Computer Aided Design for Rectangular Waveguide Leaky Wave Antenna with Meandering Longitudinal Slot

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ABSTRACT

In this study, a new simple method for design and implementation of rectangular waveguide leaky wave antenna with the longitudinal long slot is presented. In this method which has been done using HFSS, firstly, the waveguide attenuation is calculated based on the position of the slot in relation to the waveguide broad wall. Then the desired aperture illumination is fitted to the slot position on the broad wall of the waveguide by MATLAB. Finally, a Taylor-distributed rectangular waveguide leaky wave antenna with 30 dB SLL designed and fabricated in ku band. The good agreement between the simulation and the measurement results for radiated patterns verifies the effectiveness of the presented method.

KEYWORDS: Leaky wave antenna, longitudinal slot, computer aided, HFSS.

I. INTRODUCTION

Since the introduction of the Leaky-Wave Antennas (LWA) s in the 1940s, they have found many applications in the communications engineering [1 - 4]. Because of their interesting properties, this simple structure antenna has received a lot of attention in recent decades. Due to their traveling-wave and non-resonant nature, they can exhibit frequency scan behavior with high efficiency, high directivity and low SLL in radiation patterns [2, 3 and 4]. The rectangular waveguide slotted antenna has the simplest structure with many applications. This type of antenna is implemented by utilizing a longitudinal or transverse slots on the broad or the side wall of the rectangular waveguide [2, 3, and 7]. After introducing SIW structures as a planar version of the rectangular waveguide, several studies on SIW slotted LWAs have been reported [5, 8]. A simple LWA can be a long slot positioned along the broad wall of a rectangular waveguide (or an SIW). The drawback of this simple structure as an antenna is its high side-lobe level [3, 7]. To control the SLL or the aperture illumination of this antenna, it is proposed that the placement of the longitudinal long slot along the waveguide length from the centerline to the side wall of the waveguide be changed [7]. The radiation properties of the LWA are properly controlled by the complex propagation constant of its excited leaky mode. So, one can adjust the radiation functionality of the LWA by its position, if a reasonable relation between the LWA position and the propagation constant of the leaky-mode is found.

Lots of efforts have been made to control the aperture illumination and SLL of this antenna [6 - 10]. These efforts are generally based on complicated analytical methods or numerical and iterative ones. In addition to applying such methods, it is necessary to optimize the radiation pattern by time-consuming iterations in the final design stage. For example, in [7], it has been suggested that the three-dimensional analytical method is not an easy task and usually requires an iterative approach for optimal characteristics. In [9], the moment method analysis has been used for calculating the phase constant of a uniform rectangular leaky wave antenna. The method of [9] is based on the derivation of the contributions of the forward and the reflected leaky modes in the total radiation pattern of an LWA when it is connected to a short termination. The radiation pattern has two skewed main beams, one due to the forward travelling mode, and the other due to the backward travelling mode. From the specific angular positions of the main lobes, and the difference in the main lobe power levels, the phase and attenuation constants of the leaky-wave mode can be determined. Then, by choosing a suitable aperture distribution for the desired radiation pattern, it is possible to design a meandering long-slot antenna using the propagation constant data in terms of slot offset obtained from moment method analysis. In [6], the Hybrid Dielectric-Waveguide Printed-Circuit Technology (HDWPC) was examined and a specifically developed modal analysis technique

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based on the method of moments was used to analyze the structure and calculate the complex propagation constant. Finally, 3 antennas with SLL less than 20 dB were designed and tested. In [8], a method for designing and controlling the SLL of LWA based on SIW technology has been introduced. In that article, similar to this paper, the HFSS simulation software has been employed for calculating the propagation constant data as a function of slot offset. In spite of their similarities, there is one major difference between these two methods which will be explained in section III, after introducing the proposed method.

This paper presents a simple and straightforward method for designing and implementing meandering long slot leaky waveguide antennas with desired aperture illumination, SLL, and efficiency. The presented method has been implemented by HFSS software and does not require deep analytical and numerical knowledge. In the following, the theory of LWA and general design formula are first reviewed briefly and then a simple computer-aided method is presented for meandering long slot leaky waveguide antenna design with appropriate aperture illumination, SLL, and efficiency.

II. THEORY

The phase constant and the leakage constant (the leakage rate per unit length) of the leaky mode thoroughly describe the propagation characteristics of a leaky-wave antenna. The length L then forms the aperture of the line-source antenna, and the amplitude and phase of the traveling wave along the aperture are determined by the values of β and α as a function of z. When the leaky waveguide is completely uniform along its length, β and α do not change with z, and the aperture distribution has an exponential amplitude variation and a constant phase. Such an aperture distribution result in a high side-lobe level, therefore, the design of a practical leaky-wave antenna will include a variation of α with z in order to control the side-lobes in a special fashion. The values of β and α will depend on the precise cross-sectional geometry of the leaky waveguide [2, 3].

When β and α are known as a function of the frequency and the cross-sectional geometry, the principal behavioral features of a leaky-wave antenna become known very quickly. The beam direction of LWA was defined as $\sin\theta_m=\beta/k_0$, and the 3-dB beamwidth can be calculated approximately by $\Delta\theta \approx 1/ (L/\lambda_0\cos\theta_m)$. Here, θ_m is the maximum angle of the beam, measured from the broadside direction (perpendicular to the leaky waveguide axis), L is the length of the leaky-wave antenna, $\Delta\theta$ is the 3-dB beamwidth, k_0 is the free-space wave number and λ_0 is the free-space wavelength [2, 3]. In order to achieve high efficiency in practical applications, it is necessary to radiate more than 90% of the power along the aperture. The remaining power will be absorbed by the terminated load. As can be inferred, the maximum angle of the beam (θ_m) can be scanned from the broadside to the end-fire by increasing the frequency. It means that a frequency scanned antenna can be achieved by a proper LWA design.

III. PROPOSED DESIGN METHOD

The maximum angle of the beam (θ_m) is the most important parameter in designing the longitudinal long slot LWA. According to the defined θ_m, the cross-sectional dimension of the waveguide will be specified, then the length of the antenna or waveguide will be determined according to the required beamwidth. In the next step, it is necessary to determine the shape and location of the slot on the broad wall of the waveguide to achieve the desired SLL and efficiency. Since the leakage level is higher for slots at larger distances from the center line, the SLL and the efficiency of the LWA can be controlled by replacing the slot in the transverse direction. Calculating the slot location along the waveguide length is the most important and complicated section of the design procedure. To this end, it is necessary to know the attenuation of the slot (per unit length) in terms of its offset from the center line of the waveguide. As the slot can somewhat disturb the field distributions inside the waveguide, the integral equations and moment methods must be applied to completely analyze the non-resonant uniform long slot rectangular waveguide antenna [6, 7, 9]. Recently well-developed commercial soft-wares such as ANSYS HFSS are used by most practical engineers to design and analyze antennas. In this paper, the commercial HFSS software has been employed to calculate the attenuation (per unit length) of the slot according to its offset from the center line of the waveguide. The resulting attenuation will be fitted to the arbitrary aperture distribution in the next step. In order to calculate the attenuation, a model as a test antenna with a uniform straight slot on the broad wall of the waveguide is created in HFSS and analyzed as illustrated in Fig.1. It is important that attenuation of the slot, due to its offset from the center line, be calculated only in forward direction. Other attenuation factors such as the loss of waveguide wall, the loss of filling material of waveguide and reflected wave attenuation in backward direction must be omitted. In [8], a family of two ports SIWs is modeled and the straight long slot with different positions relative to the centerline is cut on the top broadside of each SIW. To accurately determine the slot attenuation, the conductor material, including metalized vias and conductor layers, is set to be the perfect electric conductor (PEC), while the dielectric material is considered lossless. The attenuation figure (S21) has been considered as the radiated power or slot attenuation. Two phenomena are responsible for this attenuation including the attenuation due to the slot for an incoming wave in the forward direction and reflected wave from the end of the slot in the backward direction. For an accurate design, these two loss factors must be separated from each other, or only the attenuation due to forward wave must be calculated. In [8], these attenuation factors had not been separated and it had required some optimizations in the final step to achieving the acceptable design. This paper proposes a method for simulation that can only calculate the attenuation of the slot in the forward direction. Therefore, it develops a straightforward design method for meandering long slot rectangular waveguide LWA with arbitrary aperture distribution and very low SLL.

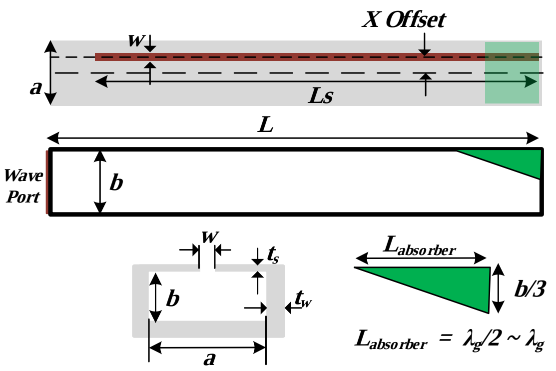

Fig. **1** Test antenna structure in HFSS

In order to cancel the effect of the reflected wave, this paper suggests an absorber material in the final section of the slot inside the waveguide, as illustrated in Fig.1. In this method, one port, instead of two ones, is used to excite the antenna; and the other end of the waveguide is filled with an absorber and closed. The radiated power of this structure is equal to the attenuated power due to the slot. By calculating the radiation efficiency of modeled structure and replacing it in (1), one can calculate the attenuation of the straight slot. Moreover, as the radiation efficiency is the ratio of the radiated power to the accepted power, the effect of returned loss is compensated.

$$\alpha = 10\log(1 - R.E) \qquad (1)$$

As illustrated in Fig.1, one-half of the wavelength ($\lambda_g/2$) in the slot end must be covered by the absorber to ensure the cancellation of the reflected wave. Since the end section of the slot which covered by absorber has its own attenuation, there will be an error in calculating attenuation. Considering the fact that the length of the covered section to the total length of the slot is very small, this error will be negligible.

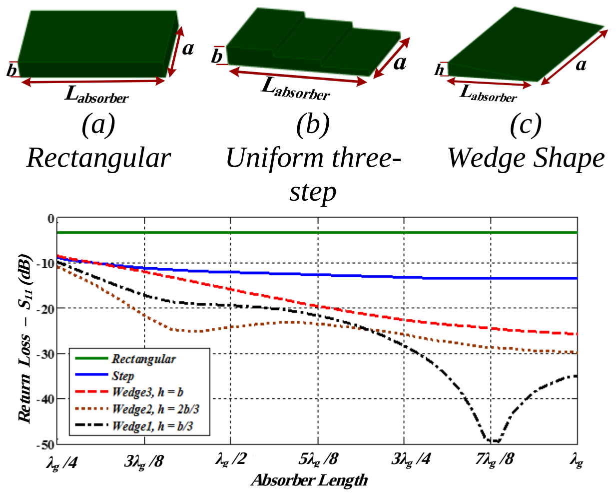

Fig. **2** Different type of absorber that placed in the end section of a shorted waveguide and simulated return loss in terms of absorber length.

In order to minimize the power reflection from the waveguide end, several absorbers of different configurations in Ansoft-HFSS environment were examined. The simulated return loss for each absorber in terms of absorber length is illustrated in Fig. 2. Referring to Fig. 2, the wedge-shaped structure with *h=b/3* for absorbing material has the best performance in reducing the reflection from the shortened end of the waveguide. The absorber with part number MF-124 made by

Emerson-Coming has been used in this paper. The design procedure can be summarized and described in 8 steps as follows:

1- Specify the desired antenna parameters such as the operation frequency, the maximum angle of the beam (*θ_m)*, 3-dB beam width, SLL, and the radiation efficiency (*e_r*)

2-a. Calculate the cross-sectional dimension of the waveguide according to the θ_m and the operating frequency specified in step 1 using the following equation [2, 3, 8]

$$\beta = k \times \sqrt{1-\left(\frac{\lambda}{\lambda_c}\right)^2} = k_0\sqrt{\epsilon_r} \times \sqrt{1-\left(\frac{\lambda_0/\sqrt{\epsilon_r}}{\lambda_c}\right)^2}$$

$$sin\theta_m = \frac{\beta}{k_0} = \sqrt{\epsilon_r-\left(\frac{\lambda_0}{\lambda_c}\right)^2}$$

$$a = \lambda_c/2 = \frac{\lambda_0}{2\times\sqrt{\epsilon_r - sin\theta_m{}^2}} \qquad (2)$$

In the above-written equation, a (as illustrated in Fig. 1) is the size of the broad wall of the waveguide, λ_C is the cut-off wavelength in the waveguide, λ_0 is the wavelength in free space and ϵ_r is the electrical permittivity of the material filled in the waveguide. The value of b, the size of the narrow wall of the waveguide, is chosen according to power handling capability and mechanical or size limitation of the antenna as well as the waveguide wall thickness.

2-b. Obtain the approximate length of the antenna according to the 3-dB beamwidth $\Delta\theta \approx 1/(L/\lambda_0 cos\theta_m)$

2- Create a uniform slot rectangular leaky wave antenna model in HFSS with the length of at least $10\lambda_0$, based on cross section parameters obtained from step 2 (Fig. 1 - the test antenna). The optimum absorber length is in the range of Lambda-g/2 to Lambda-g (Fig. 2)

3- Change the center of the slot position from centerline to edge wall and calculate the radiation efficiency for test antenna with respect to each slot position by HFSS.

4- Using (1), calculate the attenuation for each radiation efficiency. To calculate the attenuation per unit length, normalize the attenuation to slot length.

5- Specify the desired aperture illumination function, such as Taylor distribution with SLL= -30 dB, for the requested SLL. In determining the aperture illumination function, it is necessary to divide the antenna into several longitudinal sections. The closer the sections, the higher the accuracy. The minimum spacing is recommended to be $\lambda_0/2$.

6- To find the required attenuation along the antenna length$\alpha(l)$, apply the following equation [2, 3]:

$$\alpha(l) = \frac{0.5|A(l)|^2}{\frac{1}{1-R}\int_0^L |A(\xi)|^2 d\xi - \int_0^l |A(\xi)|^2 d\xi} \qquad (3)$$

In this equation, R is the power reached to the end load or the absorber of the antenna. *A(l)* and *L* will be the aperture distribution obtained in step 6, and the slot length respectively.

7- The major part of the designing procedure is fitting the required attenuation distribution to the offset distribution. It can simply be implemented by MATLAB.

IV. Implementation of the Proposed Design Method

In this section, a ku band long slot rectangular LWA is designed and simulated according to the described design method procedure. In the first step, according to design procedure, the desired antenna parameters must be defined. These parameters have been defined in Table 1.

Table **1** Requested antenna parameters

Operating frequency	13.5 ~ 16.5 GHz
Scan area	Up 40 degree from broadside
Minimum 3dB beam width	3 ~ 4 degree
Side Lobe Level	Less than -30 dB
Radiation efficiency	90%

The antenna, specification of which is in Table 1, must be able to scan up to 40 degrees from broadside within 13.5 ~ 16.5 GHz frequency band. The increase of frequency leads to increase in the value of β, considering the fact that $sin\theta_m = \beta/k_0$, as β increases, θ_m increases as well. To begin the designing, it is assumed that the maximum angle of the beam is 40 degrees at 16.5 GHz. For the air-filled waveguide, the value of (ϵ_r) is considered as 1. For $\theta_m=40$ in the equation (2), a = 11.8 mm is obtained and the value of b, considering the mechanical constraints, is taken as 3mm. The length of radiation aperture will be specified with regard to $\Delta\theta \approx 1/(L/\lambda_0 cos\theta_m)$. Regarding the minimum 3 dB beam width of 3 degrees that occurs in the upper frequency of the band (f= 16.5 GHz), the approximate length of the antenna will be 430mm or 23λ. However, considering a two-centimeter margin from the two ends of the waveguide to the slot, the total length of the antenna will 450 mm. The thickness of the slot was considered to be 1 mm for the upper wall, and 4 mm for the rest of the walls.

Table **2** Simulated test antenna parameters

a	12.5 mm	Test waveguide width
b	3 mm	Test waveguide high
L	200 mm	Total length of test antenna
Ls	190 mm	Uniform slot length
w	3,2,1 mm	Uniform slot width
t_s	1 mm	Slot thickness
t_w	4 mm	Waveguide wall thickness
L_absorb	23.5 mm	Length of absorber

A brief simulation of the test antenna (*L= 200 mm*, *Ls= 180mm*, *w=3mm*) shows that the maximum leakage angle is slightly less than 40 degree. The overall radiation pattern is calculated from the multiplication of the array factor and the element factor. The radiation pattern of a small longitudinal slot (as an element factor) along the broadside is approximately directional and it is not flat at θ=40 while the array factor is pointed to $\theta=40$ direction; therefore, the obtained θ_m is a little less than 40 degrees. To compensate for this effect, the length of the broad wall is a bit changed, and the optimal value of (a=12.5 mm) is selected for it with the help of HFSS simulations. By changing the offset of the slot center from waveguide center for 4.5 mm in steps of 0.1 mm, and simulation of the test antenna according to Fig. 1 and parameters of Table 2, the radiation efficiency for each step will be obtained by HFSS software. Replacing the radiation efficiency in equation 1, the attenuation for slot length in terms of the slot offset will be acquired. By normalizing the attenuation along the slot length, the attenuation curve (per unit length) according to the slot offset from the center line will be obtained (as shown in Fig. 3).

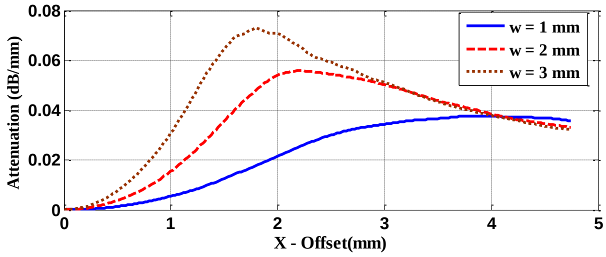

Fig. **3** The relationship between α, attenuation per unit length, and the offset of slots from the centerline of the waveguide for different slot width.

As expected, the slope of attenuation per unit length in terms of the slot offset increased as wider slot was selected [8 – 10]. It means that by increasing 1 mm in slot offset, the attenuation of the wide slot will be greater than that of the narrow one. As the width and offset of the slot increase, the excitation ratio of slot mode to leaky mode inside the waveguide increase as well [9, 10]. Considering the fact that the attenuation of slot mode is less than that of the leaky mode [9, 10], the attenuation curve in terms of slot offset is not always incremental, as shown in Fig. 3.
On the other hand, by changing the slot offset, a little change in the phase constant of the leaky wave will be seen. By examining the radiation patterns of the testing antenna, using $sin\theta_m= \beta/k_0$, the range of these changes for various slot widths has been calculated and shown in Fig. 4. To design an antenna with the lowest SLL, the variations of β/k_0 along the antenna length should be as low as possible. As mentioned earlier, for a desirable aperture illumination the slot position must be displaced from centerline of the waveguide to the edge wall. Wider slots need lower displacements therefore, the undesired β/k_0 changes will be less as well, and achieving an antenna with the least SLL would be more probable. In this paper, the width of the slot has been selected as *w=3* mm; therefore, the acceptable range in slot offset is less than 2mm, as shown in Fig. 3 and Fig. 4.

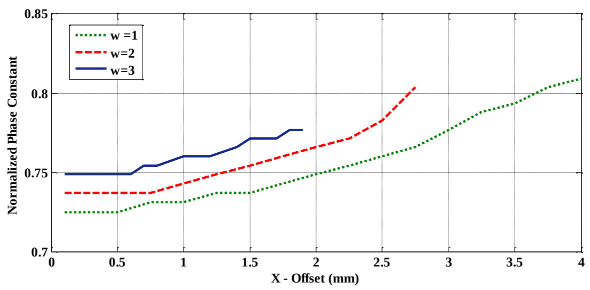

Fig. **4** The relationship between β/k_0, normalized phase constant, and the offset of slots from the centerline of the waveguide for different slot width.

In order to achieve the requested SLL and radiation efficiency, according to the step 6 from design procedure, aperture illumination of the antenna should be specified. For the antenna designed in this study, the Taylor distribution with SLL= -35 dB has been selected (as in Fig. 5). By the use of (3), the attenuation distribution along the slot length will be acquired (as in Fig. 6). The R value, in equation (3), will be given according to the antenna efficiency. As indicated in Table 1, the radiation efficiency of the antenna is kept at 90%, which corresponds to R= 0.1.

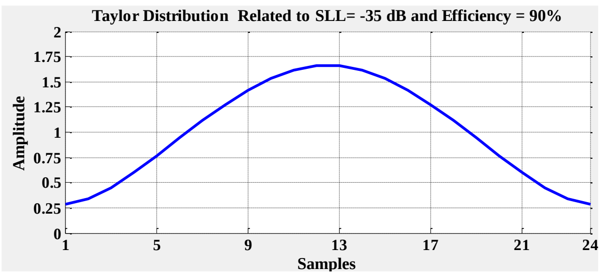

Fig. **5** Taylor distribution for aperture illumination related to -35 dB SLL and 90% efficiency

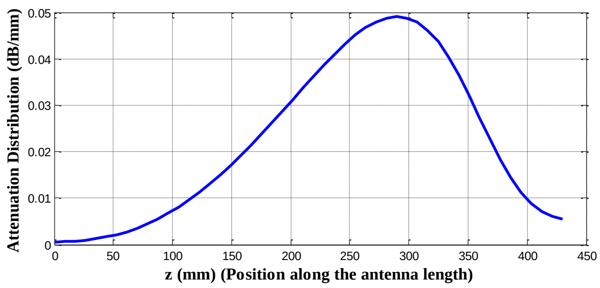

Fig. **6** Leakage rate for slots related to Taylor distribution in Fig. 5.

The final step of the design procedure is fitting the resulted curve in Fig. 6 to that of Fig. 3, which simply implemented by MATLAB. By integrating these two curves, the offset curve from the center line, in terms of the slot position along the antenna length, will be achieved (as in Fig. 7). Considering the obtained dimensions for the antenna (*a=12.5mm, b= 3mm, L=450mm*, t_s*=1mm*, t_w*=4 mm*), and the distribution of slot placement according to Fig. 7, the antenna structure is modelled in HFSS. The simulated model and the fabricated structure are shown in Fig. 8. The results have been depicted in Fig. 9 to Fig. 12 which obviously show the pattern scan in the target area with SLL of more than 27dB in 13.5~17.5 GHz frequency range. In Fig. 9 and Fig. 10 the simulated and measured results for co-polarization patterns in H-plane have been shown which perfectly corresponds to each other. In Fig. 11 the simulated and measured cross-polarization pattern in H-plane for 14.5 GHz are shown. By comparing the Fig. 10 and Fig. 11, the level of 35 dB for cross polarization have been observed. Finally, in Fig. 12 the simulated and measured co-polarization pattern in E-plane for 14.5 GHz are shown. According to simulated and measured results, the effectiveness of the proposed method in this study is verified.

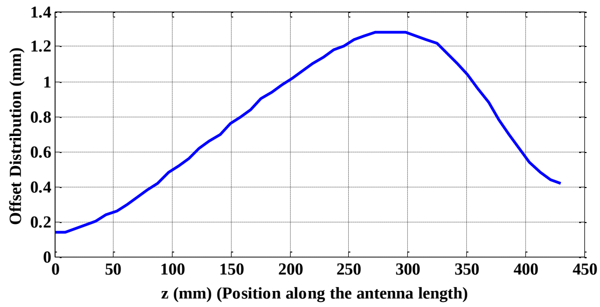

Fig. **7** Slots offset distribution along the antenna length related to Taylor distribution in Fig. 5

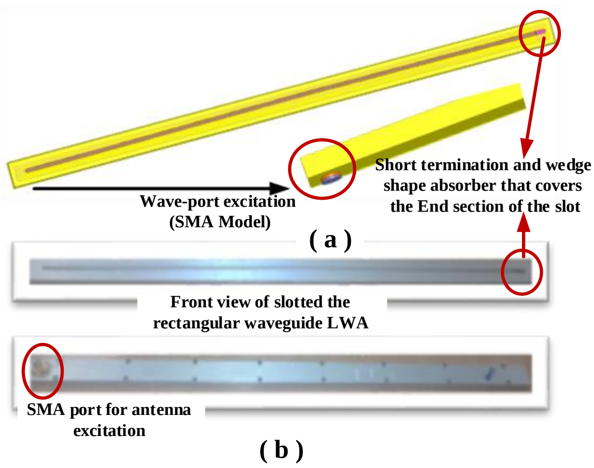

Fig. **8** (a) Designed Antenna model in HFSS

(b) Front and back view of manufactured antenna

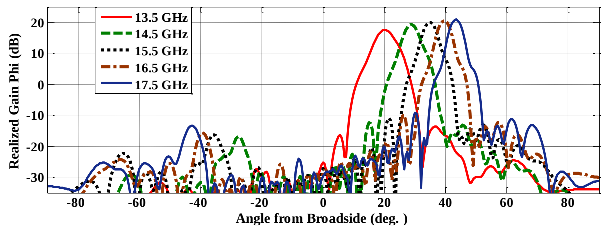

Fig. **9** Simulated H-plane co-polarization gain patterns for designed antenna in HFSS for 13.5 ~16.5 GHz

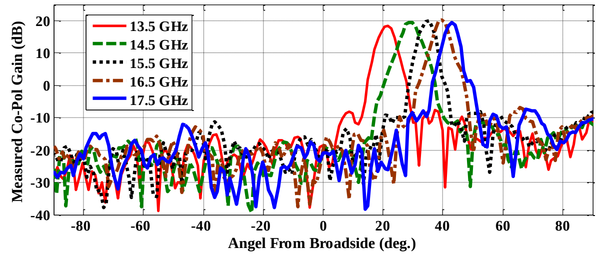

Fig. **10** Measured H-plane co-polarization gain patterns for designed antenna

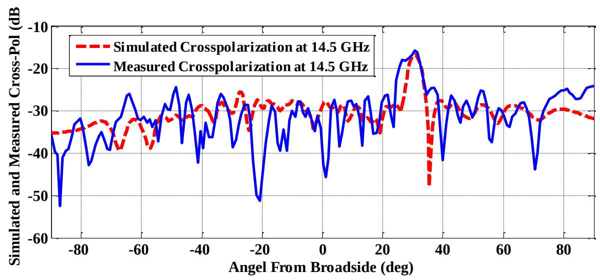

Fig. **11** Simulated and measured H-plane cross-polarization gain patterns for designed antenna for 14.5 GHz

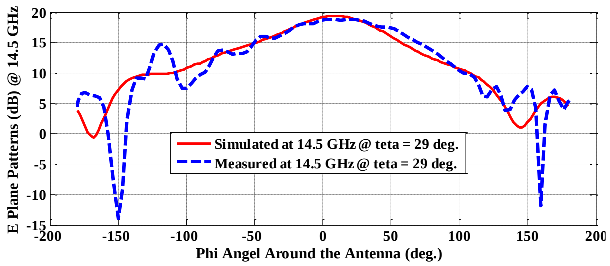

Fig. **12** Simulated and measured E-plane co-polarization gain patterns for designed antenna for 14.5 GHz

V. Conclusion

In this paper, a simple and straightforward procedure for the design of the LWAs on the rectangular waveguides is presented. In this method which has been done using HFSS, waveguide attenuation is first calculated according to the placement of a uniform long slot to the centerline of the waveguide broad wall that the end filled by a proper absorber in order to cancel the reflected wave. Then the desired aperture illumination is fitted to the slot position along the antenna length on the broad wall of the waveguide by MATLAB. The good performance of the presented method is verified by comparing the simulated and measured results.

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