

# Design of Squinted Beam Slotted Linear Array Antenna for Radar Application

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**Abstract:** *Slotted linear antenna array at Ku band for radar application is designed with design of waveguide with standard waveguide dimensions at Ku band, slot design, and array design using Taylor distribution. The main beam is oriented at an angle of  $45^\circ$  with respect to the board side of the broad wall of the rectangular waveguide at Ku band. Single slot need to be designed and optimized for resonance frequency and use the same slot in designing the linear array, optimize the inter element spacing, slot dimensions and slot locations to achieve the desired VSWR bandwidth over whole frequency band of operation. Mutual coupling effect has to be taken care in designing for improving active return loss and radiation efficiency. A coaxial probe feed has to be designed and feed at  $\lambda/4$  distance from one end of waveguide and another end need to be terminated with matched load because of non resonant antenna array.*

**Keywords:** antenna, slotted, array, rectangular waveguide, radiation pattern

## 1. Introduction

Many radar antennas and microwave communication systems employ slotted waveguide arrays with the advantages of compact structure, large power capacity, high radiating efficiency and reliability. The waveguide resonant slot array antenna, which has the advantages of good direction of radiation, low cross-polarization levels and low side-lobe levels, plays an important role in the area of microwave antennas. Waveguide slot antenna is divided into some classes, that is to say, the longitudinal the transversal and the tilted slot antenna according to the position and shape of the waveguide slot. The amplitude and phase difference of the coupling field from the waveguide to the slot can be controlled by the distance from the waveguide center and the tilted angle. Therefore the waveguide slot antenna can be applied to the antenna having the arbitrary beam shape.

Geometric simplicity, efficiency, polarization purity, conformal installation, and ability to radiate broadside beams and vertically polarized  $E$ -plane beams at very near grazing angle above a ground plane make slot-antenna arrays ideal solutions for many radar, communications, and navigation applications. Especially today with the desire to make antennas for aircraft as low profile as possible to reduce drag and conserve fuel, slot antenna arrays can be positioned above wings and on top of the fuselage while having the capability to look toward the horizon. Design of an antenna array involves a number of details: cutting the elements to resonance, spacing the elements properly, splitting the power to distribute to the elements, feeding the elements in phase through a harness of transmission lines, and providing a mounting structure for each element. For traditional arrays, each of these items may be attacked separately, but the waveguide slot antenna combines them all into a single piece of waveguide — we must find a set of dimensions that satisfies all the requirements simultaneously.

## 2. Antenna Design

Traveling-wave slot arrays avoid resonances or standing-wave conditions in the waveguide. Hence the slots of traveling-wave arrays are spaced by either more or less than one-half waveguide wavelength. As in the case of resonant waveguide slot arrays, resonant slots are used in traveling-wave arrays to maximize frequency-bandwidth performance. A matched load terminates the slotted waveguide to prevent the formation of a secondary beam due to reflected waves. Although much effort is put into minimizing reflections that occur from the termination and also from every slot along the waveguide, sometimes it is necessary to create controlled reflections to cancel the appearance of secondary lobes that are not due to grating lobes. Inter-element slot spacing is selected to be close to one-half waveguide wavelength ( $\lambda_g / 2$ ) [9].

Therefore the polarity of adjacent slots is of the opposite sense. For example, adjacent longitudinal shunt slots are on opposite sides of the guide centerline, and adjacent edge-wall shunt slots are inclined to opposite sides of the vertical centerline. The alternating displacement or rotation with respect to the waveguide axis of successive slots may produce grating lobes. If the main beam of the traveling-wave slotted array is pointing far away from broadside, the upcoming grating lobe level may exceed the desired side lobe level. The grating lobes can be pushed out of the visible array space by choosing a suitable inter-element spacing. The restrictions on grating lobes can be relaxed when the slot element pattern amplitude is taken into consideration at the angles where the grating lobes are appearing. Longitudinal shunt slots, edge-wall shunt slots, and rotational series slots are used in both traveling-wave type arrays. Traveling-wave arrays are always fed from the end of the waveguide. The progressive phase shift between elements, which changes with frequency, causes the beam to scan.

This means that as power is fed into the waveguide, the first slot couples some power, leaving the remaining power to travel to the next slot, and so on. By the time the remaining power arrives at the last slot, that slot must couple most of it to meet its prescribed excitation level. Since there are too many factors that can affect the precise amount of power that travels from slot to slot, and since it is impossible for the last slot to couple 100 percent of the remaining power, the array is designed to let about 5 percent to 10 percent of the power be absorbed by the termination. This helps to stabilize the excitation of the last few slots before the termination. The process to determine the slot conductance or resistance can be simplified as follows if the waveguide can be considered as lossless and if the reflection coefficient due to each slot is minimal.

Consider the equation for the power input to the waveguide

$$P_{in} = P_{all\ slots} + P_{load} = \sum_{i=1}^N P_i + P_L$$

Where  $P_{in}$  is the input power to the waveguide,  $P_{all\ slots}$  is the power radiated by all the slots in that waveguide,  $P_{load} = P_L$  is the power absorbed by the load at the end of the waveguide,  $P_i$  is the normalized power radiated by slot  $i$  given by  $a^2(m, i)$ , the calculated slot excitation.

Power calibration factor (K) is given by  $K = \frac{P_{in} - P_L}{\sum_{i=1}^N P_i}$ . If the relative excitation level of the  $n^{th}$  is  $a_n$ , the power  $P_n$  radiated by this slot will be proportional to  $a_n^2$ . Thus when we specify the required amplitude distribution  $a_n$  to yield the desired beam width and side lobe level we will know that  $P_n$  to be within a constant of proportionality. Let  $P_L$  be the fraction of the incident power to be dissipated in the matched load. The power incident at slot  $N$  will be  $P_L + P_N$  for unit input power to the array. The equivalent voltage across the transmission line of unit characteristic impedance at this point is  $V_N$  and is such that  $\frac{1}{2}|V_N|^2 = P_L + P_N$  since reflection are being neglected. The power radiated by the  $N^{th}$  slot with conductance  $g_N$  is thus given  $\frac{1}{2}|V_N|^2 g_N$  and must be equal to  $P_N \cdot g_N = \frac{P_n}{\sum_{i=n}^N P_i + P_L} = \frac{P_n}{1 - \sum_{i=1}^{n-1} P_i}$

Since  $P_L$  plus the sum of all radiated powers must add up to unity. When the  $g_n$  have been found the slot offsets can be determined from the Stevenson's solution. For the given beam tilt angle ' $\theta$ ' and the selected slot arrangement ' $\lambda_g$ ' is calculated either from equation 4.10. The waveguide cut off frequency ' $\lambda_c$ ' is calculated using the formula

$$\frac{1}{\lambda_c^2} = \frac{1}{\lambda_0^2} - \frac{1}{\lambda_g^2}$$

For a  $TE_{10}$  mode wave propagating in the waveguide we know that  $\lambda_c = 2a$ , where ' $a$ ' is the wider dimension of the waveguide. Generally for the rectangular waveguide the narrower dimension of the waveguide is half of the wider dimension [4]. For the given operating frequency and for the beam tilt angle,  $\lambda_0$ , and  $\lambda_g$  values are calculated. From these values  $\lambda_c$  is calculated as explained in the previous chapter. From  $\lambda_c$  we can calculate the waveguide dimensions. Assuming slots to be on same side of the offset and the beam tilt angle  $\theta = 45^\circ$  we get the values of  $\lambda_g$  and  $\lambda_0$  as  $\lambda_g = 29.26\ mm$  and  $\lambda_c = 29.26\ mm$

Assuming a  $TE_{10}$  mode wave propagating in the waveguide, the waveguide inner dimensions are  $a = 14.63\ mm$ ,  $b = 7.315\ mm$ . Assuming a waveguide wall thickness of 1.016 mm the waveguide outer dimensions are  $A = 16.662\ mm$  and  $B = 9.3470\ mm$ . The conductance of a longitudinal shunt slot cut in the broad face of a waveguide is given by  $g = 2.09 \left(\frac{a}{b}\right) \left(\frac{\lambda_g}{\lambda}\right) \cos^2 \left(\frac{\lambda\pi}{2\lambda_g}\right) \sin^2 \left(\frac{x\pi}{a}\right)$ , where  $\lambda$  is the free-space wavelength,  $\lambda_g$  is the guide wavelength,  $x$  is the slot displacement from the waveguide centre line, and  $a$  and  $b$  are the waveguide width and height [1].

Generally, there are two common ways to arrange slots on the waveguide broad wall. The first is to place all the slots on the same side of the center line and the second is to place them on both sides alternately. Both of these arrangements cause increasing phase due to  $\beta d_{n-1}$  (the traveling wave displacement phase) [9]. But in the case of alternately spaced slots, a phase difference of  $-\pi$  is further added to the phase increase  $\beta d_{n-1}$  resulting in a more controllable pattern.

Excitation of the slots is by means of a  $TE_{10}$  mode and if the aperture distribution is designed to give a sum pattern, and if the direction of offset (tilt) is not alternated, the pointing position of the main beam is given by

$$\theta_0 = \arccos \left(\frac{\beta}{k}\right)$$

The range of greatest use in the design of slot array is  $0.95 < l/l_r < 1.05$  where ' $l$ ' is the slot length and ' $l_r$ ' is the resonant length given by  $\frac{\lambda_g}{2}$  [2]. Initially a slot of width 1.6002 mm Curve Poly-fitting the obtained curve results in the following equation

$$l = 0.2032 * x + 9.8196$$

The above equation is an important relation which gives the relationship between the slot resonant length and the slot offset.

### 3. Simulation and Measurement Analysis

The specifications for the linear slotted array antenna are operating frequency of the antenna is in Ku-band (14.5GHz), antenna gain of 14 dB, beam tilt angle of  $45^\circ$ , antenna side lobe levels -30 dB, angular width of 17 dB. A Taylor distribution was specified that would give a -30 dB side lobe level. Assuming 5% of power to be absorbed in the matched load, so  $P_L = 0.05$  and the rest of the power 95% of the power is made to dissipate through the slots.

The total length of the waveguide is selected in such a way that all slots are accommodated on the broader face of the waveguide. The starting slot and the last slot are spaced in such a way that the distance from the center of the slot to the end plate of the waveguide is maintained at a distance of  $\lambda_g/4$ . The slot width is taken as 1.6002 mm and the inter-element spacing is chosen to be  $= 0.545 \lambda$ . Upon simulating the antenna structure the following figures shows the  $S_{11}$  plot, 3-D radiation pattern, and the 2-D radiation pattern without placing the coaxial probe.



Figure 1: Antenna Structure

The  $S_{11}$  plot shows that the  $S_{11}$  value much below the -20 dB line at the operating frequency

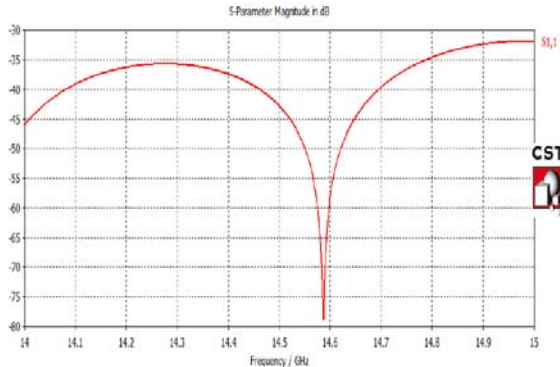


Figure 2: S<sub>11</sub> Plot

The following figure shows the 3-D radiation pattern of the antenna in free space

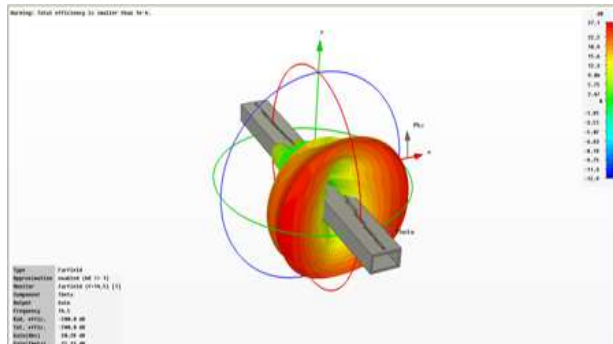


Figure 3: 3-D Radiation pattern

In the slotted waveguide antenna the feeding is done by placing the coaxial probe. For the perfect matching between the waveguide and the coaxial probe the coaxial probe must be placed at appropriate position for perfect coupling between the probe and the waveguide. The coaxial probe dimensions have the dimensions of the SMP connector. The outer conductor which is made of the Teflon has the radius of 2.08 mm and the inner conductor which is of metal has radius of 0.65 mm. The coaxial probe is placed on the waveguide such that the coaxial metal center is placed at a distance of  $\lambda_g/4$  from the short circuited metal plate and also it should be at a distance of  $\lambda_g$  from the center of the last slot.

The following figure shows the 3-D pattern of the antenna with the coaxial probe.

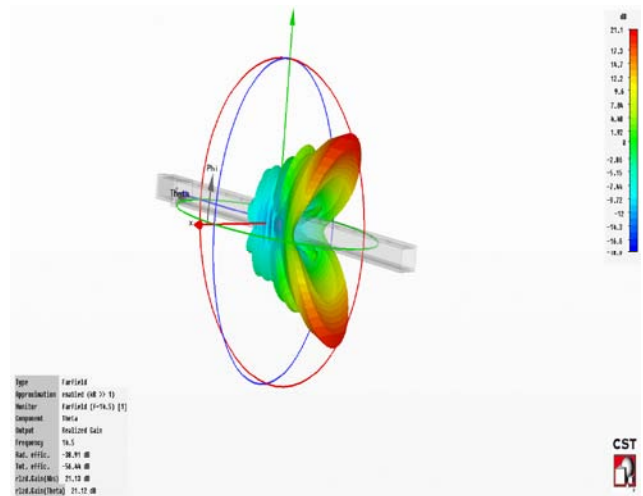


Figure 4: 3-D Radiation Pattern

Upon simulation we obtain the antenna parameters with a gain of 12.1 dB, main lobe oriented at an angle of  $45^\circ$  and the side lobe levels of -23.0 dB. Thus the simulated results are meeting with the specifications of the antenna.

#### 4. Conclusion

An effective design method is presented for the design of non-uniformly spaced longitudinal slot arrays on the broad wall of rectangular waveguides. The theory developed by Elliott for the travelling-wave-fed slot arrays is extended to non-uniform arrays. This design method is advantageous by the fact that it combines the determination of slot parameters and impedance matching with the array pattern synthesis (including the element factor and the mutual coupling) in the form of a computer automated procedure so as to increase the design speed and accuracy. Two examples of symmetrical and asymmetrical patterns were presented, showing very good agreement between the MLS results and CST simulations.

The procedure can also be extended to the design of other common slot array configurations such as transverse or centre inclined slots on the broad wall. In this project, a suitable radiating element i.e. rectangular waveguide slot antenna has been analyzed and also the design equations of the waveguide slot antenna for the given specifications are discussed. The slot antenna which can operate over wide band is designed using Computer Simulation Technology software and analyzed for optimum performance.

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