

Design of Slotted Waveguide Antennas with Low Sidelobes for High Power Microwave Applications

Hilal M. El Misilmani^{1, *}, Mohammed Al-Husseini², and Karim Y. Kabalan¹

Abstract—Slotted waveguide antenna (SWA) arrays offer clear advantages in terms of their design, weight, volume, power handling, directivity, and efficiency. For broadwall SWAs, the slot displacements from the wall centerline determine the antenna's sidelobe level (SLL). This paper presents a simple inventive procedure for the design of broadwall SWAs with desired SLLs. For a specified number of identical longitudinal slots and given the required SLL and operating frequency, this procedure finds the slots length, width, locations along the length of the waveguide, and displacements from the centerline. Compared to existing methods, this procedure is much simpler as it uses a uniform length for all the slots and employs closed-form equations for the calculation of the displacements. A computer program has been developed to perform the design calculations and generate the needed slots data. Illustrative examples, based on Taylor, Chebyshev and the binomial distributions are given. In these examples, elliptical slots are considered, since their rounded corners are more robust for high power applications. A prototype SWA has been fabricated and tested, and the results are in accordance with the design objectives.

1. INTRODUCTION

Rectangular Slotted Waveguide Antennas (SWAs) [1] radiate energy through slots cut in a broad or narrow wall of a rectangular waveguide. This means the radiating elements are an integral part of the feed system, which is the waveguide itself, leading to a simple design not requiring baluns or matching networks. The other main advantages of SWAs include relatively low weight and small volume, their high power handling, high efficiency, and good reflection coefficient [2]. For this, they have been ideal solutions for many radar, communications, navigation, and high power microwave applications [3].

SWAs can be resonant or non-resonant depending on the way the wave propagates inside the waveguide, which is a standing wave in the former case and a traveling-wave in the latter [4, 5]. The traveling-wave SWA has a larger bandwidth, but it requires a matched terminating load to absorb the wave and prevent it from being reflected, which reduces its efficiency. It also has the shortcoming of the dependency of the main beam direction on the operating frequency. Resonant SWAs, on the other hand, have the end of the waveguide terminated with a short circuit, which results in a higher efficiency due to no power loss at the waveguide end. In addition, the main beam is normal to the array independently of the frequency, but these advantages come at the cost of a narrower operation band.

The design of a resonant SWA is generally based on the procedure described by Stevenson and Elliot [4, 6–9], by which the waveguide end is short-circuited at a distance of a quarter-guide wavelength from the center of the last slot, and the inter-slot distance is one-half the guide wavelength. For rectangular slots, the slot length should be about half the free-space wavelength. However, since sharp corners aggravate the electrical breakdown problems, slot shapes that avoid sharp corners are

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more suitable, especially for high power microwave applications. Elliptical slots are thus an excellent candidate for such applications [10, 11].

The resulting sidelobe level (SLL) for antenna arrays is related to the excitations of the individual elements. In SWAs, the excitation of each slot is proportional to its conductance. For the case of longitudinal slots in the broadwall of a waveguide, the slot conductance varies with its displacement from the broadface centerline [6]. Hence, for each desired SLL, a suitable set of slots displacements should be determined.

In his well-known procedure, Elliott has proposed two main equations that should be solved simultaneously to determine the values of the displacement and length for each slot. These two equations are based on Stevenson equations and Babinet's principle, and also rely on Tai's formula [12] and Oliner's length adjustment factor [13], in addition to Stegen's assumption of the universality of the resonant slot length [14]. In brief, the existing resonant SWA design procedures are complex, and mostly rely on numerically solving several equations to deduce both the displacement and length of each slot. This paper presents a simplified procedure by which all the slots have the same uniform length, and closed-form equations are used to determine the slots non-uniform displacements, for a desired SLL. The other parameters such as the slots inter-spacing along the length of the waveguide, and their distances from both the feed port and the shorted end, are obtained from the guidelines set by Elliott and Stevenson.

For rectangular slots, the slot length is about half the free-space wavelength. However, for elliptical slots, as the ones used in this work, the exact length is to be optimized. For a desired SLL, the conductances of the slots are obtained from a certain distribution, Chebyshev, Taylor, or Binomial; then an equation that relates these conductances to the displacements from the centerline is used to deduce these displacements. A computer program written in Python has been developed to perform the design calculations and output the resulting slots dimensions and coordinates. Several examples are given in this paper to illustrate the presented procedure. An S-band SWA with 10 elliptical slots is used for these examples. For each example, results for the obtained displacements, reflection coefficients and radiation patterns are presented. A prototype SWA with 7 elliptical slots, operating at a frequency of 3.4045 GHz, has been designed, fabricated, and measured, and the results show good analogy with the simulated ones.

2. CONFIGURATION AND GENERAL GUIDELINES

For the illustrative examples, an S-band WR-284 waveguide with dimensions $a = 2.84''$ and $b = 1.37''$ is used. The design is done for the 3 GHz frequency. Ten elliptical slots are made to one broadwall. The waveguide is shorted at one end and fed at the other.

2.1. Slots Longitudinal Positions

There are general rules for the longitudinal positions of the slots on the broadwall:

- The center of the first slot, *Slot 1*, is placed at a distance of quarter guide wavelength ($\lambda_g/4$), or $3\lambda_g/4$, from the the waveguide feed,
- The center of the last slot, *Slot 10*, is placed at $\lambda_g/4$, or $3\lambda_g/4$, from the waveguide short-circuited side,
- The distance between the centers of two consecutive slots is $\lambda_g/2$.

The guide wavelength is defined as the distance between two equal phase planes along the waveguide. It is a function of the operating wavelength (or frequency) and the lower cutoff wavelength, and is calculated according to the following equation:

$$\lambda_g = \frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda_0}{\lambda_{cutoff}}\right)^2}} = \frac{c}{f} \times \frac{1}{\sqrt{1 - \left(\frac{c}{2a \cdot f}\right)^2}} \quad (1)$$

where λ_0 is the free-space wavelength calculated at 3 GHz, and c is the speed of light. In this case, $\lambda_g = 138.5$ mm.

Based on the above guidelines, the total length of the SWA is $5\lambda_g$, as shown in Fig. 1.

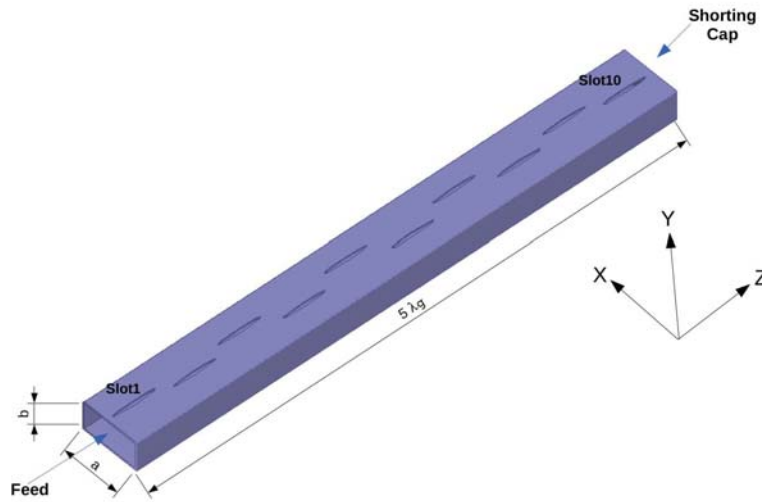


Figure 1. Slotted waveguide with 10 elliptical slots.

2.2. The Slot Width

The width of each elliptical slot, which is 2 times the minor radius of the ellipse, is fixed at 5 mm. This is calculated as follows: for X-band SWAs, the width of a rectangular slot the mostly used in the literature is 0.0625", corresponding to $a = 0.9$ ". By proportionality, the width of the elliptical slot for this S-band SWA is computed as follows:

$$\text{SlotWidth} = a \times \frac{0.0625}{0.9} = 2.84 \times \frac{0.0625}{0.9} = 0.197'' = 5 \text{ mm}$$

2.3. The Slot Displacement

A slot displacement refers to the distance between the center of a slot and the centerline of the waveguide broadface, as illustrated in Fig. 2.

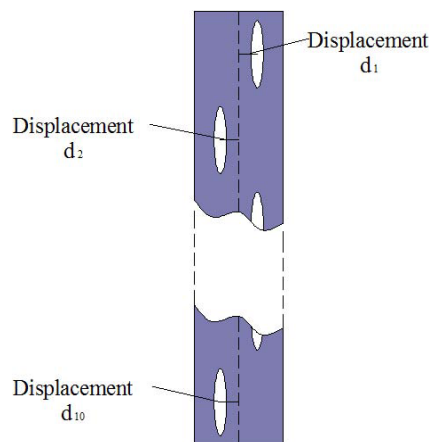


Figure 2. Slotted waveguide with 10 elliptical slots.

With uniform slot displacements, all slots are at the same distance from the centerline. This is similar to the case of antenna arrays with discrete elements having equal excitation, which results in an SLL around -13 dB. Lower SLLs are obtained upon using non-uniform slots displacements. In both the uniform and non-uniform displacement cases, the slots should be placed around the centerline in

an alternating order. This is done to ensure that all slots radiate in phase and hence result in higher efficiency of the antenna.

The value of the uniform slot displacement that leads to a good reflection coefficient is given by [15, 16]:

$$d_u = \frac{a}{\pi} \sqrt{\arcsin \left[\frac{1}{N \times G} \right]} \quad (2)$$

where:

$$G = 2.09 \times \frac{a}{b} \times \frac{\lambda_g}{\lambda_0} \times \left[\cos \left(0.464\pi \times \frac{\lambda_0}{\lambda_g} \right) - \cos(0.464\pi) \right]^2 \quad (3)$$

In Equation (2), N is the number of slots, which is equal to 10. In Equation (3), $\lambda_0 = 100$ mm at 3 GHz. Combining Equations (2) and (3), d_u is found to be 7.7 mm.

2.4. The Slot Length

For rectangular slots, the length is usually $0.98 \times \lambda_0/2 \simeq \lambda_0/2$. Because of the narrower ends of elliptical slots, their length (double the major radius) is expected to be slightly larger than $\lambda_0/2$. The optimized elliptical slot length is determined as follows: the SWA, having 10 slots, is modeled assuming a uniform displacement ($d_u = 7.7$ mm); this 10-slot SWA is used to obtain the optimized slot length which takes into account the effect of mutual coupling on the slot resonant length. An initial length of $0.98 \times \lambda_0/2$ per slot; the length is increased while inspecting the computed reflection coefficient S_{11} until the antenna resonates at 3 GHz with a low S_{11} value. In our case, the elliptical slot length is found to be 54.25 mm.

For these uniform displacement and slot length, the resulting sidelobe level ration (SLR) is around 13 dB, which is as expected. The reflection coefficient S_{11} and the YZ -plane gain pattern in this case are given in Figs. 3(a) and 3(b), respectively. A peak gain of 16.6 dB and an SLR of 13.2 dB are recorded. The half-power beamwidth (HPBW) in this plane is 7.2 degrees. These values are obtained using CST Microwave Studio, and then verified with ANSYS HFSS.

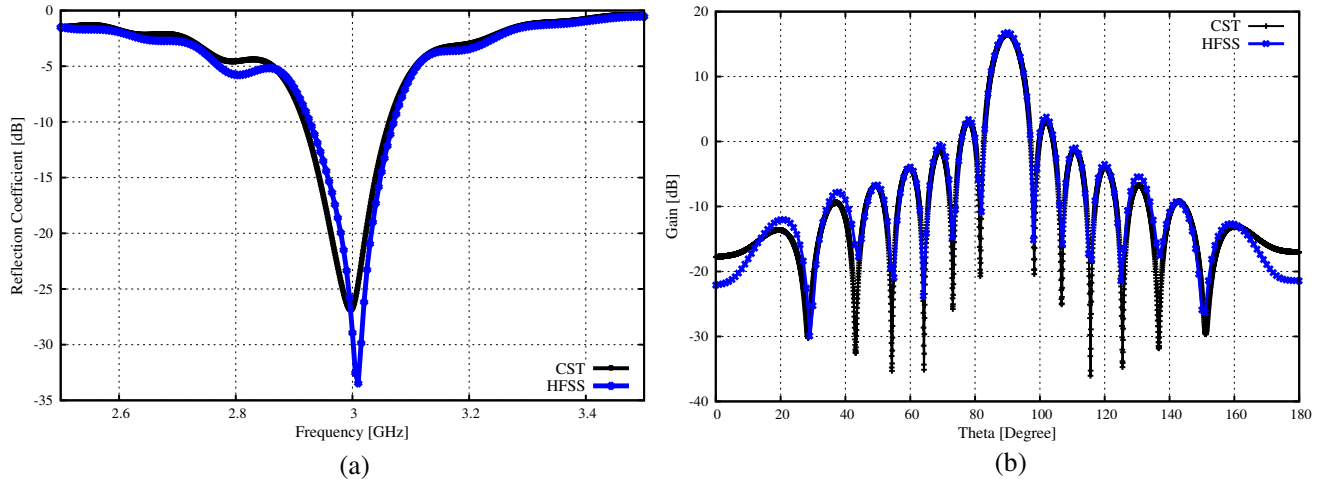


Figure 3. Antenna's reflection coefficient and YZ -plane pattern for the case of uniform slot displacement. (a) S_{11} for uniform slots displacement. (b) Pattern in the YZ plane.

3. NON-UNIFORM DISPLACEMENT CALCULATION PROCEDURES

The simulations performed in this paper have proven that the resonating length of the elliptical slots is not very sensitive to the slots displacements calculated using the method proposed in this paper. This

will be addressed again in later sections. For this, in the next calculations the length of all slots is fixed at 54.25 mm. The displacement of the n th slot is related to its normalized conductance g_n by [15, 17–19]:

$$d_n = \frac{a}{\pi} \arcsin \sqrt{\frac{g_n}{2.09 \frac{\lambda_g}{\lambda_0} \frac{a}{b} \cos^2 \left(\frac{\pi \lambda_0}{2 \lambda_g} \right)}} \quad (4)$$

$$g_n = \frac{c_n}{\sum_{n=1}^N c_n}. \quad (5)$$

In Equation (5), N is the number of slots, and c_n s are the distribution coefficients that should be determined to achieve the desired SLL. Equation (5) guarantees that $\sum_{n=1}^N g_n = 1$.

Several distributions (tapers) well-known in discrete antenna arrays can be used to generate the c_n s (e.g., Taylor and Chebyshev). However, the resulting SLL of the SWA is always higher than the SLL used for the discrete array distribution. To reach the desired SWA SLL, a few iterations of the simulation setup are required, where in each the SLL of the discrete array used to generate the taper values is decreased. Illustrative examples are shown below to further highlight this design procedure.

3.1. Example 1: 20 dB SLR with Chebyshev Distribution

In this example, the target is an SLR of 20 dB, where the c_n s are selected according to a Chebyshev distribution.

3.1.1. Coefficients and Slots Displacements

The coefficients c_n s for a Chebyshev distribution are calculated from equations in [20, 21], as given in the following. The array factor of a generalized Chebyshev array can be written as:

$$f(u) = \prod_{n=1}^p \left(\frac{1}{R_n} T_{N_n-1} \left(\gamma_n \cos \frac{u}{2} \right) \right) = \frac{1}{R} \prod_{n=1}^p \left(T_{N_n-1} \left(\gamma_n \cos \frac{u}{2} \right) \right) \quad (6)$$

where:

- T_x denotes a Chebyshev polynomial of order x ,
- $\gamma_n = \cosh[\cosh^{-1}(R_n)/(N_n - 1)]$,
- $u = 2\pi(d/\lambda)(\cos \theta - \cos \theta_0)$ with d being the inter-element spacing and θ_0 the elevation angle of maximum radiation,
- R_n is the sidelobe level ratio of the n th basis Chebyshev array,
- and N_n is the number of elements of the n th basis array.

For a uniform spacing and an amplitude symmetrical about the center, the array factor can be written as:

$$f(u) = \begin{cases} 2 \sum_{m=1}^{N/2} I_m \cos[(m - 1/2)u], & \text{for } N \text{ even} \\ \sum_{m=1}^{(N+1)/2} \epsilon_m I_m \cos[(m - 1)u], & \text{for } N \text{ odd} \end{cases} \quad (7)$$

where ϵ_m equals 1 for $m = 1$ and equals 2 for $m \neq 1$. Finally, the excitation coefficients are found using:

$$I_m = \begin{cases} \frac{2}{NR} \sum_{q=1}^{N/2} f[u=p] \cos[q], & \text{for } N \text{ even} \\ \frac{1}{NR} \sum_{q=1}^{\frac{N+1}{2}} \epsilon_q f[u=v] \cos[w], & \text{for } N \text{ odd} \end{cases} \quad (8)$$

where:

- $p = 2\pi/N(q - 1/2)$,
- $q = 2\pi/N(m - 1/2)(q - 1/2)$,
- $v = 2\pi/N(q - 1)$,
- and $w = 2\pi/N(m - 1)(q - 1)$

Equation (8) uses Chebyshev polynomials and the computed excitation currents result in a normalized array factor.

For a -35 dB Chebyshev taper, the c_n s and their corresponding slots displacements, calculated from Equation (8), are given in Table 1. The -35 dB Chebyshev taper has been selected after some simulation iterations, as it provides the desired -20 dB SLL for the SWA. A -20 dB Chebyshev taper leads to SWA sidelobes higher than the -20 dB goal.

Table 1. -35 dB Chebyshev taper coefficients and corresponding slots displacements leading to an SWA SLL of -20 dB.

Slot Number	Chebyshev Coefficient	Displacement (mm)
1	1	3.74
2	2.086	5.42
3	3.552	7.11
4	4.896	8.4
5	5.707	9.11
6	5.707	9.11
7	4.896	8.4
8	3.552	7.11
9	2.086	5.42
10	1	3.74

It is clear from Table 1 that the slots near the two waveguide ends are closest to the broadface center line, whereas those toward the waveguide center have the largest displacement. This property applies to all the examples.

3.1.2. Results

For the previously determined slot parameters (length, width, and coordinates), the SWA computed results show a resonance at 3 GHz, an SLR of 20 dB, and a peak gain of 16.1 dB. The YZ -plane HPBW has increased to 8.4 degrees, compared to the uniform displacement case, as shown in Fig. 4. The broadening of the main beam is expected since the sidelobes have been forced to go lower.

3.2. Example 2: 20 dB SLR with Taylor (One-parameter) Distribution

In this example, the SWA is designed to have an SLR of 20 dB, where the c_n s will be obtained from a Taylor one-parameter distribution [22].

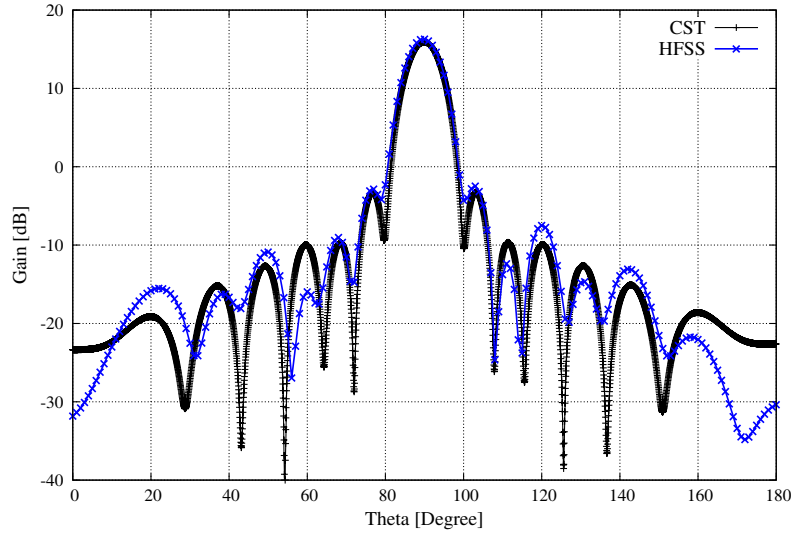


Figure 4. Antenna's YZ -plane pattern for the case of non-uniform slots displacements with Chebychev distribution. A 20 dB SLR is obtained.

3.2.1. Coefficients and Slots Displacements

The c_n s for a Taylor one-parameter distribution can be computed using the equations in [23] or [24], as given in the following. The excitation coefficients, $I_n(z')$, for continuous line distribution of length l , are equal to:

$$I_n(z') = \begin{cases} J_0 \left[j\pi B \sqrt{1 - \left(\frac{2z'}{l} \right)^2} \right], & \text{for } -l/2 \leq z' \leq +l/2, \\ 0, & \text{elsewhere} \end{cases} \quad (9)$$

For the discrete case [24], the current magnitudes of an N -element linear array with symmetric excitation are equal to:

$$a_m = \begin{cases} I_0 \left[\beta \sqrt{1 - \left(\frac{m - 0.5}{M - 0.5} \right)^2} \right], & \text{for } N = 2M \\ I_0 \left[\beta \sqrt{1 - \left(\frac{m - 1}{M - 1} \right)^2} \right], & \text{for } N = 2M - 1 \end{cases} \quad (10)$$

where:

- $1 \leq m \leq M$,
- a_1 is the excitation of the array's center element(s),
- and a_M is that of the two edge elements.

For a -20 dB SLL for the SWA, a -30 dB Taylor (one-parameter) taper is required. The resulting coefficients, and the corresponding slots displacements are listed in Table 2.

3.2.2. Results

For the slots displacements in Table 2, the antenna keeps its resonance at 3 GHz, shows an SLR of about 20 dB, and has a peak gain of 16 dB. The YZ -plane HPBW is 8.5 degrees, as shown in Fig. 5. It is to note that for the same SLL of -20 dB, the determined Chebyshev and Taylor (one-parameter) coefficients have led to almost identical radiation patterns, HPBW and gain parameters.

Table 2. -30 dB Taylor (one-parameter) coefficients and corresponding slots displacements leading to an SWA SLL of -20 dB.

Slot Number	Taylor-based Coefficient	Displacement (mm)
1	1	3.493
2	2.467	5.518
3	4.137	7.194
4	5.597	8.419
5	6.449	9.070
6	6.449	9.070
7	5.597	8.419
8	4.137	7.194
9	2.467	5.518
10	1	3.493

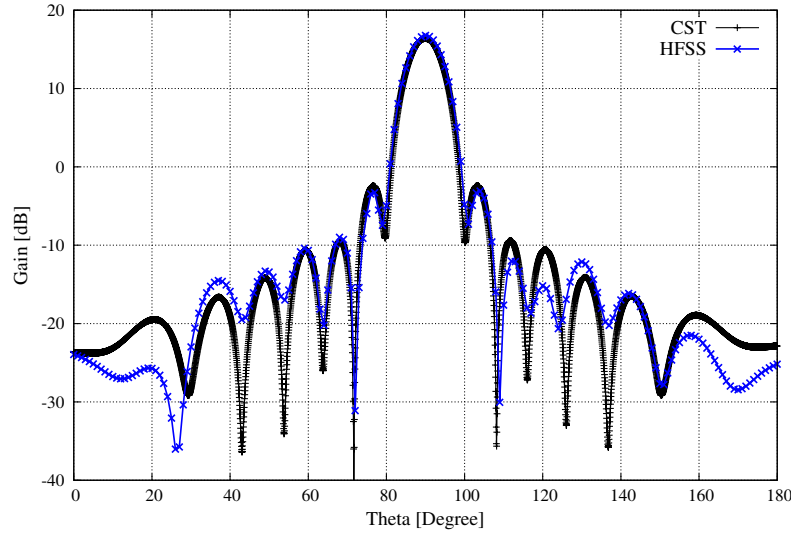


Figure 5. Antenna's YZ -plane pattern for the case of non-uniform slot displacement with Taylor (one-parameter) distribution for an SLR of 20 dB.

3.3. Example 3: 30 dB SLR with Taylor (One-Parameter) Distribution

In this example, a Taylor (one-parameter) distribution is used to obtain an SWA SLR of 30 dB. For this, the taper coefficients for a -40 dB Taylor (one-parameter) distribution are required, and these are listed in Table 3 alongside their corresponding slots displacements. The results show an antenna resonance at 3 GHz, and a peak gain of 15.3 dB. The -30 dB SLL has been attained, and the YZ -plane HPBW has increased to 10 degrees. The YZ -plane gain pattern is shown in Fig. 6.

3.4. Example 4: Binomial Excitation

Although it is not directly possible to use a binomial distribution to control the SLL, it is interesting to use the c_n s from a Binomial distribution and observe the resulting SWA SLL. The binomial coefficients are obtained from the binomial expansion:

$$(1+x)^{m-1} = 1 + (m-1)x + \frac{(m-1)(m-2)}{2!}x^2 + \frac{(m-1)(m-2)(m-3)}{3!}x^3 + \dots \quad (11)$$

Table 3. -40 dB Taylor (one-parameter) coefficients and corresponding slots displacements leading to an SWA SLL of -30 dB.

Slot Number	Taylor-based Coefficient	Displacement (mm)
1	1	1.631
2	6.611	4.215
3	16.828	6.785
4	28.573	8.937
5	36.519	10.181
6	36.519	10.181
7	28.573	8.937
8	16.828	6.785
9	6.611	4.215
10	1	1.631

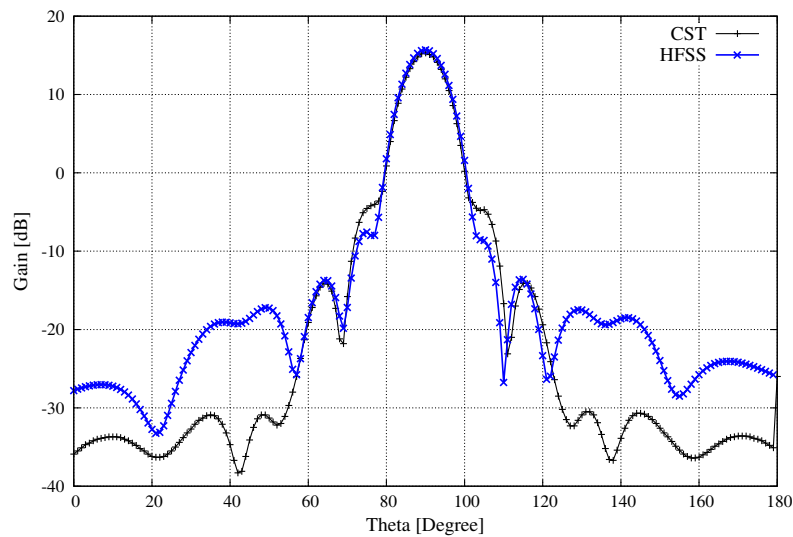


Figure 6. Antenna's YZ -plane pattern for the case of non-uniform slots displacements with Taylor Line-Source distribution for an SLR of 30 dB.

Table 4. Binomial coefficients and corresponding slots displacements.

Slot Number	Binomial Coefficient	Displacement (mm)
1	1	0.964
2	9	2.900
3	36	5.847
4	84	9.069
5	126	11.268
6	126	11.268
7	84	9.069
8	36	5.847
9	9	2.900
10	1	0.964

For the case of 10 slots, the binomial coefficients and the resulting slots displacements are listed in Table 4. For these displacements values, the obtained SLR is 33.5 dB, and the peak gain is 15 dB. The YZ -plane HPBW increases to 11.1 degrees, as shown in Fig. 7.

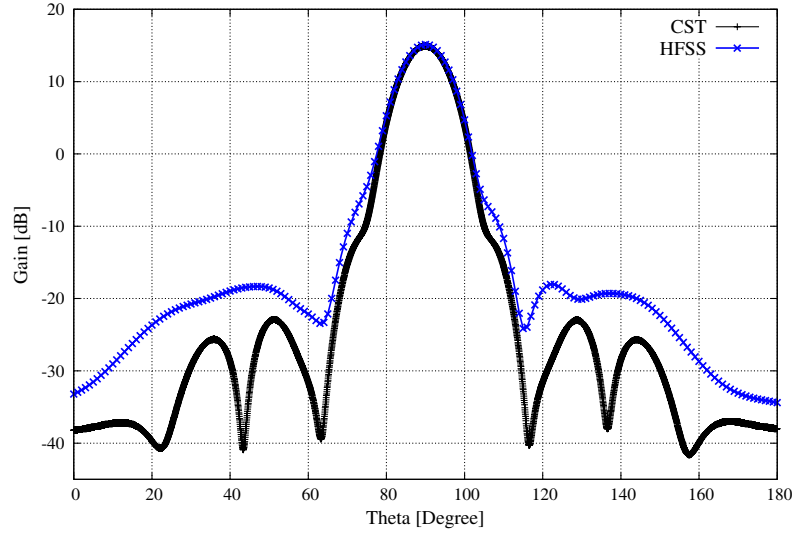


Figure 7. Antenna's YZ -plane pattern for the case of non-uniform slots displacements with binomial distribution.

3.5. Reflection Coefficients

The S_{11} plots for the four examples are shown in Fig. 8. For all the studied examples where all the slots have a fixed length of 54.25 mm, the SWAs retain resonance at 3 GHz, despite the different slots displacements used. This is evident by comparing the S_{11} plot for the case of uniform displacements in Fig. 3(a) to those of the four SWA examples in Fig. 8, where the resonating length of the elliptical slots proved insensitive to the slots displacements.

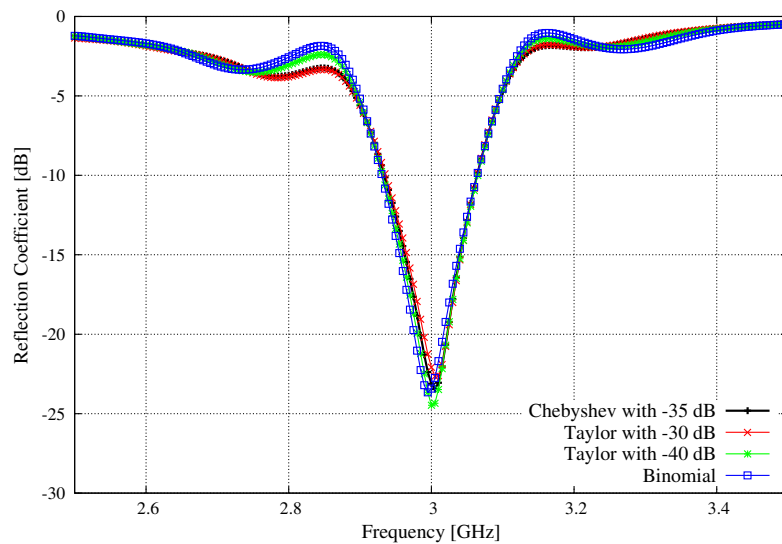


Figure 8. Reflection coefficient plots for the four illustrated examples in case of non-uniform displacements (using CST).

4. COMPUTER PROGRAM

A computer program written in Python has been written to generate the slots displacements for a desired SLL. The program takes as input the design frequency, waveguide dimensions a and b , the number of slots, and the highest allowable SLL. It computes and outputs λ_0 , λ_g , the total needed waveguide length, the resonant length of a rectangular slot (which serves as a starting point in optimizing the length of any used slot shape), the width of the slot (which is kept the same for any slot type), the taper coefficients (Chebyshev or Taylor), and the corresponding slots displacements. The units are indicated on the program graphical user interface (GUI). A screenshot of the program output is given in Fig. 9. This program was used for the examples in Section 3, and for the design in Section 5. Improvements to the program interface are still being done.

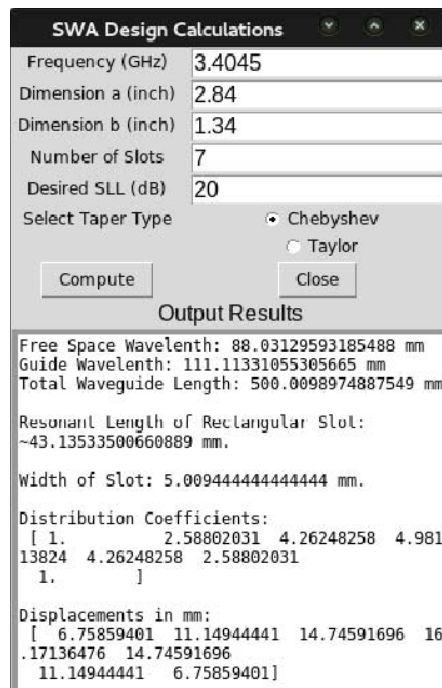


Figure 9. A screenshot of the python program output.

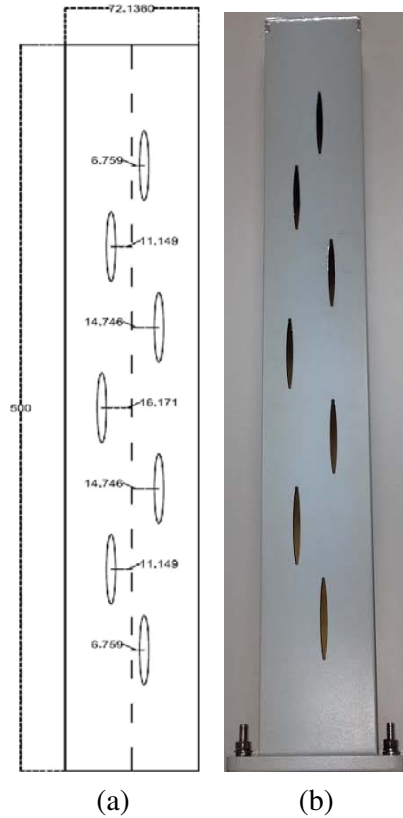
5. FABRICATION AND MEASUREMENTS

In order to validate the procedure illustrated in this paper, a prototype SWA array has been fabricated and tested. The waveguide in hand has a length of 50 cm. This length is not enough to fit 10 slots respecting the different slot distance and length guidelines, so the design has been made with 7 slots, of elliptical shape. To avoid the two edge slots intersecting the waveguide flanges, the distance between each of these two slots and the nearby waveguide edge has been increased from $\lambda_g/4$ to $3\lambda_g/4$, leading to a total SWA length of $4.5\lambda_g$. This change was accounted for in the Python computer program, which was used for this design. To keep the waveguide length of 50 cm, the SWA is designed for a frequency of 3.4045 GHz. At this frequency, $\lambda_g = 111.11$ mm, and $4.5\lambda_g = 50$ cm. After initially designing the SWA with the correct uniform distribution displacement, the elliptical slot length has been optimized to get to this resonance frequency. It is found equal to 48 mm. With this optimized length, and for a slot width of 5 mm, the SWA has later been designed to radiate with a sidelobe level of less than -20 dB. A Chebyshev distribution of -35 dB has been used to calculate the excitation coefficients in this case. These coefficients and the corresponding slots displacements are listed in Table 5.

Table 5. Normalized Chebyshev taper coefficients and corresponding slots displacements.

Slot Number	Chebyshev Coefficient	Displacement (mm)
1	1	6.759
2	2.588	11.149
3	4.262	14.746
4	4.981	16.171
5	4.262	14.746
6	2.588	11.149
7	1	6.759

The design of the fabricated antennas and a photo of the fabricated prototype are shown in Fig. 10. The reflection coefficient plot in Fig. 11 shows a comparison between the results simulated computed using both CST and HFSS software, and two measured results. During Measurement 1, the antenna had some protrusions on the corners of the elliptical slots, which were filed for Measurement 2, resulting in a perfect elliptical shape of the slot. The gain patterns computed in both HFSS and CST compared to the measured results are also shown in Fig. 12. Inspecting the S_{11} and pattern figures, credible analogy has been revealed despite the slight difference, which is due to the other inaccuracies in the fabrication. An SLL of less than -20 dB has been achieved, with a gain of around 14.5 dB, validating the design procedure illustrated in this paper.

**Figure 10.** SWA: (a) designed (dimensions in mm), (b) fabricated.

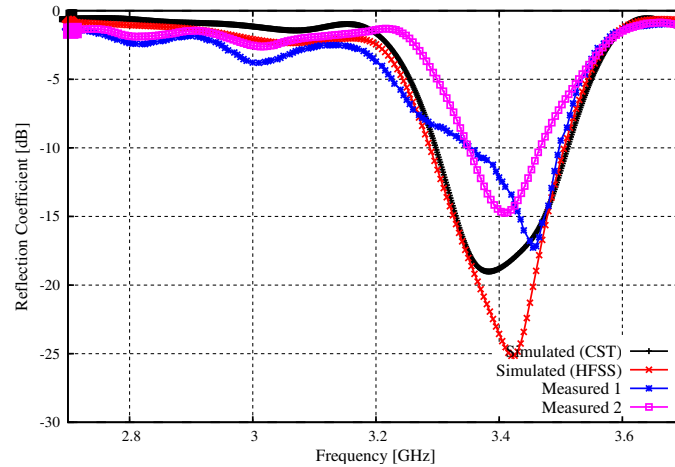


Figure 11. The compared measured and simulated reflection coefficient results.

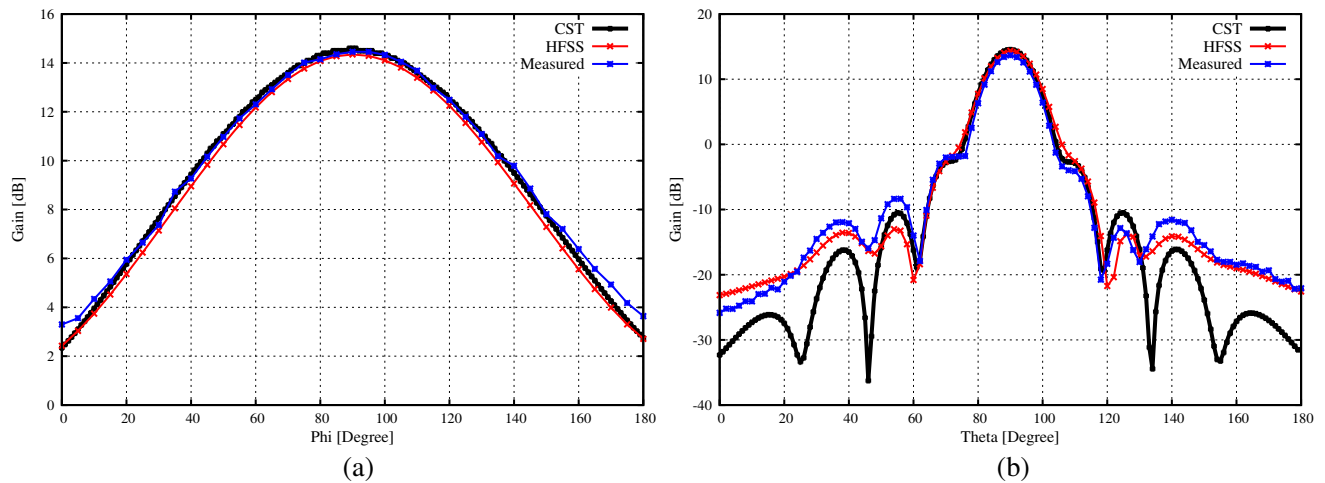


Figure 12. The compared measured and simulated gain pattern results using HFSS and CST: (a) XY -plane, (b) YZ -plane.

6. CONCLUSION

This paper presented a simple procedure for designing SWAs with specified SLLs. General guidelines for the slots width, length and longitudinal positions were first given. The offsets of the slots positions with respect to the waveguide centerline, which determine the SLL, were then obtained from well-known distributions. An intuitive rule regarding the used distribution was deduced, which was to select a distribution with an SLL 15 dB lower than the desired SWA SLL. This procedure was implemented using a Python computer program. Illustrative examples showing the distribution coefficients, slots displacements, resulting patterns and S_{11} plots were given. A prototype antenna was fabricated and tested, and the results were presented.

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