Design and implementation of Slotted Waveguide Antennas with Low Sidelobe Level in X-band for High Power Application

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Abstract*– slotted waveguide array (SWA) antennas are popular omnidirectional microwave antennas. These antennas feature omnidirectional gain around the azimuth with horizontal polarization.it offers clear advantages in terms of their design, weight, volume, power handling, directivity, and efficiency. They are a popular antenna in navigation, radar and other high-frequency systems. For broad wall SWAs, the slot displacements from the centerline control the antenna's side lobe level (SLL). This paper introduces a simple creative procedure for the design of broad wall SWA with a desired lower SLLs and lower reflection coefficients. The paper shows the comparison between making the slots rectangular or using elliptical slots. For a given number of longitudinal slots with equal length, width, spacing along the length of the waveguide but non uniform displacements from the centerline and showing the advantage from using equal offsets. Matlab programs with GUI is created to perform the design calculations of slots data and displacements using Chebyshev coefficient distribution. Designing an array by the column to make planner antenna with pencil beam. A prototype column of SWA has been fabricated and tested, and the results are matched with the design objectives.

I. INTRODUCTION

A waveguide is a very low loss transmission line. It allows to propagate signals to a number of smaller antennas (slots). Each of these slots allows a little of the energy to radiate [1]. Slot impedance and resonant behaviour for a single slot are dependent on slot placement and size. Its exceptional directivity in the elevation plane gives it quite high power gain. The slotted waveguide has achieved most of its success when used in an omnidirectional role to make the unidirectional antenna radiate over the entire 360 degrees of azimuth.

The radiating elements of a waveguide slot array are an integral part of the feed system, which is the waveguide itself so this simplifies the design. The other main advantages of SWAs are small volume, low weight, high efficiency, high power handling capability, Geometric simplicity and can be positioned above wings since having the capability to look toward the horizon [2]. A familiarization with the modal fields within a waveguide is necessary to understand where to place slots so that they are properly excited. Narrow slots that are parallel to waveguide wall currents do not radiate and also slots aligned on the broad wall centre line. However, when a slot is cut into a waveguide wall and it interrupts the flow of current, forcing it to go around the slot, power is coupled from the waveguide modal field through the opening to free space. To have good control of the excitation of a linear slot array, it is recommended that the waveguide only operate in a single mode, preferably the lowest mode [1, 3].

Waveguide slot arrays are classified into two groups: (1) standing-wave arrays and (2) traveling-wave arrays. The standing-wave arrays (the resonant) have elements spaced half guided wavelength and radiate a beam broadside to the waveguide. The fields repeat in a waveguide every half guided wavelength but are of opposite phase. Therefore, the slots are placed in a +/− configuration so that they are all fed in phase. Standing wave arrays can be fed either at one end of the waveguide with the other end terminated short circuit, or at the centre of the waveguide with matched load or short circuit terminations at the waveguide ends. As it provides for a more efficient array since the reflected wave from the waveguide ends can be phased with the incident wave, this allows for a higher power handling capability and no power loss at the waveguide end. In addition, the main beam is normal to the array but trade-off narrower operation band. Traveling-wave arrays (non-resonant) are used in applications where the direction of the main beam is pointed at angles that are not broadside to the waveguide wall or where frequency scanning is desired. But it requires a matched terminating load to absorb the wave. Inter-element spacing does not have to be the same between the elements, and half guided wavelength spacing is particularly avoided. Traveling-wave arrays can only be fed from the ends of the waveguide. To maximize the impedance bandwidth of the array, the slot elements are designed to be resonant at their centre operating frequency so called resonant slots.

The design of a resonant SWA using the procedure of Stevenson and Elliot [4-7].by which the waveguide is terminated by a short circuit at a distance of quarter guided wavelength from the centre of the last slot, using transmission-line theory and the waveguide modal Green's functions, Stevenson derived the values of the resonant resistance and conductance, normalized to the waveguide impedance, for various slot types along a rectangular waveguide [6, 10, 12]. Slot shaping affects the cross-polarization, Rectangular slots are sharp corners but elliptical slots are more suitable and consider the best choice for high power microwave application [13, 14].

For antenna Arrays side lobe level (SLL) is depending on the excitation feed of the elements (column). But for SWAs it is proportional to its conductance [8], for longitudinal slots it is proportional to the displacements from the centre line of the broad wall for uniform ones the SLL is almost -13dB but we can reduce it by using non-uniform displacements such as Chebyshev, Binomial, Taylor. Using Chebyshev configuration is the best choice for SLL and Gain [14, 15].

Elliott derives two expressions for slot-array active admittances in terms of slot excitation voltages, slot parameters, and the complementary dipole array active impedances. By combining these two expressions with the corresponding dipole array solution, a small-array slot geometry can be specified by using the iterative procedure as described by Elliott [4, 5]. Elliott and Kurtz then adjusted Stevenson's formula for slot displacement to account for the actual resonant length.by solving several equations to calculate length and displacement.in this paper resonant SWAs using uniform length and width and spacing of the slots and using closed form equations of non-uniform displacement Chebyshev calculations, their distance from short and port according to Elliot [11].

For rectangular slots the length is half the free space wavelength and its pattern is narrow but it's s-parameters (s11) is not bad, for elliptical slots the length is to be optimized and its pattern is little wide than rectangular one but it's s-parameters (s11) is very good as no sharp edge. A computer program is performed to design the whole calculations. A prototype SWA at x-band operating at frequency of 10.3GHz of 16 slots has been designed, fabricated, measured and the results show good analogy with the simulated ones

An Array by the elements(column) is performed with spacing of half guided wavelength between elements to reduce mutual coupling and the result is a narrow beam in both azimuth and elevation (pencil beam) with low side lobe level of -40dB [16,17].

II. CONFIGRATION AND GENERAL GUIDELINES

For the illustrative examples, an x-band WR-90 waveguide with diminutions a=22.86mm and b=10.16mm .the design is done for the 10.3GHz frequency as it is the centre of the X-band (8.20-12.40) GHz frequency.16 Rectangular and another one elliptical slots are made to one broad wall to compare the results between them .the waveguide is shorted at one end and fed from the another port .An array is performed by the column (elements) to perform a planner array.

A. slots positions and wavelengths

Some rules used since longitudinal slots are used on the broad wall:

1- The centre of first slot (slot1) can be placed at **λ_g/4, or 3λ_g/4,** from the short circuit at the end of the waveguide. We know that a short-circuited quarter-wavelength stub of transmission line appears as an open-circuit, so that the closed end does not affect the impedance.

2- The centre of first slot (slot16) can be placed at **λ_g/4, or 3λ_g/4,** from the feed

3- The distance between centres of any slots (slot spacing) is **λ_g/2**. We can alternate the slot displacement around the centre line and have a total phase difference of 360° between slots, putting them in phase.

The Wavelengths

1- λ_0=C/F λ_0….. Free space wavelength and c is the speed of light

2- λ_c=2*a λ_c….. The cut-off wavelength

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 cut-off wavelength, and is calculated according to the following equation:

$$\textbf{3-}\quad \lambda_g = \frac{\lambda_0}{\sqrt{1-(\frac{\lambda_0}{\lambda_{\text{cut off}}})}} = \frac{c}{f} * \frac{1}{\sqrt{1-(\frac{c}{2a.f})}}$$

Where λ_0 is calculated at frequency of 10.3 GHz in this case λ_0=29.12mm,
λ_c=45.72mm.
And so λ_g=37.78mm and the total length of the waveguide is 15*spacing+ λ_g=324.136mm

Structure of rectangular slots

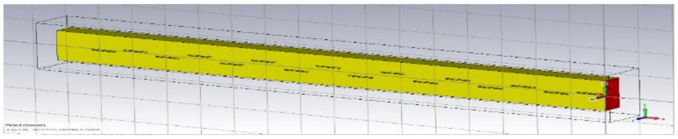


Figure 2.1 Slotted waveguide with 16 rectangular slots

Structure of elliptical slots

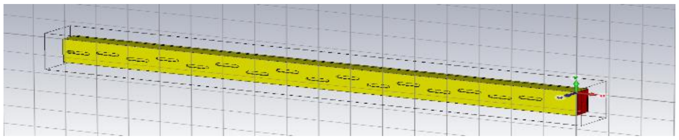


Figure 2.2 Slotted waveguide with 16 elliptical slots

B. The slot width

The Width of a Slot can be calculated as follows:

$$\boldsymbol{slot\ width = a * \frac{0.0625}{0.9}}$$

slot width=1.58 but has a big dependent on the s-parameters and radiation pattern it can be tuned to be 1mm but for non-uniform elliptical slots it is tuned to be 3mm to have good results.

C. slot displacements

A slot displacement refers to the distance between the centre of a slot and the centreline of the waveguide broad face, as illustrated

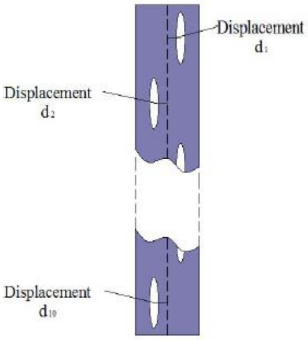


Figure 2.3 *Slots* ***Displacement***

With uniform slot displacements, all slots are at the same distance from the centreline. Which results in an SLL around −13dB. The slots should be placed around the centreline in an alternating order, the slots are placed in a +/− configuration so that they are all fed in phase.

$$\mathbf{d_u} = \frac{\boldsymbol{a}}{\boldsymbol{\pi}}\sqrt{\boldsymbol{arcsin}(\frac{\mathbf{1}}{\boldsymbol{N * G}})}$$

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

Where *N* is the number of slots in our case 16 slots

So d_u=2.306mm but in our paper, it can be tuned to be 4mm to have a good reflection coefficient

D. The Slot Length

Slot length can be calculated as illustrated

$\mathrm{G\_2\_slot} = 1.0/\mathrm{N}$ Where N is the number of Slots

$$\mathrm{Slot\_wl} = 0.210324 * \mathrm{G\_2\_slot} * 4 - 0.338065 * \mathrm{G\_2\_slot} * 3 + 0.12712 * \mathrm{G\_2\_slot} * 2 + 0.034433 * \mathrm{G\_2\_slot} + 0.48253$$

$Slot\ length = \lambda_0 * Slot\_wl$

For our case slot length can be optimized for case of rectangular slots is 14.18mm but for elliptical slots is 14.3mm.

E. The Slot Spacing

It can be calculated as follows

$$\boldsymbol{Ss = \lambda g/2}$$

From our design slot spacing is 18.89mm but can be optimized for rectangular slots is19.2mm but for elliptical slots is19.09mm. It is clearly that spacing shifts the s11 as if the length increased it shifts the s11 curve to the left (lower frequency) and verses via.

F. Non-Uniform Displacement Calculations

The displacement of the *n*th slot is related to its normalized conductance $\mathbf{g_n}$ by

$$\boldsymbol{dn} = \frac{\boldsymbol{a}}{\boldsymbol{\pi}}\boldsymbol{arcsin}\sqrt{\frac{\mathbf{g_n}}{\mathbf{2.09}\frac{\boldsymbol{\lambda_g}}{\boldsymbol{\lambda_0}}\frac{\boldsymbol{a}}{\boldsymbol{b}}\mathbf{cos^2}(\frac{\boldsymbol{\pi}}{\mathbf{2}}\frac{\boldsymbol{\lambda_0}}{\boldsymbol{\lambda_g}})}}$$

Where *N* is the number of slots, and *cns* are the distribution coefficients that should be determined to achieve the desired SLL.

In our paper, we use Chebyshev distribution as it is a best choice for reflection coefficient and Gain using -40 dB SLR

$$\boldsymbol{Tn(x) = 2xTn - 1(x) - Tn - 2(x)}$$

$$\mathbf{D} = \frac{\mathbf{32400}}{\boldsymbol{\theta 1 * \theta 2}}\ (\mathbf{1})$$

$$\boldsymbol{D} = \mathbf{2} * \boldsymbol{N}\frac{\boldsymbol{d}}{\boldsymbol{\lambda}}\ (\mathbf{2})$$

Where $\theta 1$& $\theta 1$ the beam width of azimuth and elevation

D is the directivity & N are number of column (elements)

D is the spacing between elements

In our case $\theta 1 = 5.9deg$ & $\theta 2 = 3deg$

d is taken to be $\lambda/2$ to reduce coupling

$$\mathbf{10log(D)} = \mathbf{2} * \boldsymbol{N}\frac{\boldsymbol{d}}{\boldsymbol{\lambda}}\ (\mathbf{3})$$

AS it is in dB form then we have D=N=32

For rectangular slots it Leeds to 26.6 dB but for elliptical case23.3 dB but this leakage is compensated for s-parameter (s11)

Slot number	Chebyshev coefficients	Displacements
1	0.11376	0.9378
2	0.19636	1.2347
3	0.33194	1.6107
4	0.49260	1.9702
5	0.66131	2.2927
6	0.81633	2.5577
7	0.93534	2.7466
8	1	2.8449

Notice that the other last eight coefficient and displacements is a repeat of the first eight one but reversed (the last one is the first one)

III. RESULTS

Structure on cst with flang

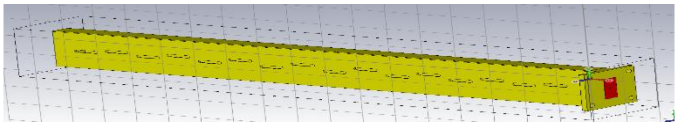


Figure 2.4 SWA with flang

S-parameters (s11)

For rectangular slots

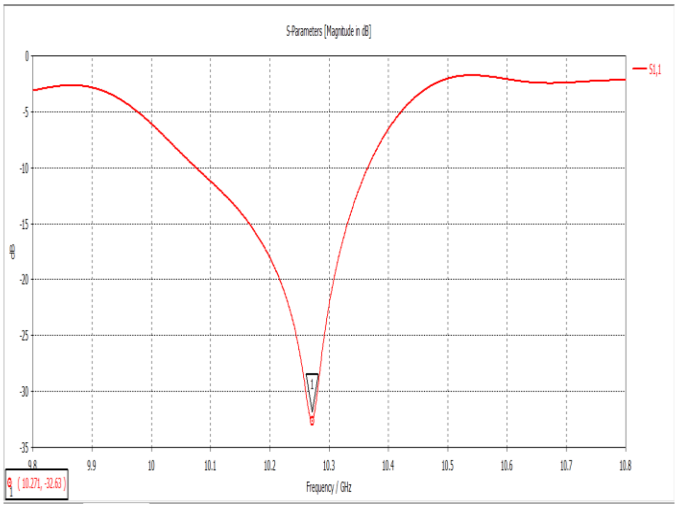


Figure 2.5.a s11 for rectangular slots with S11= -32.6 dB

For elliptical slots

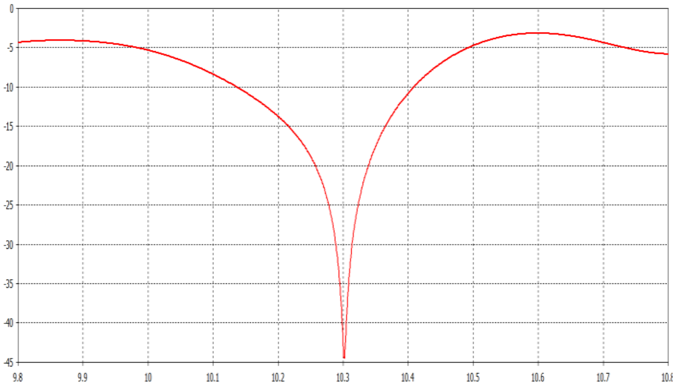


Figure 2.5.b s11 for elliptical slots with S11= -45 dB

3D-radiation pattern

For rectangular slots

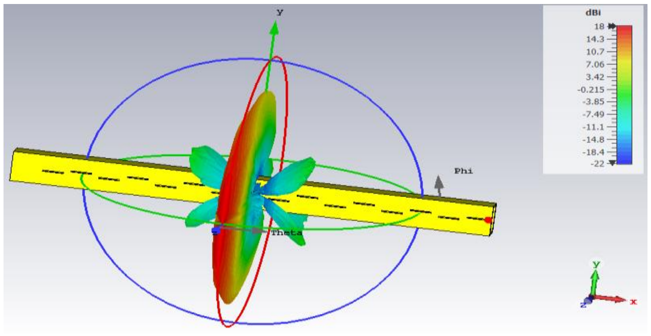


Figure 2.6.a pattern for rectangular slots

For elliptical slots

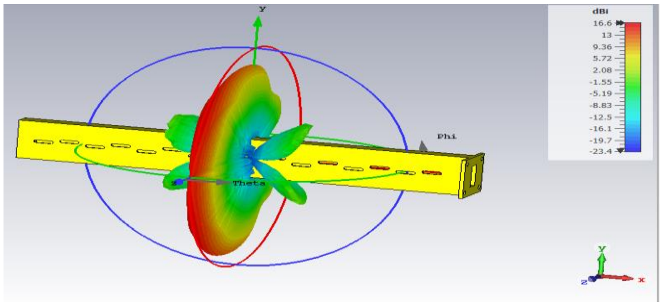


Figure 2.6.b radiation pattern for elliptical slots

Farfield Directivity for (pi=0) (polar plot)

For rectangular slots

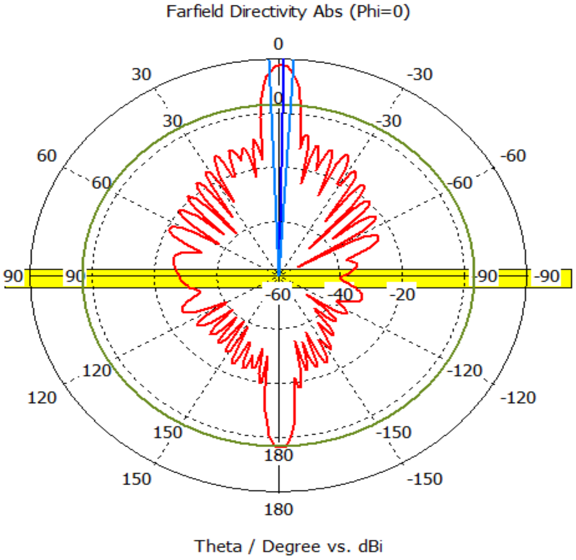


Figure 2.7.a Farfield Directivity for rectangular slots

For elliptical slots

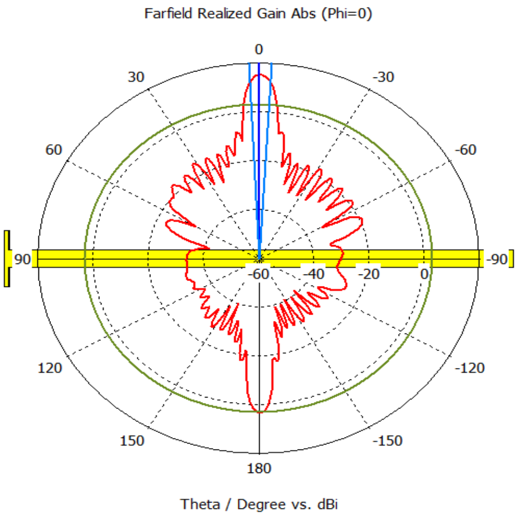


Figure 2.7.b Fairfield Directivity for rectangular slots rectangular slots elliptical slots

Farfield Directivity for (pi=0) (Rectangular plot)

For rectangular slots

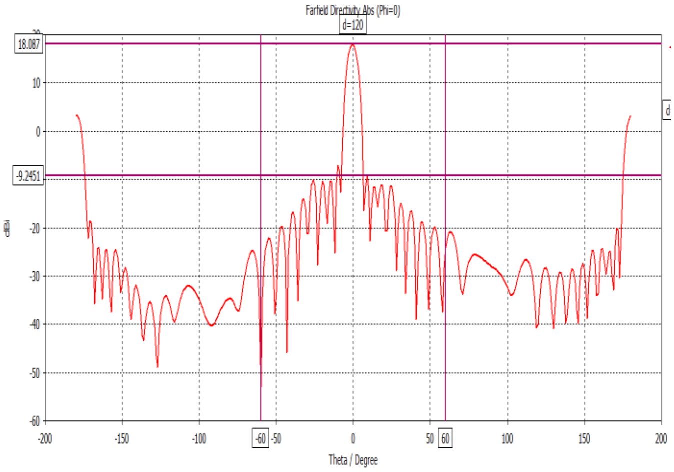


Figure 2.8.a Farfield Directivity for rectangular slots

For rectangular slots it has Gain of 17.97 with efficiency of 99.27% but for elliptical slots it has a Gain of 16.67 with efficiency of 99.76%.

For rectangular slots the beam is ideal narrow with beam width of 5.9deg in the azimuth but for elliptical slots the beam is narrow at the top with beamwidth of 5.8deg but at the end (closer to sidelobes) it became little wider and this clear at figures.

For elliptical slots

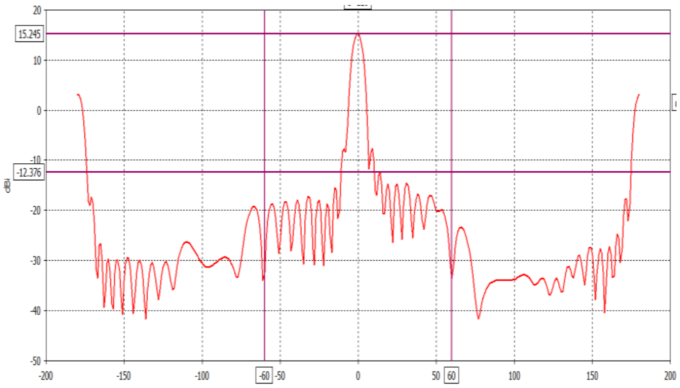


Figure 2.7.b Farfield Directivity for rectangular slots elliptical slots

For planner (Array)

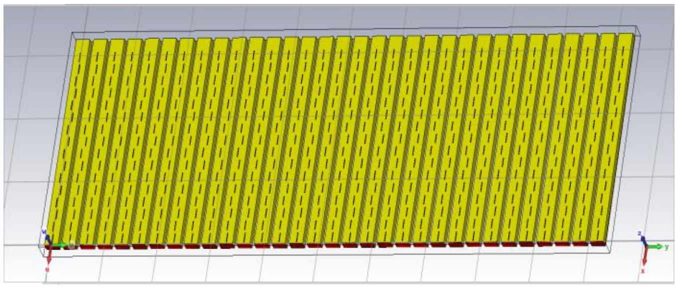


Figure 3.1 Array of SWA with rectangular slots

The array is performed by columns of SWAs with rectangular slots, the distance between columns is $\lambda g/2$ =20mm to reduce coupling between elements, the feed of the column is a Chebyshev coefficients of 40dB sidelobe level with number of elements of 32 column to have a beam width of 3deg in elevation and the azimuth beam width of 6deg forming pencil beam. This number of column can be calculated according to the directivity equation of Kraus and broadside directivity by equating the both.

3D-radiation pattern

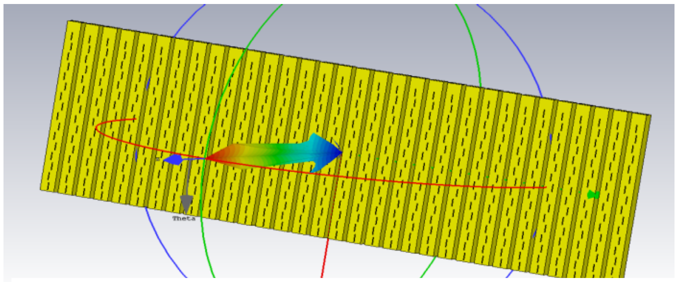


Figure 3.2 3D-radiation pattern of the array

S-parameters

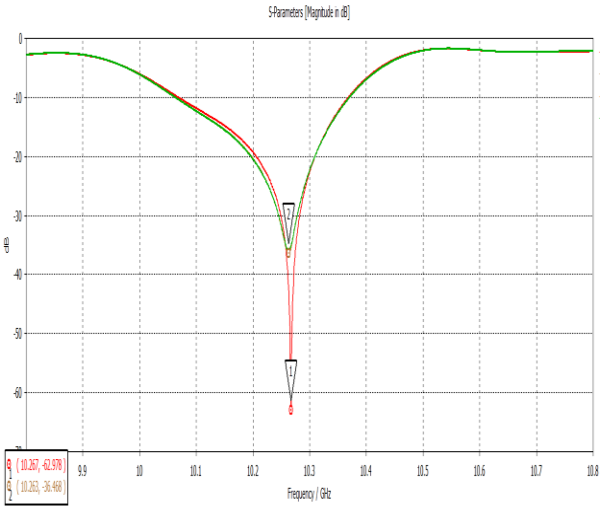


Figure 3.3 total s11 of the 32 column

We can see the effect of coupling that shifts s11, also we notice that the edged columns (1, 32) their s11 are identical because the coupling comes from one side, but the others have coupling from the two sides of the column so also their s11 are identical.

Farfield Directivity for (pi=90)

We notice the perfect radiation pattern of low sidelobes of -40 dB at frequency of 10.3GHz Leeds to main lobe directivity magnitude 32.7 dBi with 3 deg beam width

(Rectangular plot)

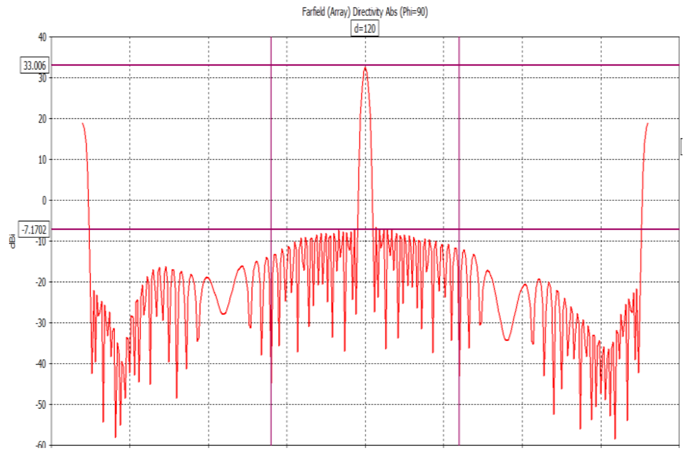


Figure 3.4 Rectangular plot of farfield directivity of the array with side lobe level of -40dB

(Polar plot)

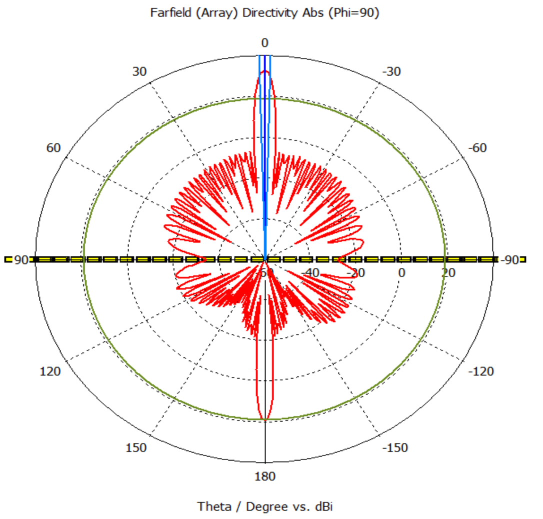


Figure 3.5 Polar plot of farfield directivity of the array with side lobe level of -40dB

Smith chart

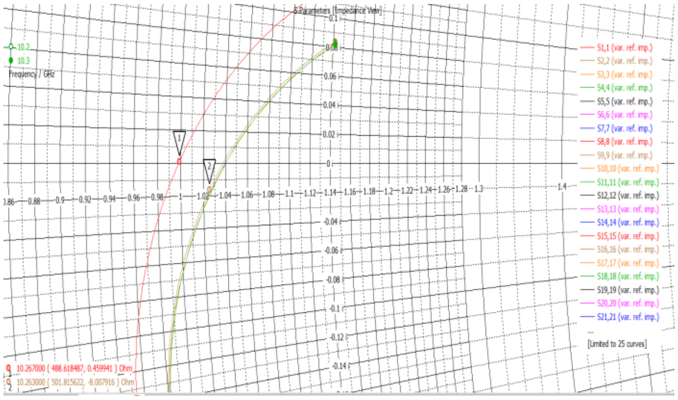


Figure 3.6.a smith chart of the total 32 column

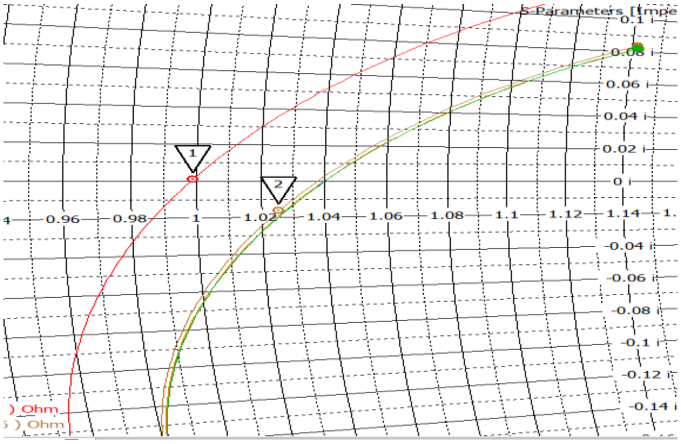
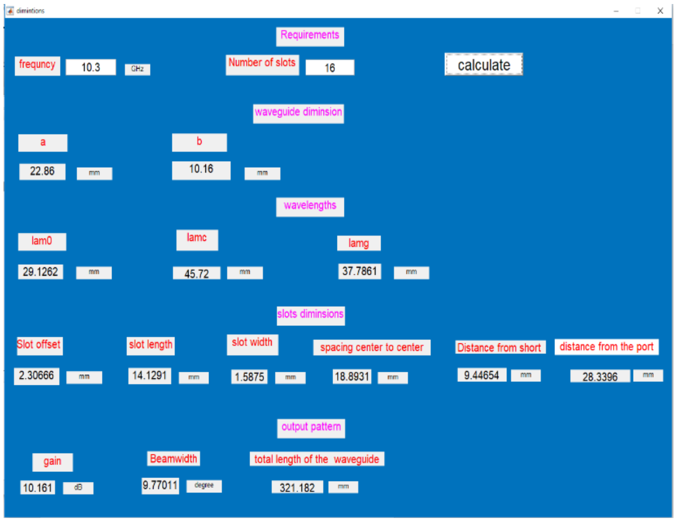


Figure 3.6.b smith chart of the total 32 column

Computer programs

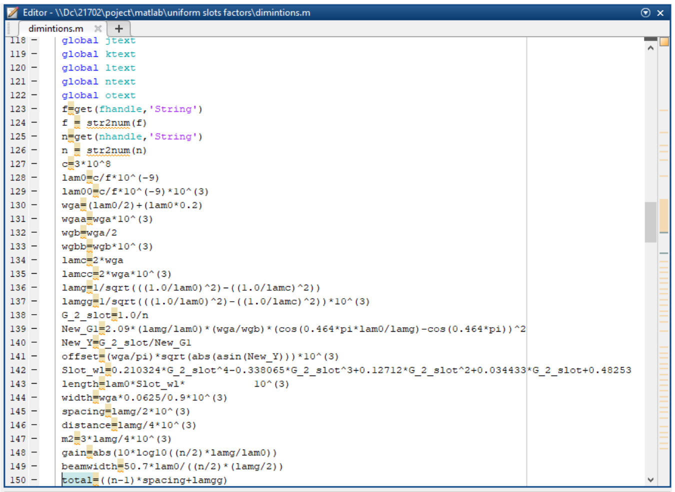
Computer programs in MATLAB with GUI has been written to generate the slots data and another to calculate the slots displacements for desired s11.

The first program has input of frequency, waveguide diminutions a and b, the number of slots and calculating the hole slots data, wavelengths total length of waveguide, gain and beamwidth



frequncy 10.3 GHz
Number of slots 16
a 22.86 mm
b 10.16 mm
lam0 29.1262 mm
lamc 45.72 mm
lamg 37.7861 mm
Slot offset 2.30666 mm
slot length 14.1291 mm
slot width 1.5875 mm
spacing center to center 18.8931 mm
Distance from short 9.44654 mm
distance from the port 28.3396 mm
gain 10.161 dB
Beamwidth 9.77011 degree
total length of the waveguide 321.182 mm

Figure 4.1.a firs Program for slots data

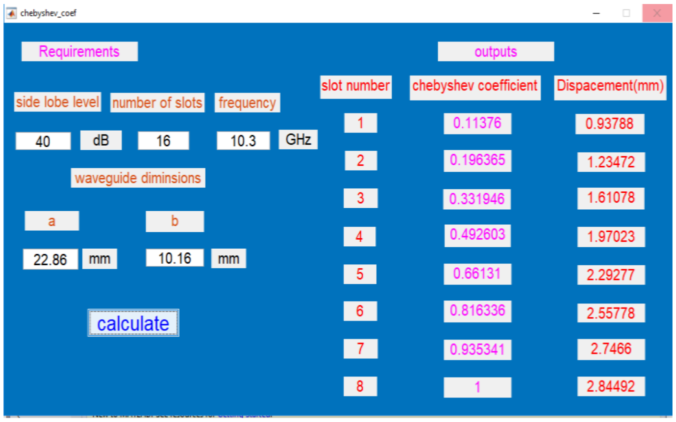


```
global jtext
global ktext
global ltext
global ntext
global otext
f=get(fhandle,'String')
f = str2num(f)
n=get(nhandle,'String')
n = str2num(n)
c=3*10^8
lam0=c/f*10^(-9)
lam00=c/f*10^(-9)*10^(3)
wga=(lam0/2)+(lam0*0.2)
wgaa=wga*10^(3)
wgb=wga/2
wgbb=wgb*10^(3)
lamc=2*wga
lamcc=2*wga*10^(3)
lamg=1/sqrt(((1.0/lam0)^2)-((1.0/lamc)^2))
lamgg=1/sqrt(((1.0/lam0)^2)-((1.0/lamc)^2))*10^(3)
G_2_slot=1.0/n
New_G1=2.09*(lamg/lam0)*(wga/wgb)*(cos(0.464*pi*lam0/lamg)-cos(0.464*pi))^2
New_Y=G_2_slot/New_G1
offset=(wga/pi)*sqrt(abs(asin(New_Y)))*10^(3)
Slot_wl=0.210324*G_2_slot^4-0.338065*G_2_slot^3+0.12712*G_2_slot^2+0.034433*G_2_slot+0.48253
length=lam0*Slot_wl*           10^(3)
width=wga*0.0625/0.9*10^(3)
spacing=lamg/2*10^(3)
distance=lamg/4*10^(3)
m2=3*lamg/4*10^(3)
gain=abs(10*log10((n/2)*lamg/lam0))
beamwidth=50.7*lam0/((n/2)*(lamg/2))
total=((n-1)*spacing+lamgg)
```

Figure 4.1.b firs Program for slots data

The second program has been performed to calculate Chebyshev coefficients and displacements which has input of frequency, waveguide diminutions a and b, the number of slots and side lobe level required.

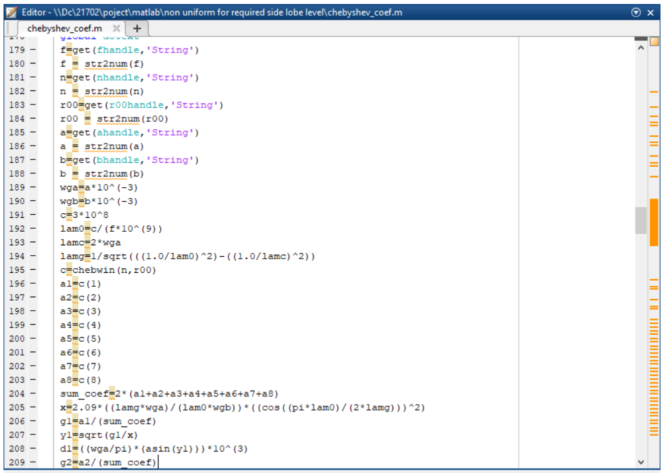
Notice that the other last eight coefficient and displacements is a repeat of the first eight one but reversed (the last one is the first one)



side lobe level 40 dB
number of slots 16
frequency 10.3 GHz
a 22.86 mm
b 10.16 mm

slot number	chebyshev coefficient	Dispacement(mm)
1	0.11376	0.93788
2	0.196365	1.23472
3	0.331946	1.61078
4	0.492603	1.97023
5	0.66131	2.29277
6	0.816336	2.55778
7	0.935341	2.7466
8	1	2.84492

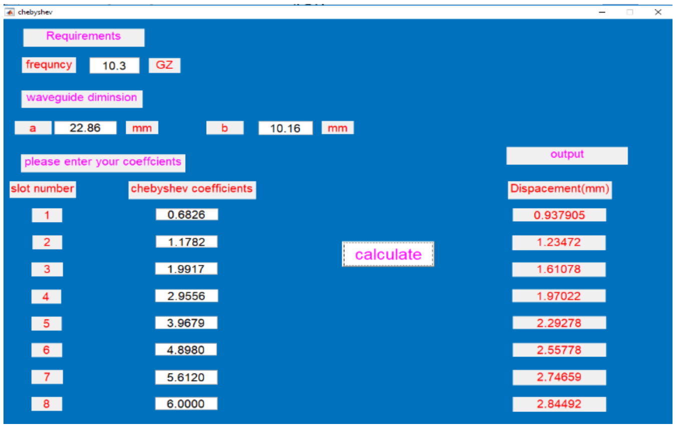
Figure 4.2.a second Program for non-uniform slots displacements



```
f=get(fhandle,'String')
f = str2num(f)
n=get(nhandle,'String')
n = str2num(n)
r00=get(r00handle,'String')
r00 = str2num(r00)
a=get(ahandle,'String')
a = str2num(a)
b=get(bhandle,'String')
b = str2num(b)
wga=a*10^(-3)
wgb=b*10^(-3)
c=3*10^8
lam0=c/(f*10^(9))
lamc=2*wga
lamg=1/sqrt(((1.0/lam0)^2)-((1.0/lamc)^2))
c=chebwin(n,r00)
a1=c(1)
a2=c(2)
a3=c(3)
a4=c(4)
a5=c(5)
a6=c(6)
a7=c(7)
a8=c(8)
sum_coef=2*(a1+a2+a3+a4+a5+a6+a7+a8)
x=2.09*((lamg*wga)/(lam0*wgb))*((cos((pi*lam0)/(2*lamg)))^2)
g1=a1/(sum_coef)
y1=sqrt(g1/x)
d1=((wga/pi)*(asin(y1)))*10^(3)
g2=a2/(sum_coef)
```

Figure 4.2.b second Program for non-uniform slots displacements

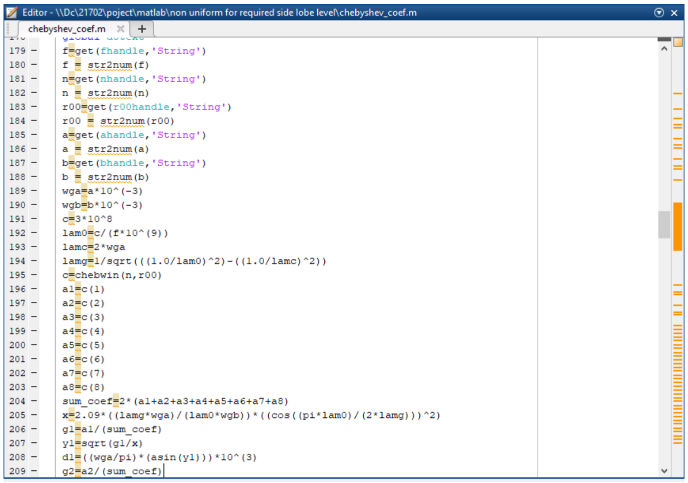
The third program if you have your coefficient that give the required side lobe level and you need to calculate their related displacements



frequncy 10.3 GZ
a 22.86 mm
b 10.16 mm

slot number	chebyshev coefficients	Dispacement(mm)
1	0.6826	0.937905
2	1.1782	1.23472
3	1.9917	1.61078
4	2.9556	1.97022
5	3.9679	2.29278
6	4.8980	2.55778
7	5.6120	2.74659
8	6.0000	2.84492

Figure 4.3.a third Program for non-uniform slots displacements if you have your own coefficients



```
f=get(fhandle,'String')
f = str2num(f)
n=get(nhandle,'String')
n = str2num(n)
r00=get(r00handle,'String')
r00 = str2num(r00)
a=get(ahandle,'String')
a = str2num(a)
b=get(bhandle,'String')
b = str2num(b)
wga=a*10^(-3)
wgb=b*10^(-3)
c=3*10^8
lam0=c/(f*10^(9))
lamc=2*wga
lamg=1/sqrt(((1.0/lam0)^2)-((1.0/lamc)^2))
c=chebwin(n,r00)
a1=c(1)
a2=c(2)
a3=c(3)
a4=c(4)
a5=c(5)
a6=c(6)
a7=c(7)
a8=c(8)
sum_coef=2*(a1+a2+a3+a4+a5+a6+a7+a8)
x=2.09*((lamg*wga)/(lam0*wgb))*((cos((pi*lam0)/(2*lamg)))^2)
g1=a1/(sum_coef)
y1=sqrt(g1/x)
d1=((wga/pi)*(asin(y1)))*10^(3)
g2=a2/(sum_coef)
```

Figure 4.3.b third Program for non-uniform slots displacements if you have your own coefficients

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