

PARAMETRIC STUDY OF WAVEGUIDE SLOTS AND ANALYSIS OF RADIATION PATTERN FOR THE DESIGN OF WAVEGUIDE ARRAY ANTENNA

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Abstract—The characteristics of radiating longitudinal slots in a rectangular waveguide have been studied. A moment method solution is used with entire basis expansion and testing functions (Galerkin) including the effect of wall thickness. It is shown in this paper. 1) The determination of different parameters like VSWR, reflection coefficients and insertion loss are calculated with the results of normalize reactance and conductance. 2) The Taylor distribution approach with specific SLL for desired linear aperture array antenna. The resonant conductance or resistances are calculated from desired amplitude distribution. The formulation uses transmission matrix approach. The computed result shows excellent agreement with measured results. CST Microwave studio is used for the simulation and is totally based on FIT techniques.

1. INTRODUCTION

A waveguide slot array antenna is mainly used for high gain flat antennas in millimeter-wave wireless communication systems due to their unique features such as lower loss in comparison with microstrip antennas, and simpler structure in comparison with reflector antennas. The design of waveguide array of longitudinal shunt slots (slotted waveguide array) require a accurate mutual coupling

analysis as indicated by Elliott [1, 2] and Sangester and McCormick [3] Hamadallah [4]. Their works focus on small slotted array [8, 20], which includes the input impedance match and the aperture excitation distribution. The required computer cost and excessive computing time restrict their solution to small slotted array. Taking advantage of the results reported in the existing literature, the computation of impedance can be extended to that for a slot in a large array environment. It assumes that the radiated power is proportional to the slot active conductance. The array aperture distribution [9, 16] and input impedances [10, 15] depend upon the knowledge of these slot active admittance.

Waveguide slot array antennas have wide applications in radar and wireless communication systems because of their various advantages such as high power handling capability, low losses, and good control over side lobe levels (SLL). Desired array pattern is obtained controlling slot excitation, by adjusting the slot offset from the center line of the waveguide. Prior to the design of an array it is required to determine the resonant slot length, equivalent circuit and variation of the circuit parameters with the change in offset values. S -parameters of the slotted waveguide are computed for this purpose.

2. SYNTHESIS OF A LINEAR ARRAY ANTENNA

Design of a linear array antenna incorporating waveguide longitudinal slots as radiators is described. Prior to the design of an array it is required to determine the resonant slot length, equivalent circuit and variation of the circuit parameters with the change in offset value. S -parameters of the slotted waveguide are computed for this purpose. The resonant conductance or resistances resulting in the desired amplitude distribution are evaluated by using the similar recursive formulation developed.

The aperture distribution can be written as

$$A(v) = F(0) + 2 \sum_{n=1}^{\infty} [F(n\pi) \cos(n\pi v)] \quad (1)$$

where $v = z/L$ (z being the variable point on the aperture and length of the aperture is $2L$).

The expression for the radiation pattern is

$$F(u) = \sum_{n=1}^{\infty} F(n\pi) \frac{\sin(u - n\pi)}{(u - n\pi)} \quad (2)$$

and $F(n\pi) = 0$ for $n \geq \bar{n}$. where

$$u = \frac{L'}{\lambda} \sin \theta$$

L' = length of the array

θ = angle measured from the direction of maximum radiation

$(\bar{n} - 1)$ is the number of equal side lobes. The power distribution across the linear aperture for 20 dB SLL and $\bar{n} = 3$, normalized power distribution across the length is shown in Fig. 1.

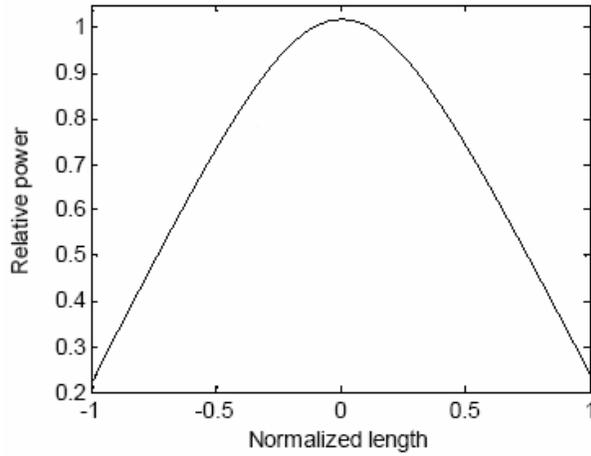


Figure 1. Power distribution across the length of the aperture for SLL=20 dB and $\bar{n} = 3$.

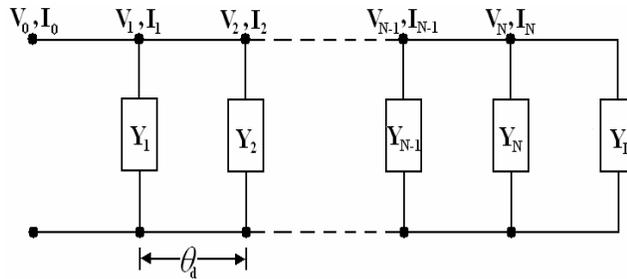


Figure 2. Transmission line model of an array of shunt radiators.

The transmission line modes of an array of N shunt radiators.

The voltage and current at the $(N - 1)$ th mode can be written as,

$$\begin{bmatrix} V_{N-1} \\ I_{N-1} \end{bmatrix} = \begin{bmatrix} \cos \theta_d & \dots & j \sin \theta_d \\ j \sin \theta_d & \dots & \cos \theta_d \end{bmatrix} \begin{bmatrix} 1 & \dots & 0 \\ Y_N & \dots & 1 \end{bmatrix} \begin{bmatrix} V_N \\ I_N \end{bmatrix} \quad (3)$$

Where V_{N-1} and I_{N-1} are the input side of the network, V_N and I_N are the output of the network (N th section).

$$\theta_d = \frac{2\pi}{\lambda_g} d + \pi$$

λ_g being the guided wavelength of primary feed waveguide and d is the interelement spacing.

Y_N is the admittance of N th radiator with respect to the characteristic impedance of the transmission line. Let the waveguide is matched terminated. If P_N is the normalized power and Δ is the fraction of power.

Dissipated at matched termination can be written that,

$$\sum_{n=1}^N P_n + \Delta = 1 \quad (4)$$

For a system having normalized impedance equal to unity:

$$\Delta = V_N^2 \quad (5)$$

The conductance presented by the N -th radiation can be obtained

$$g_n = \frac{P_N}{V_N^2} = \frac{P_N}{\Delta} \quad (6)$$

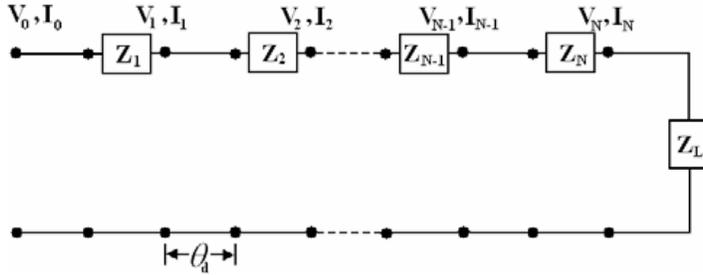


Figure 3. Transmission line model of an array of series radiators.

The transmission line model of an array of N series radiators. The voltage and current at $(N - 1)$ th node can be written as,

$$\begin{bmatrix} V_{N-1} \\ I_{N-1} \end{bmatrix} = \begin{bmatrix} \cos \theta_d & \dots & j \sin \theta_d \\ j \sin \theta_d & \dots & \cos \theta_d \end{bmatrix} \begin{bmatrix} 1 & \dots & Z_N \\ 0 & \dots & 1 \end{bmatrix} \begin{bmatrix} V_N \\ I_N \end{bmatrix} \quad (7)$$

Z_N is the impedance of the N th radiators normalized with characteristic impedance of transmission line.

The resistance of the radiator required for a particular aperture distribution can be determined by:

$$r_N = \frac{P_N}{I_N^2} = \frac{P_N}{\Delta} \quad (8)$$

r_0 and I_0 are calculated using the values of $g_N \cdot r_0/I_0$ gives the input reflection coefficients and $20 \log_{10} |(I_N/I_0)|$ gives the insertion loss. The voltage standing wave ratio is

$$\text{VSWR} = \frac{1 + |R_0/I_0|}{1 - |R_0/I_0|}. \quad (9)$$

Tilt of beam from the broadside direction

$$\theta_0 = \sin^{-1} \left(\frac{\lambda}{\lambda_g} - \frac{\lambda}{2d} \right) \quad (10)$$

3. DETERMINATION OF SLOT PARAMETER

For a large array, the conductance's presented by successive junctions are negligibly small, the reflection from the individual junctions can be neglected for the evaluation of desired conductance values. The values of I_N and g_N , using the transmission matrix for N th junction calculation. Calculate the values of this design of slot conductance assumes all the slots to be at resonance, for that particular case the inter element spacing is equal to $\lambda_g/2$. The required shunt conductance to obtain the desired amplitude distribution for given power dissipation in a match terminated load and for given inter element spacing. The expression for the slot conductance with power can be written in close form and is given by

$$g_n = \frac{P_n}{\sum_{m=1}^N P_m} \frac{(1 - \Delta)}{\Delta} \quad (11)$$

The conductance satisfying the desired amplitude distribution for inter element spacing equal to $\lambda_g/2$. Fraction of power (Δ) are varies from 0.1 to 0.2. R_0 and I_0 are calculated using the value of g_n . The voltage standing wave ratio (VSWR) is given by

$$\text{VSWR} = \frac{1 + |R_0/I_0|}{1 - |R_0/I_0|} \quad (12)$$

Using the above relation variation of VSWR, insertions loss and input reflection coefficients with frequency are evaluated for frequency range between 9 GHz to 11 GHz.

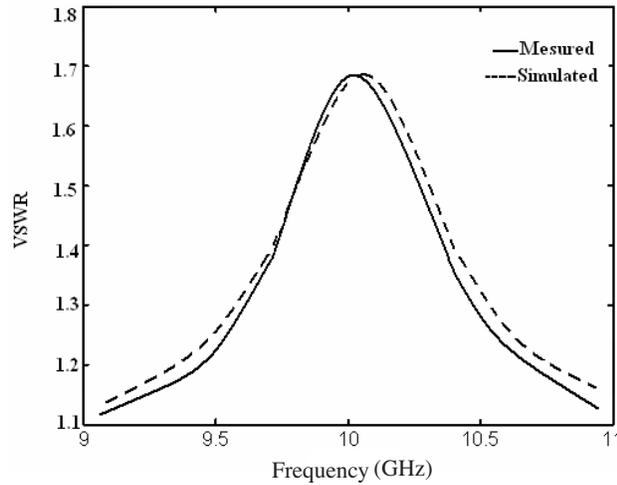


Figure 4. Measured (solid line) and simulated (dashed line) for VSWR calculation of the array.

4. DESIGN OF A LINEAR ARRAY ANTENNA

A linear array antenna operating at 10 GHz has been designed employing the slot doublets as radiators. The array consists of seven longitudinal slots and is matched terminated. Offset of each slot is computed so that the radiation conductance at the slot resonant frequency satisfies the aperture distribution required to obtain a 20 dB SLL according to Taylor distribution. Then the theoretically computed slot dimensions are put in the full-wave simulator to take into account the external mutual couplings between the array elements and the finite ground plane effects. The synthesis carried out for matched

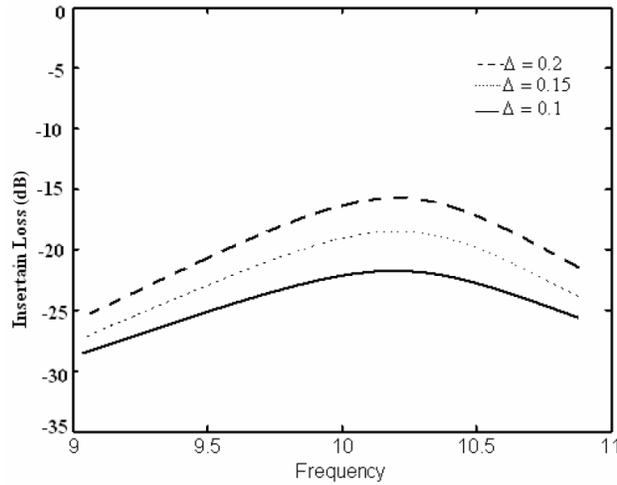


Figure 5. Variation of insertion loss with frequency.



Figure 6. Linear array antennas.

termination of the primary guide and the fraction of incident of power absorbed in the terminating load. The mathematical relation for the evaluation of conductance contain the inter element spacing as a parameter in the recursive relation. The array is symmetric with respect to the central element and offsets of the first, second, third and fourth elements are 3, 4, 5, 6 and 7 mm respectively. Length and width of each slot are 14.5 and 2 mm respectively. Here, the slot lengths are taken identical due to our limited fabrication facility. Inter element spacing is taken as 25 mm for proper input impedance matching.

The waveguide array antenna is shown in Fig. 6.

Measured and simulated S -parameters are shown in Fig. 7. The experiment was performed in general lab environment, measured and simulated result will differ due to scattering problem. Corresponding radiation patterns in the E and H -planes are shown in Fig. 8 and Fig. 9 respectively. An Agilent 8510C vector network analyzer has been used to measure the S -parameters. The radiation pattern has been measured in an indoor far field laboratory. Measured S_{11} and S_{21} at the

design frequency are -21 and -7.9 dB respectively. Measured beam tilt angle towards the matched termination is 13° . SLL is -14.8 dB.

It is seen that the strength of the slot aperture electric field increases with the increase of displacement from the waveguide center line. The measured results are quite similar with simulated results.

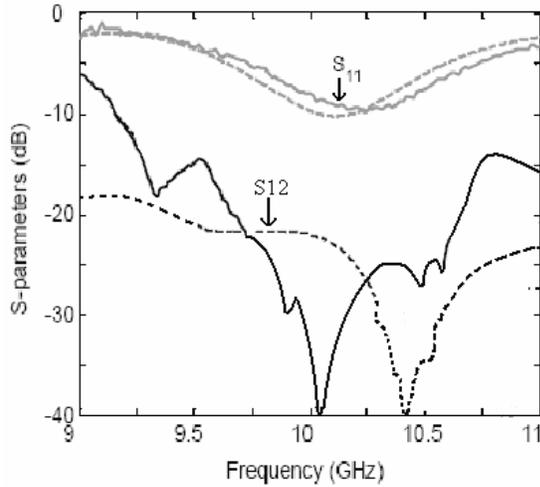


Figure 7. Measured (solid line) and simulated (dashed line) for S parameter calculations.

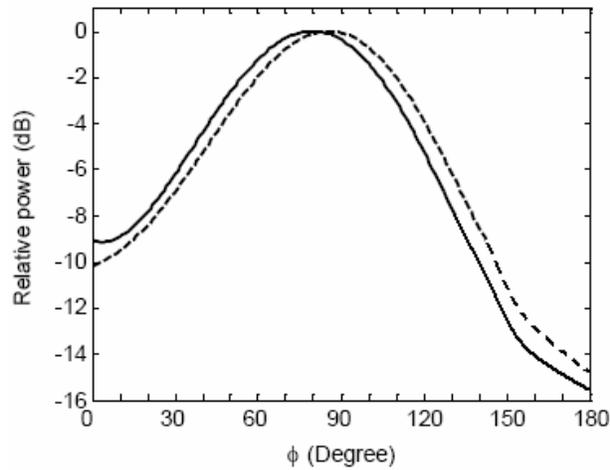


Figure 8. Measured (solid line) and simulated (dashed line) for E -plane calculation of the array at 10 GHz.

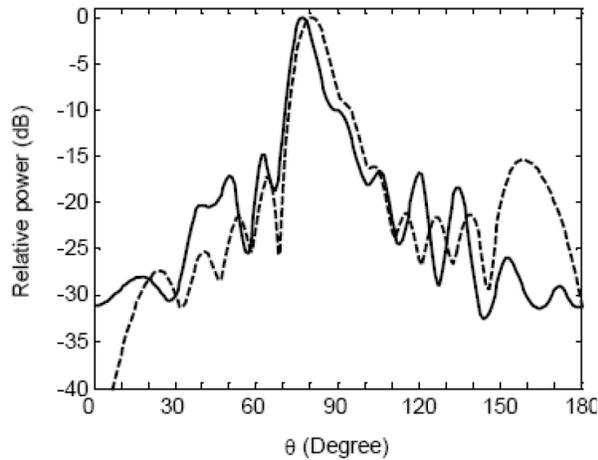


Figure 9. Measured (solid line) and simulated (dashed line) for H -plane calculation of the array at 10 GHz.

5. CONCLUSION

In this paper, a linear array antenna of waveguide longitudinal slots and its experimental results are presented. The procedure to design a linear array antenna with a specified SLL is described. Taylor distribution for a linear aperture has been adopted to obtain the required SLL. Required resonant conductance or resistances to achieve the desired aperture distribution are determined by considering a transmission line model of the array. The simulated radiation patterns of an isolated longitudinal slot show that the diffraction effects from the edges of finite size ground plane only affects the E -plane radiation patterns of the slot.

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