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RESEARCH ARTICLE

Design Procedure of Two-Dimensional Slotted Waveguide Antenna Arrays with Controllable Sidelobe Level Ratio for High Power Microwave Applications

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Summary

This paper presents a complete design procedure, with an optimized feeding method, of two-dimensional slotted waveguide antenna arrays (2D SWAs). For a desired sidelobe level ratio, the proposed system provides a pencil shape pattern with a narrow halfpower beamwidth, controllable sidelobe level ratio (SLR), and very low sidelobe levels (SLL), which makes the proposed 2D SWA system suitable for high power microwave applications. The radiating slotted waveguide antennas use longitudinal slots, designed for a specified slidelobe level ratio and resonance frequency. The resulting two-dimensional slotted waveguide antenna array is formed by stacking a number of similarly designed radiating SWAs, and fed with an additional SWA. The proposed feeding method uses longitudinal coupling slots rather than the conventional inclined coupling slots, which can provide better values of SLR and easily obtain very low SLLs, in comparison with the conventional systems. The feeder dimensions and slots positions are deduced from the dimensions and total number of the radiating SWAs. For a desired SLR, the slots excitation in the radiating and feeder SWAs are calculated based on a specified distribution. Then, using simplified closed-form equations and for a desired resonance frequency, the slots lengths, widths, and their distribution along the length of the radiating SWAs and feeder SWA can be found. Two examples are illustrated with different number of slots and radiating elements, and one is fabricated and tested. Chebyshev distribution is used to estimate the excitations of the SWA slots in the examples. The obtained measured and simulated results are in accordance with the design objectives.

KEYWORDS:
Antenna arrays, High power microwave applications, Slotted waveguide antennas (SWA), Sidelobe level (SLL), Sidelobe level ratio (SLR)

1 | INTRODUCTION

High Power Microwave (HPM) technology is well known in both military and commercial applications [1]. An efficient antenna to be used as the radiating system in such applications is required to have a well directive pattern, low sidelobe levels, large sidelobe level ratio, and high gain. It should also have high power handling capability required to extract the high power microwaves from the HPM source. Slotted Waveguide Antennas (SWA)[2] are taking a major interest in this field, with their major ability of beam pointing, in addition to their high power microwave handling capability[3]. SWAs can be also directly connected to Reltron high power microwave sources, without the need for additional mode converter, which makes them suitable for high power microwave applications.

Slotted waveguide antennas are made of rectangular waveguides, having slots cuts used to radiate the energy. The conventional cuts have a rectangular shape. The slots can be made either on the broadwall or the narrow wall of the waveguide. SWAs can be either resonant or non-resonant antennas, also known as standing wave or traveling wave antennas. The resonant SWAs are preferred to their counterparts due to the short circuit termination that increases their efficiency, with no power loss and normal main beam independent of the resonance frequency, but with a narrower frequency range[4,5]. The traveling-wave slotted waveguide antennas have a larger bandwidth, but suffer from lower efficiency due to the matched load used to prevent the reflections of the waves. In addition, a phase difference is present between the radiating slots, whereas, for resonant slots their impedance or admittance are real values. In this work, resonant slotted waveguide antennas are designed and investigated.

The design of one-dimensional resonant slotted waveguide antennas was first presented by Stevenson and Elliott[4,6,7]. Two main equations, based on Stevenson equations and Babinet's principle, should be solved simultaneously to determine the different slots displacements from the waveguide centerline and the slots length. Solving these equations depends on Stegen's assumption of the universality of the resonant slot length[8], in addition to Tai's formula[9] and Oliner's length adjustment factor[10]. This conventional design method is complicated, and mostly rely on numerically solving several equations to deduce both the displacement and length of each slot. The excitations of the SWA individual slots, which are translated into slots displacements, control the resulting SLR of the SWA array[6]. In our previous work in[11,12], these conventional design equations of one-dimensional slotted waveguide antennas have been simplified, by which all the slots are considered to have the same uniform length, and closed form equations are used to determine the slots non-uniform displacements, for a desired sidelobe level ratio.

The latest research in the slotted waveguide antenna design field focuses on obtaining a pencil shape pattern, with high gain, large sidelobe level ratio, and narrow half power beamwidth. To achieve these features, slotted waveguide antenna arrays can be formed by stacking a specified number of radiating slotted waveguide antennas, designed for a specified sidelobe level ratio using the conventional design procedure. These conventional systems use inclined coupling slots to couple the power from an additional slotted waveguide antenna to the stacked SWA radiating elements. The rotation angles of these coupling slots from the waveguide centerline are either considered to be uniform or non-uniform. To control the typical inclined coupling slots, usually complicated equations that relate the inclination angle to the excitation voltage and distribution are used, different than those used for the design of longitudinal slots, which makes designing large arrays a complicated procedure[13,14,15,16,17,18]. Other feeding mechanisms use complicated structures to achieve low sidelobe levels[19,20].

This paper expands our work in[11] from the design procedure of one-dimensional slotted waveguide antennas to the full design of two-dimensional slotted waveguide antenna arrays with an optimized feeding method. The proposed feeding technique employs longitudinal coupling slots rather than the conventional inclined coupling slots, designed for a specified sidelobe level ratio. The usefulness of the proposed method is seen in the simplicity of the design procedure and the achieved very low SLL results and high gain. The design is simplified by using the same proposed closed-form equations in the design of both the radiating SWAs and the feeder SWA. By choosing a large sidelobe level ratio, negligible values of sidelobe levels can be achieved.

The proposed design procedure in this work is outlined as follows and illustrated in details in the following sections. Starting with a desired sidelobe level ratio, the slots excitation of the broadwall longitudinal slots for both the radiating slotted waveguide antennas and the feeder slotted waveguide antenna, are calculated from a certain distribution. The slots excitations are then used to calculated the required slots displacements, as will be explained in details in the following sections. The feeder slotted waveguide antenna is then coupled to the radiating slotted waveguide antennas in an efficient manner to obtain very low sidelobe levels and large sidelobe level ratio. To verify the validity of this 2D SWA array design method, two examples are illustrated that differ in their operating frequency range, number of slots, and number of radiating slotted waveguide antennas. The two examples are denoted by 8×8 and 10×10 2D SWAs, having eight slots with eight radiating SWAs, and ten slots with tens radiating SWAs respectively. The 10×10 example is presented for comparison purposes with a similar system using conventional design equations and inclined coupling slots. The 8×8 proposed system is then fabricated and tested.

The following sections are organized as follows. Section 2 presents the complete design procedure of one-dimensional slotted waveguide antenna with longitudinal slots for a desired sidelobe level ratio, to be used for both the radiating slotted waveguide antennas and the feeder slotted waveguide antenna. Section 3 presents the proposed feeding method to couple the power from the feeder slotted waveguide antenna to the radiating slotted waveguide antennas. Coupling the feeder SWA to the radiating SWAs is illustrated through two examples. Section 4 presents the simulations and results of both illustrated examples, with a comparison with a conventionally designed 2D SWA array system. Section 5 presents the fabrication and testing of one of the illustrated examples, and the measured results are compared to the simulated ones and presented at the end of this work.

2 | DESIGN PROCEDURE OF ONE-DIMENSIONAL SLOTTED WAVEGUIDE ANTENNA

This section presents the proposed design procedure of one-dimensional slotted waveguide antennas with broadwall longitudinal slots, to be used to design the radiating slotted waveguide antennas and feeder slotted waveguide antenna. It starts by defining the slot shape used in this work, and illustrates how to find the position of these slots along the length of the waveguide in Section 2.1. Section 2.2 presents the calculation of the slots lengths and width. The calculation of the slots displacements, used to control the sidelobe level ratio of the slotted waveguide antenna, is presented in Section 2.3.

2.1 | Slots Positions and Shape

The position of the slots along the length of the slotted waveguide antenna plays an important role in ensuring feeding the slots in phase. The phase shift between consecutive slots is determined by the electrical distance $2\pi d/\lambda_g$. Using longitudinal slots, the waveguide itself acts as a transmission line. Taking a transverse electric field in each slot, the TE_{10} mode scattering is considered to be symmetrical. Using an equivalent transmission line, each slot is modeled as a shunt element. This assumption is proved to be valid using the Method of Moment (MoM) when the width of the slots is narrow, their offsets are not too large, and the height of the waveguide is relatively large[21].

Since in resonant slotted waveguide antennas the end is terminated by a short circuit, open circuit impedance is found at a quarter guide wavelength down the length of the waveguide, using analogy with transmission line theory. For this, a distance of quarter guide wavelength $\lambda_g/4$, or $3\lambda_g/4$, is placed between the terminating end terminal of the slotted waveguide antenna and the last slot. The guide wavelength (λ_g) is defined as the distance traveled by the electromagnetic wave along the length of the waveguide to undergo a phase shift of 2π radians, hence obtaining two equal phase planes, given by (1), with λ_0 being the free-space wavelength and c is the speed of light. In the same way, the distance between the first slot and the start of the waveguide is $\lambda_g/4$, or $3\lambda_g/4$.

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

In order to have the same input impedance viewed a half guide wavelength away, the separation between the slots is taken to be $\lambda_g/2$. In this way, all the slots can be viewed as being in parallel. The shunt admittance of these terminations then vanishes at the last slots and so does not affect the input impedance. The input impedance and admittance for an N element SWA can be calculated as in (2) and (3). The admittance of each slot should have a value of $1/N$, in order for the normalized slot admittances to add up to unity, and hence ensure a perfect impedance matching at the input. For this, a good matching at the desired frequency can be achieved in such systems with a matching circuit, if the design parameters are properly optimized.

$$Y_{in} = \sum_{1}^{N} Y \tag{2}$$

$$Z_{in} = \frac{1}{\sum_1^N Y} \tag{3}$$

The conventional rectangular slots used in the traditional SWA design could aggravate electrical breakdown problems when working at high power microwave. Avoiding sharp corners is a must in such applications. For this, and to improve high power operation and manufacturability, rounded-ended slots[8] are used in this design, seen in Figure 1.

2.2 | The Slots Length and Width

To reach an optimal coupling of slots and feeding waveguide, and to have an optimal radiation at the required operating frequency, the length of all slots are taken to be at their resonant length, typically around half wavelength or 0.49λ, as presented by Stevenson

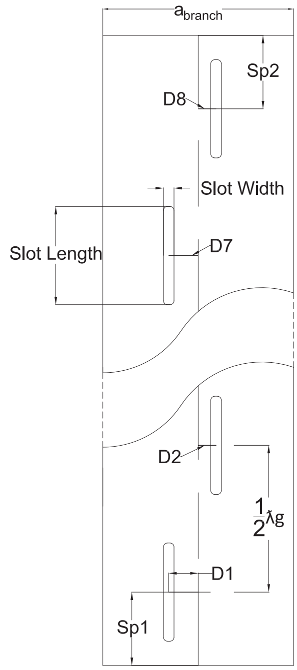

FIGURE 1 One-dimensional slotted waveguide antenna design structure with 8 longitudinal slots.

in[6]. This 0.49λ length is usually taken for rectangular slots. In corner edge slots, as the ones used in this paper, an optimization of this length is recommended, for which the slots displacements and positions are fixed, and the length is varied starting with an initial value of 0.49λ, while checking the reflection coefficient results till getting an acceptable value at the desired frequency. Throughout all the simulations that we did with this method, the optimized values usually differed from the initial value in a range of $1-3\%$ only. Nevertheless, although the conventional design method requires finding optimized length for each slot, assuming uniform slot length has been adopted in several papers in the design of slotted waveguide antenna for simplicity purposes, and it turned out to give excellent results, in accordance with the design objectives[11,18,22,23,24,25,26,27,28]. The width of the slot is calculated based on proportionality with other designed slotted waveguide antennas, as will be shown in the illustrated examples.

2.3 | The Slots Displacements

The distance separating the waveguide broadwall centerline and the center of the slot is specified as slot displacement. Although the slots could be placed at the same distance from the centerline, it was shown in[11] that such a configuration results in a sidelobe level ratio of around 13 dB, which is similar to the case of having equal excitations to discrete elements in an antenna array. For this, non-uniform displacement are used to design the radiating slotted waveguide antennas for larger sidelove level ratio. Referring to Figure 1, the slots displacement are indicated by ***Dn*** for which *n* is the index of each slot. To achieve higher efficiency, all slots must radiate in phase. For this, the slots are placed in an alternating order on the length of the waveguide.

Figure 2 illustrates the methodology used to calculate the slots displacements for both the radiating slotted waveguide antennas and the feeder slotted waveguide antenna. The slots displacements are calculated as follows. Starting with a desired sidelobe level ratio, the conductances of the slots are obtained from a certain distribution. Taylor, Chebyshev, and Binomial distributions have been used previously in our 1D SWA work[11]. For the case of simplicity, only Chebyshev distribution is used here in the illustrated design procedure. Using the obtained slots conductances, the slots displacements can be then deduced. The slots displacements control the excitation of every radiating slot, and hence they can be used to control the total sidelobe level ratio of the slotted waveguide antenna array, achieving very low sidelobe levels.

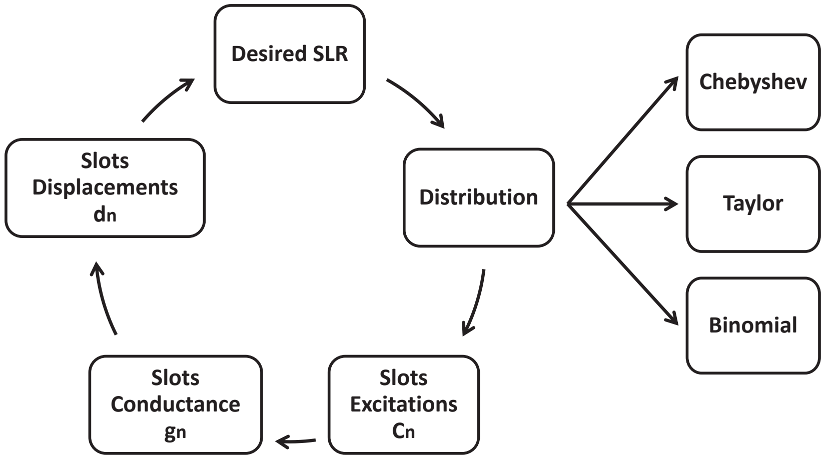

FIGURE 2 Methodology used in the calculation of the slots displacements for a desired sidelobe level ratio.

Beginning with the equation of the array factor of a generalized Chebyshev array[29,30] given in (4), the array factor is then calculated for a uniform spacing and an amplitude symmetrical about the center, as given in (5). The excitation coefficients can be then obtained using (6).

$$f(u) = \frac{1}{R}\prod_{n=1}^{p}\left(T_{N_n-1}(\gamma_n cos\frac{u}{2})\right). \tag{4}$$

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

$$f(u) = \begin{cases} 2\sum_{m=1}^{N/2} I_m cos[(m-1/2)u], & \text{for N even} \\ \sum_{m=1}^{(N+1)/2} \epsilon_m I_m cos[(m-1)u], & \text{for N odd} \end{cases} \tag{5}$$

where ϵ_m equals 1 for $m = 1$ and equals 2 for $m \neq 1$.

$$I_m = \begin{cases} \frac{2}{NR}\sum_{q=1}^{N/2} f[u=p]cos[q], & \text{for N even} \\ \frac{1}{NR}\sum_{q=1}^{\frac{N+1}{2}} \epsilon_q f[u=v]cos[w], & \text{for N odd} \end{cases} \tag{6}$$

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 $w = 2\pi/N(m-1)(q-1)$

After calculating the slots excitations coefficients, the slots displacements can be calculated. The normalized conductance of the n^{th} indicated by g_n can be calculated using (7) and (8)[11], with N being the number of slots, and $c_n s$ are the distribution coefficients calculated using Chebyshev distribution for a desired SLR.

$$d_n = \frac{a}{\pi}\arcsin\sqrt{\frac{g_n}{2.09\frac{\lambda_g}{\lambda_0}\frac{a}{b}\cos^2\left(\frac{\pi\lambda_0}{2\lambda_g}\right)}} \tag{7}$$

$$g_n = \frac{c_n}{\sum_{n=1}^{N} c_n}. \tag{8}$$

3 | DESIGN PROCEDURE OF THE TWO-DIMENSIONAL SLOTTED WAVEGUIDE ANTENNA ARRAY

After describing in Section 2 the method to design one-dimensional slotted waveguide antennas, this section uses the presented design procedure to design two-dimensional slotted waveguide antenna array. Two examples, with different total number of radiating slotted waveguide antennas and desired sidelobe level ratio, are illustrated using the proposed design procedure, in Sections 3.1 and 3.2. The procedure starts with the design of one-dimensional radiating slotted waveguide antennas for a desired sidelobe level ratio and at a required operating frequency, as presented in Section 3.1.1. Using the same desired sidelobe level ratio, the dimensions of the radiating SWA, and the total number of the radiating SWAs, the feeder slotted waveguide antenna can be then designed, as illustrated in Section 3.1.2. Afterwards, the radiating slotted waveguide antennas are stacked side by side, and the feeder slotted waveguide antenna is coupled to feed each slotted waveguide antenna in an optimized technique and for a desired sidelobe level ratio, as presented in Section 3.1.3. At the end of this section, the mutual coupling that might be found in such systems, along with ways to suppress its effect, are presented in Section 3.3.

3.1 | Example 1

3.1.1 | Radiating Slotted Waveguide Antennas Design

In this example, the design of eight radiating slotted waveguide antennas, with eight longitudinal coupling slots made on each radiating SWA, is illustrated. The radiating slotted waveguide antennas are indicated hereafter by branchlines SWAs, and Example 1 is indicated by 8×8 2D SWA. The 8×8 2D SWA is designed to operate at a frequency of 3.952 GHz, with a sidelobe level ratio of not less than 20 dB in both radiating planes, and with a narrow halfpower beamwidth. The standard waveguide WR-229 is used for this design, with inner dimensions a of 2.29 in, and inner height b of 1.15 in.

Using the design procedure presented in Section 2, the following design specifications are obtained. The slots length and width are found to be 36.2 mm ($\simeq 0.477\lambda$) and 5 mm ($\simeq 0.066\lambda$) respectively. With a guide wavelength of 100.05 mm ($\simeq 1.324\lambda$), the slots are separated by a distance of 50.025 mm ($\lambda_g/2 \simeq 0.66\lambda$), whereas a distance of 25.0125 mm ($\lambda_g/4 \simeq 0.33\lambda$) is separating the first and last slot (8^{th}) from the two end terminals. Using Chebyshev distribution, with a desired sidelobe level ratio of 20 dB, the slots displacements are calculated using the equations provided in Section 2.3, and listed in Table 1.

3.1.2 | Feeder Slotted Waveguide Antenna Design

After designing the SWA branchlines responsible of the main radiation of the slotted waveguide antenna array, the feeder slotted waveguide antenna is designed in this section. In Section 3.1.1, the dimensions of the radiating slotted waveguide antennas were chosen as per the desired frequency of operation. As for the feeder SWA, the inner dimensions are unknown from the beginning and must be found before as will be explained in the following.

Referring to Figure 3, in order to place the longitudinal coupling slots of the feeder SWA centered at the centerline of every SWA branchline (radiating SWA), the separating distance between two consecutive coupling slots must be equal to the inner width dimension of the SWA branchline ($a_{branchline}$), in addition to twice the dimension of the wall thickness of each SWA branchline (W). Referring to the design procedure presented in Section 2, the distance separating two consecutive slots must be equal to $\lambda_g/2$ for highest efficiency. As such, the guide wavelength of feeder SWA ($\lambda_{g(feed)}$) should be as close as possible to twice the distance separating two consecutive coupling slots ($a_{branch} + 2 \times W$).

For Example 1, the distance separating two consecutive coupling slots is 62.23 mm ($\simeq 0.82\lambda$). Hence, the closest waveguide having guide wavelength as close as possible to 124.46 mm ($\simeq 1.64\lambda$) at 3.952 GHz is the WR-187 waveguide, having a guide wavelength $\lambda_{g(feed)}$ of 125.92 mm ($\simeq 1.66\lambda$), inner width (a_{branch}) of 1.872 in, and inner height of 0.872 in. It is worth mentioning here that, since the distance between consecutive slots is not exactly equal to $\lambda_{g(feed)}$, the slot length of the feeder should be again optimized for best efficiency at 3.952 GHz. Doing this, the optimized slot length in the SWA feeder is found to be equal to 37 mm ($\simeq 4.88\lambda$). The width of the slot is taken also to be 5 mm ($\simeq 0.066\lambda$). To calculate the slots displacements along the length of the feeder SWA, indicated by D_{feed} in Figure 3, Chebyshev distribution is also used, with a desired sidelobe level ratio of 20 dB. The obtained slots displacements are listed in Table 1, 3^{rd} column.

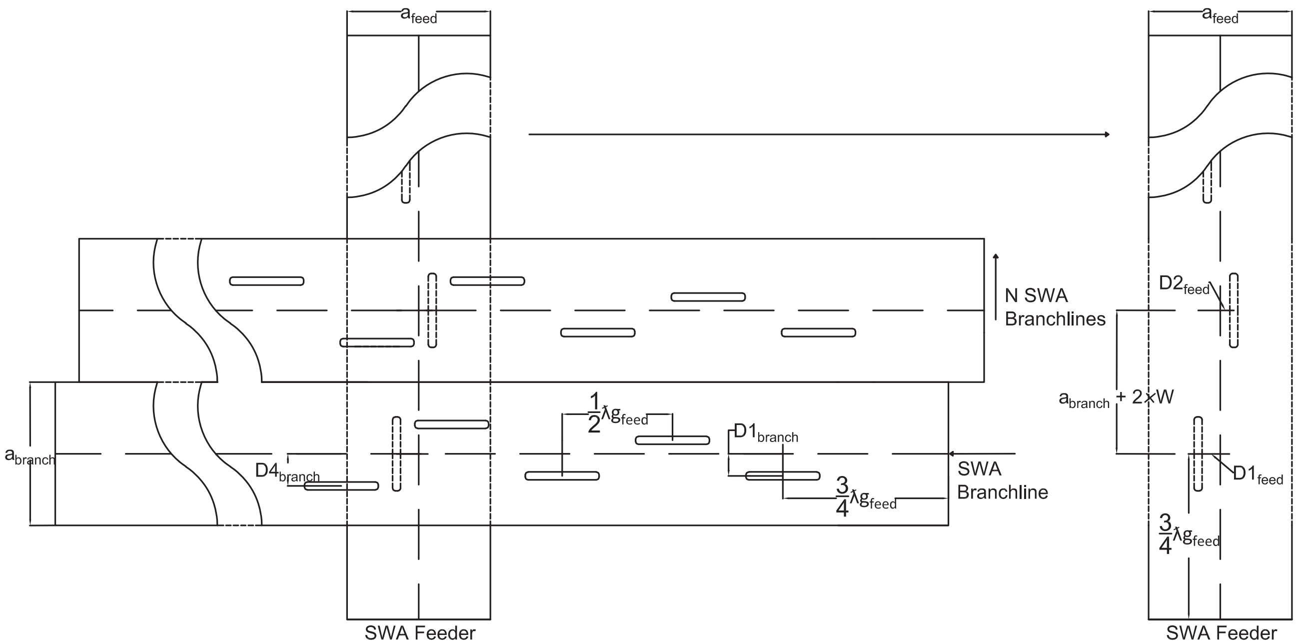

FIGURE 3 2D SWA design showing only two SWA branchlines and the SWA feeder. D_{branch} refers to the displacement of each radiating slot from the branchline SWA centerline. D_{feed} refers to the displacement of each coupling slot from the feeder SWA centerline. W refers to the wall thickness of all SWAs. Only one part of the SWA branchlines is also shown. Each SWA branchline is moved by D_{feed} as per the displacement of the coupling slot feeding it.

TABLE 1 Slot displacements in branchlines and feeder SWAs of the 8 × 8 2D SWA array of Example 1.

Slot Number	Distribution Coeff. (C_n)	Normalized Conductance (g_n)	Displacement (d_n)	
			Branchlines (WR-229)	**Feeder** (WR-187)
1 & 8	1.000	0.039	4.260	1.888
2 & 7	2.420	0.095	6.715	2.948
3 & 6	4.094	0.161	8.880	3.852
4 & 5	5.221	0.205	10.148	4.363

3.1.3 | Two-Dimensional Slotted Waveguide Antenna Array Design

After designing the feeder slotted waveguide antenna, the eight radiating SWAs are stacked side by side, and the feeder SWA is collected at the bottom of the their broadwall faces. It is observed in this manner that the coupling slots are not properly placed at an equidistant from the neighboring radiating slots on each radiating SWA. This might affect the radiation pattern of the complete system, through increasing the grating lobes and hence decreasing the sidelobe level ratio of the system. For this, each branchline SWA is re-positioned as per the displacement of its corresponding feeding slot, as shown in Figure 3. The complete system is shown in Figure 4. The simulations of Example 1 system are presented in Section 4.1.

3.2 | Example 2

In the second example, a 10×10 two-dimensional slotted waveguide antenna array, with ten radiating slotted waveguide antennas, with ten longitudinal slots made on the waveguides broadwall faces, is designed to operate at 2.9 GHz, with a sidelobe level ratio of 20 dB. The complete design is similar to the one shown in Figure 4, but with different number of radiating SWAs, radiating slots, and feeding slots. WR-284 waveguides are used here for the SWA branchlines, with inner width (a_{branch}) of 2.84 *in*, and

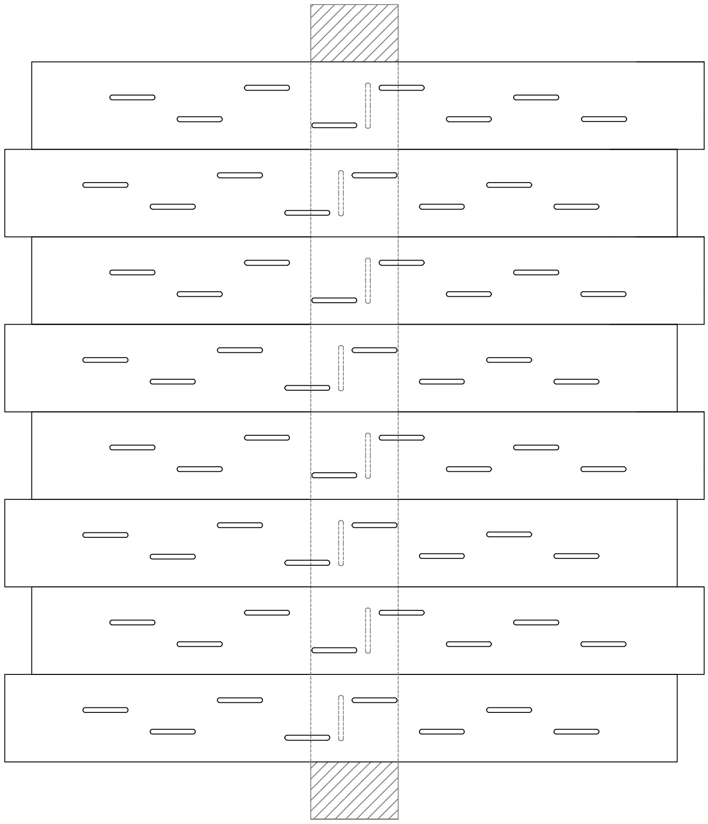

FIGURE 4 Complete design of the 8 × 8 2D SWA array of Example 1.

TABLE 2 Slot displacements in branchlines and feeder SWAs of the 10 × 10 2D SWA array of Example 2.

Slot Number	**Distribution Coeff.** (C_n)	**Normalized Conductance** (g_n)	**Displacement** (d_n) **Branchlines & Feeder** (WR-284)
1 & 10	1.000	0.029	3.411
2 & 9	2.085	0.061	4.946
3 & 8	3.535	0.103	6.475
4 & 7	4.874	0.142	7.644
5 & 6	5.682	0.165	8.280

inner height of 1.34 *in*. In this case, the distance separating the coupling slots should be equal to 76.2 mm ($\simeq$ 0.737λ). The waveguide that has a value of guide length as close as possible to 152.4 mm ($\simeq$ 1.474 λ) is also the WR-284 waveguide used for branchlines, with a guide wavelength $\lambda_{g(feed)}$ of 148.109 mm ($\simeq$ 1.432 λ).

Using Chebyshev distribution, with a desired sidelobe level ratio of 20 dB, the slots displacements are calculated using the equations provided in Section 2.3, and listed in Table 2. The simulations of Example 2 system, along with a comparison of the obtained results with a conventional similar two-dimensional slotted waveguide antenna array, are presented in Section 4.2.

3.3 | Mutual Coupling Suppression

In such systems, two different mutual coupling effects can arise. The first is due to the coupling between the radiating slots on the broadwall of the radiating SWAs (branchlines). The second is due to the coupling between the coupling slots and the radiating slots. Both of these effects have been suppressed and hence neglected in the equations as outlined in the following.

3.3.1 | Mutual Coupling between the Radiating Slots

This type of coupling is mainly affected by the separating distance between the shunt slots, and their location on the waveguide broadwall. Their separating distance has been investigated in several papers, for which it was shown that the mutual coupling is much smaller when the slots are separated by half-waveguide length. In fact, it was concluded in[31] that this type of mutual coupling can be neglected if this distance is adopted between the slots. In[32], it was also shown that this type of mutual coupling can be also neglected in the design of shunt slot arrays, unless the SWA has a short length and few lots.

For slotted waveguide antennas, and as described in Section 2, the driving impedance of the radiating slots depends on their excitation, position, and displacement along the length of the waveguide, with respect to neighboring slots. For this, the procedure presented in this work mainly focuses on calculating the elements excitations for optimized radiation. These excitations, in their turn, control the displacement of each slot, and hence the coupling between the elements. The distance separating any consecutive radiating slots is chosen to have the least mutual coupling in between. The slots are also separated by half guide wavelength in each branchline SWA and feeder SWA, and placed in an alternating order for maximum efficiency and to suppress the mutual coupling between neighboring slots. Nevertheless, the mutual coupling between the neighboring slots in the same SWA branchline is not necessarily negligible in all designs, and this will be investigated in further work.

3.3.2 | Mutual Coupling between the Coupling and Radiating Slots

The coupling effect between two antennas is commonly modeled as an impedance variation. When mutual coupling is present in slotted waveguide antennas, it generally results in an increase of 8% in slot conductance[32]. The effect of mutual coupling in such designs can be simplified as follows. The resonant slot length might be affected and could result in a shift of the resonance frequency to a higher value, the impedance bandwidth (VSWR) is shifted to a higher frequency in the SWA branchlines (radiating SWAs), whereas in the feeder SWA the voltage standing wave ratio (VSWR) is shifted to a lower frequency. The combination of these effects could still lead to results as desired.

The effect of the mutual coupling on the radiation pattern and the reflection coefficient results for slotted waveguide antennas have been presented in several papers, for which some of them have neglected this effect[6,8,16,33,32,34,35,36,37,38], which is a valid assumption for resonant slotted arrays[39]. It was shown in[37] that the effect of mutual coupling on the array performance is minimal. In[21], it was concluded that the effects of higher order internal coupling modes can be ignored for full- and half-height guide. In[38], it was shown that this type of coupling is only significant for small offsets or tilts.

In this work, the input to each radiating SWA, i.e. each coupling slot, is located at a distance of $\lambda_g/4$ from the radiating slots to the left and to the right, as seen in Figure 3. Doing this, the impedance to the left and right of the input is transformed through quarter-wavelength sections and hence should have the same normalized values. In addition, the inner dimension, b, of the feeder slotted waveguide antennas, is chosen to be relatively large, and hence the internal higher order mode coupling between adjacent slots can be ignored[21]. For the two-dimensional slotted waveguide antenna array, the distance separating the radiating slots between the nearest SWA branchlines is larger than half wavelength, as such the mutual coupling between the slots in different SWA branchlines is negligible[16].

In addition, some work showed that the analytical results in the case of considering the mutual coupling in the calculations of the slots excitations are very close to those resulting from CST simulation software[33,40,41]. Taking into account the mutual coupling effects, the radiation characteristics can be slightly enhanced in terms of the SLLs and return loss. In this work, we were able to achieve the desired SLL at the required resonance frequency, and hence any further enhancement that can result from including the mutual coupling effects in the design equations is not essential for the overall results. Nevertheless, CST simulation software is used in the simulations of this work which takes into account the effects of mutual coupling in the computational evaluation. Inspecting the results achieved in this paper in later sections, even with the mutual coupling not taken into account in the calculations, the results turned out to have good analogy with the design requirements and specifications.

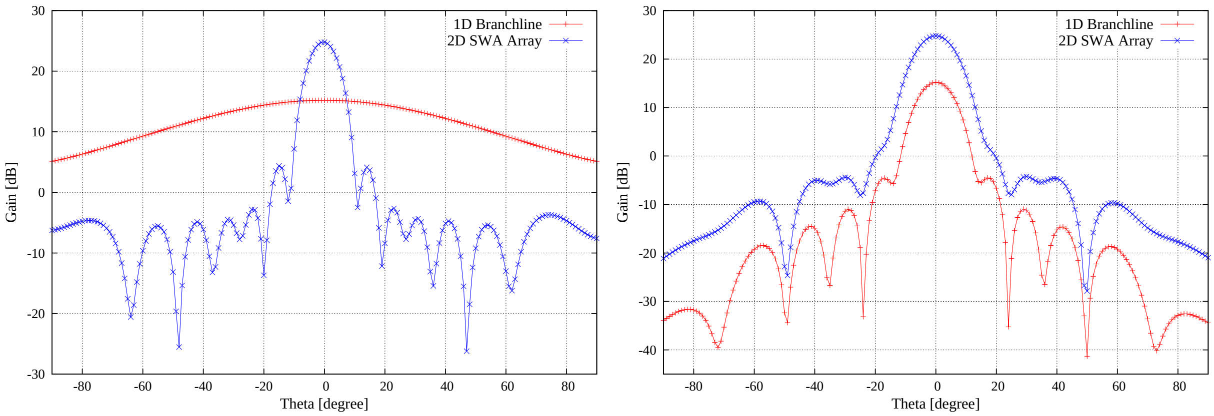

FIGURE 5 Rectangular gain pattern comparison of the 1D and the 8 × 8 2D SWA of Example 1, (left) E-plane, (right) H-plane, computed using CST.

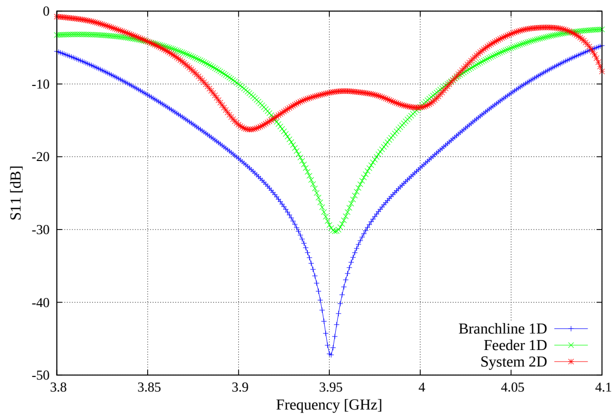

FIGURE 6 S_{11} results of the SWA branchline, SWA feeder, and the 8 × 8 2D SWA array of Example 1, computed using CST.

4 | SIMULATIONS AND RESULTS

After going through the illustrated examples in Section 3, this section presents the simulations results of both examples. The reflection coefficient, in addition to the radiation pattern plots are presented, with a comparison of the one-dimensional slotted waveguide antenna results, and the two-dimensional slotted waveguide antenna array results.

4.1 | Example 1

The two-dimensional slotted waveguide antenna array system design of Example 1, designed to operate at a frequency of 3.952 GHz, and for a sidelobe level ratio of 20 dB in Section 3.1, is first simulated and studied. The advantage of the proposed design procedure in this work is clearly seen in the radiation pattern results. Figure 5 shows the gain pattern plots of the two-dimensional slotted waveguide antenna, in comparison with that of one branchline (radiating) slotted waveguide antenna, in both radiating planes. Table 3 compares the halfpower beamwidth, sidelobe level ratio, and gain, of 1D SWA and 2D SWA array system. As can be inspected, the SLR is at least 20 dB in both planes, as per the design requirement, with an SLR of 20.4 dB in the E-plane, and 29.0 dB in the H-plane. The total gain has increased from 15.2 dB to 24.8 dB. The HPBW in the E-plane has also decreased from 80.1° to 8.8°, with 12° in the H-plane, resulting in a pencil shape pattern, suitable for applications requiring high power well-directive patterns.

Figure 6 compares the reflection coefficient results (S_{11}) of the one-dimensional slotted waveguide antenna, the feeder slotted waveguide antenna, and the two-dimensional slotted waveguide antenna array of Example 1. It can be seen that 2D SWA system is still resonating in the desired operating frequency of 3.952 GHz. A variation in the value of the reflection coefficient is also seen, which could be the result of the mutual coupling effect previously discussed, but neglected for simplicity. The total simulated efficiency of this antenna is 86%.

The breakdown capability of this antenna array has been also studied. The maximum value of the voltage has been calculated on the slot responsible for the maximum radiation. The slots that give the maximum radiation are the slots found in the middle of the array system: having the maximum fed power input from the SWA feeder, and the maximum displacements from the SWA branchline centerline where the slots are located. Simulating the design taking a high input power to the feeder SWA of a 6.25 MW, the maximum voltage on these slots is found to be equal to 5.55×105 V/m. This maximum voltage is still lower than the onset of air breakdown 3×10^6 V/m that can cause the air to begin to break down. A lower value of this maximum voltage, and hence a higher value of power radiated, can be attained using larger slot width value, if needed.

4.2 | Example 2

The two-dimensional slotted waveguide antenna array system design of Example 2, designed to operate at a frequency of 2.9 GHz, and for a sidelobe level ratio of 20 dB in Section 3.2, is then simulated and studied. Figure 7 shows the simulated gain pattern plots for both E- and H- planes of the 10×10 2D SWA array of Example 2, with Figure 8 showing the 3D gain pattern. As desired, a high gain has been achieved with a large sidelobe level ratio, and narrow halfpower beamwidth.

The purpose behind designing and studying Example 2 is to compare the proposed design procedure in this work with a similar 2D SWA array, with the same number of radiating SWAs, same total number of slots, and the same operating frequency presented in [16] using the conventional design procedure. For this, the obtained gain pattern results are then compared with two 2D SWA array systems presented in [16], as indicated in Table 4. The first system consists of a 10×10 2D SWA array, with the conventional inclined coupling slots made on the SWA feeder. In order to increase the gain and further decrease the sidelobe level ratio, the second system in [16] collected four of the 10×10 2D SWA array of the first system, with a total of 40 SWA branchlines, and four feeders SWAs. The total achieved SLR of the second system in [16] reached 22.2 dB in the E-plane and 22.72 dB in the H-plane. In comparison with our design procedure illustrated in this paper, the advantage of the proposed method is clearly seen in the larger sidelobe level ratio achieved in the proposed work here, reaching SLR values of 27.4 dB in the E-plane and 27.7 dB in the H-plane, outperforming the SLR of the four collected 10×10 2D SWA array in [16]. This confirms the validity of the simplified closed-form equations used in the design procedure of the proposed two-dimensional slotted waveguide antenna arrays, and the assumptions adopted.

TABLE 3 Gain characteristics comparison of the case of 1D SWA and the designed 8×8 2D SWA, computed using CST.

Case	E-Plane		H-Plane		Gain (dB)
	HPBW°	SLR (dB)	HPBW°	SLR (dB)	
1D SWA	80.1	NA	11.4	20	15.2
2D SWA Array	8.8	20.1	12	20.1	24.7

TABLE 4 Gain characteristics comparison of the proposed antenna and the conventional design in [16].

Antenna	SLR (dB)		Gain (dB)
	E-Plane	H-Plane	
Proposed Single Array 10×10	27.4	27.7	25.3
Single Array 10×10 in [16]	13.67	13.67	25.4
Four Arrays 10×10 each in [16]	22.2	22.72	31.4

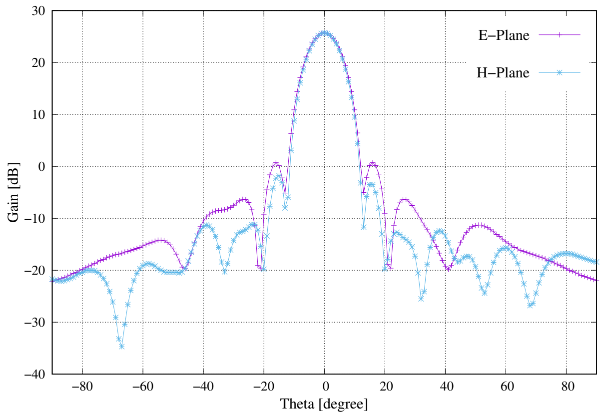

FIGURE 7 Gain pattern of the 10 × 10 2D SWA of Example 2, computed using CST.

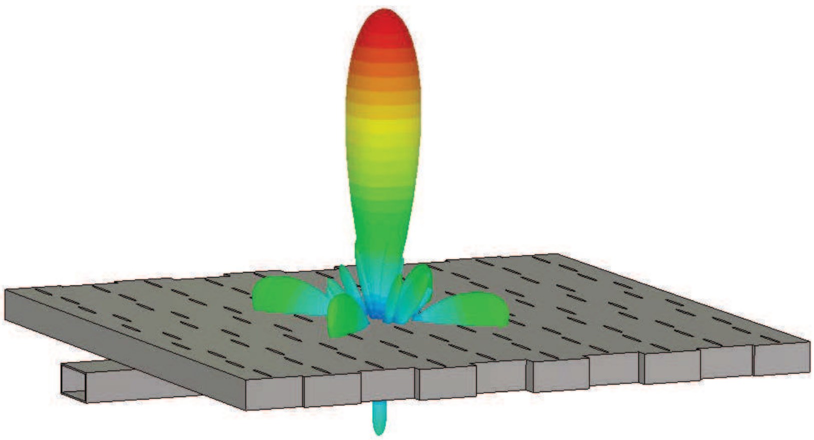

FIGURE 8 3D Gain pattern of the 10 × 10 2D SWA of Example 2, computed using CST.

5 | FABRICATION AND TESTING

In order to validate the results experimentally, the 8×8 two-dimensional slotted waveguide antenna array of designed in Example 1, Section 3.1, is chosen for fabrication. Eight WR-229 waveguides (a = 2.29 in, b = 1.15 in), in addition to a single WR-187 waveguide, are needed to be used for the branchlines SWAs and the feeder SWA respectively. Due to some constraints however, the available waveguides are: one WR-187, and other waveguides having the following dimensions: a = 5.6 cm = 2.204 *in*, b = 1.6 cm = 0.63 *in*. The latter waveguides are used for branchlines instead of the WR-229, which needed further design optimization. For this, the 8×8 2D SWA in Example 1 is re-designed taking into account the changes in the branchline waveguide inner dimensions (a and b), which lead to a change in the slots displacements needed to attain a sidelobe level ratio of a minimum of 20 dB at a frequency of 3.952 GHz. As for the feeder, and taking into account the needed separation between the slots on the broadwall of the feeder SWA, the guide wavelength should be around 60 mm ($\simeq 0.79\lambda$). At 3.952 GHz the WR-187 is the closest waveguide, with a guide wavelength of 63.132 mm ($\simeq 0.832\lambda$). Hence, the available WR-187 can be used as the feeder. The updated slots displacements as per the new available waveguide dimensions are listed in Table 5.

After designing the branchlines SWAs and the feeder SWA, the two-dimensional slotted waveguide antennas has been fabricated and tested. The fabrication process, as illustrated in Section 3.1.3, is done as follows. The feeder SWA and the eight SWA branchlines are first fabricated. CNC HAAS VF-6 three axis milling machine with a precision of 0.001 mm has been used to drill the slots using a 3 mm type carbide. The eight branchlines SWAs are then stacked side by side, before moving each one,

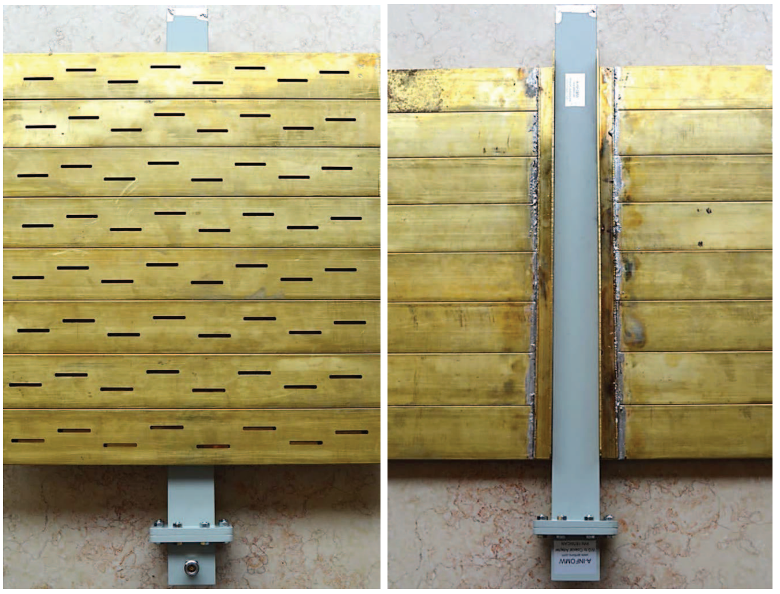

FIGURE 9 Fabricated 8 × 8 two-dimensional slotted waveguide antenna array, (left) front view, (right) back view.

upward or downward, according the displacement of the coupling slot. The eight moved branchlines are then collected using a glue. The feeder SWA is then attached to the branchlines SWAs, and welded using L-shaped copper corners on the back of the branchlines SWAs. The fabricated 2D SWA array is shown in Figure 9.

Testing the antenna, the measured gain results are compared to the simulated ones using CST in Figure 10. The measured reflection coefficient results are also compared to those simulated using CST in Figure 11. As can be seen, the obtained measured results are very close to the simulated ones, and they are also in accordance with the design objectives of having the antenna operating at 3.952 GHz, with a sidelobe level ratio of 20 dB, high gain, and very low sidelobe levels.

6 | CONCLUSION

This paper presented a complete design procedure, with an optimized feeding method, of two-dimensional slotted waveguide antenna arrays with controllable sidelobe level ratio (SLR), very low sidelobe levels, and a pencil shape pattern, suitable for high power microwave applications. Longitudinal slots made on the broadwall of the waveguides are used for coupling the wave and radiating it. The procedure starts by designing the radiating slotted waveguide antennas taking as input the desired sidelobe level ratio, resonance frequency, total number of radiating SWAs, and total number of slots made on each radiating SWA. Using the dimensions of the radiating SWAs, the feeder SWA is designed to operate at the same resonance frequency, and the same value of sidelobe level ratio of the radiating SWAs. Using simplified closed-form, the distribution of slots along the length of the radiating SWAs and feeder SWA are calculated based on the slots excitation from a specified distribution. Two examples were illustrated with different number of slots and radiating elements, and one has been fabricated and tested. The obtained measured and simulated results are in accordance with the design objectives.

TABLE 5 Slot Displacements in branchlines and feeder SWAs for the fabricated 8 × 8 2D SWA array system.

Slot Number	Displacement (mm)	
	SWA Branchlines (WR-229)	SWA Feeder (WR-187)
1 & 8	2.78	1.88
2 & 7	4.36	2.94
3 & 6	5.71	3.85
4 & 5	6.48	4.36

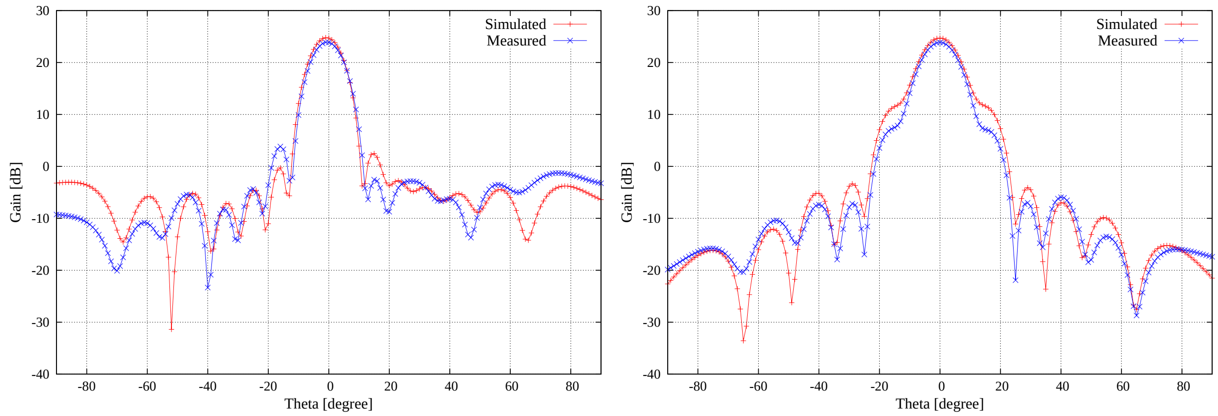

FIGURE 10 Gain pattern comparison of the simulated and fabricated two-dimensional slotted waveguide antenna array system, (left) E-plane, (right) H-plane.

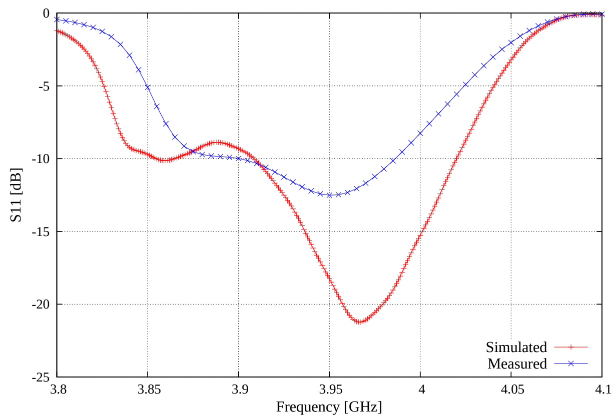

FIGURE 11 S_{11} results comparison of the simulated and fabricated two-dimensional slotted waveguide antenna array.

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Conflict of interest

The authors declare no potential conflict of interests.

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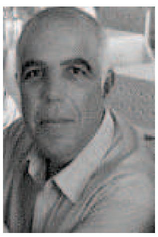

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