain of this antenna are −23.2 dB, 8.4° and 15.3 dBi, respectively. Comparison between the results of theory, simulation and measurement, shows a good agreement.

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