Design of Slotted Waveguide Array Antenna Fed by H-Plane Power Divider

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Abstract: **In this paper, design of a 4 x 4 slotted waveguide array fed by 1:4 equal power divider at centre frequency of 12.3 GHz is proposed and analysed using High Frequency Structure Simulator (HFSS). First, a single waveguide with broad wall longitudinal shunt slots displaced from the centre line is optimally designed with low return loss and also slot impedance is matched with the impedance of the waveguide. This result is successfully extended to design a 4 x 4 slotted waveguide array. A single Tee junction is modelled. The design is optimized using a septum and the input port is matched with the help of inductive windows (iris). An end feed system is designed by cascading Tee junctions. The slotted waveguide array is fed by this end feed system. Slotted waveguide array and end feed system are analysed separately. Their combination results in an efficient highly directive broadside antenna.**

Keywords: Slotted Waveguide Array, H-Plane Power Divider, WR75

I. INTRODUCTION

Waveguide fed slot array antenna has emerged as a popular candidate in radar applications, remote sensing, navigation and many other high frequency communication applications [1]. Because of the integration of the feed system and radiating elements they are low loss, exhibiting high values of radiation efficiency. They radiate linear polarization with reduced cross-polarization. The basic radiation mechanism for such antennas is very simple: a hole appropriately cut in the wall of a waveguide leaks some of the guided energy contributing to the outer space radiation. If the slot is a half wavelength one and properly positioned on the waveguide wall, the impedance is well matched and optimum radiation pattern can be achieved. Further, multiple slots may be cut in a waveguide to form a linear array of slots. Two dimensional planar arrays can also be formed by arranging two such linear arrays in two orthogonal directions. By optimal choice of the number of slots in linear and or planar arrays, phase excitation, positions and size one can control the critical antenna parameters like main radiation beam, side lobe level, front to back ratio, bandwidth and choose an optimal design depending on the desired requirement. Design of a slotted waveguide array antenna involves a number of details: cutting the elements to resonance, spacing the elements properly, splitting the power for proper distribution to the elements and feeding the elements in proper phase.

A longitudinal slot cut into the wall of a waveguide interrupts the transverse current flowing in the wall, forcing the current to travel around the slot, which induces an electric field in the slot. The position and orientation of the slot in the waveguide determines the current flow. Thus, the position and orientation determines the impedance presented to the transmission line and the amount of energy coupled to the slot and radiated from the slot. A slot in the exact centre of the broad wall of the waveguide cannot radiate at all, since the electric field is symmetrical around the centre of the guide and thus is identical at both edges of the slot. As the slot is positioned away from the centreline, the difference in field intensity between the edges of the slot is larger, so that more current is interrupted and more energy is coupled to the slot, increasing the radiated power. As we approach the sides of the waveguide, the field is very small (since the sidewalls are short circuits for the electric field) resulting in very weak induced current. Thus longitudinal slots far away from the centre of the waveguide or in the sidewall will not radiate significantly. This demands an optimal positioning of the slots slightly offset from the centre of the guide conceived in the proposed paper.

In the proposed slotted waveguide array we have used end feed configuration to feed the array. It gives rise to narrow frequency bandwidth. It consists of T-junctions which divides the total input power into all the radiating waveguides with slots in its wall in alternating phase. The paper has been organised in the following manner, the section II deals with the design of the linear array, the section III deals with the design of the H-plane power divider, section IV deals with the planar array design and the section V represent the directivity of the planar antenna. In section we present the design procedure and the simulated results of the corresponding section. The commercially available 3D electromagnetic solver HFSS [2] is used to simulation.

II. DESIGN OF LINEAR ARRAY

Figure 1 shows the top view of the design in which four longitudinal shunt slots are kept on either side of the centerline. Since, broad wall longitudinal shunt slot appears as a shunt load in a waveguide [3], the input admittance that appears at the port is net admittance of the 4 slots. The slots are fed in phase by spacing their centres at electrical half-wavelength intervals along the waveguide. The electrical wavelength in waveguide is longer than in free space, so we must calculate the guide wavelength:

$$\lambda_g = 1 \Big/ \sqrt{\frac{1}{\lambda_o^2} - \frac{1}{\lambda_c^2}}$$

where λ_C, is the cutoff wavelength, which is twice the wider dimension of the waveguide. Spacing the slots at $½\lambda_g$ intervals in the waveguide is an equivalent to an electrical spacing of 180^o - each slot is exactly out of phase with its neighbours, so their radiation will cancel each other [4]. However, slots on opposite sides of the centreline of the guide will be out of phase (180^o), so we can alternately switch the slot displacement around the centreline and have a total phase difference of 360^obetween slots, putting them back in phase.

The centre of the last slot is the guide quarter-wavelength from the closed end of the waveguide. The resonant slot length in our antenna is half of the free space wavelength whereas slot width is one twentieth of free space wavelength. Excitation port is placed at the end opposite to the shorter end of waveguide. The details of the design parameter of the waveguide, slot dimensions and their positions are summarized in TABLE 1.

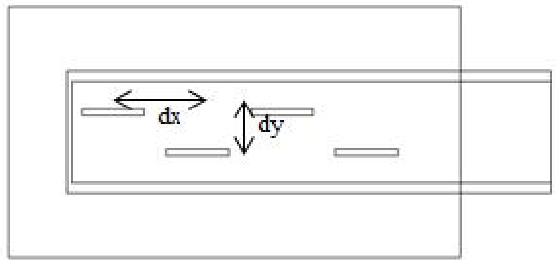

Figure 1: Top view of the linear array schematic

The proposed linear array antenna was designed and simulated in a commercial available electromagnetic solver and return loss obtained is shown in Fig. 2 which is as low as -42.92dB at the resonance frequency.

TABLE I

DESIGN PARAMETERS OF THE PROPOSED ANTENNA

Frequency Limits (GHz)	X-Ku band (10.0 to 15.0)
Waveguide Standard Dimensions (mm)	WR-75 (19.05 x 9.525)
a (broader dimension of w/g)	19.05mm
b (height of w/g)	9.525mm
$\lambda_c = 2a$	38.1mm
$\lambda_o = c/f$	24.3mm
λ_g	31.74mm

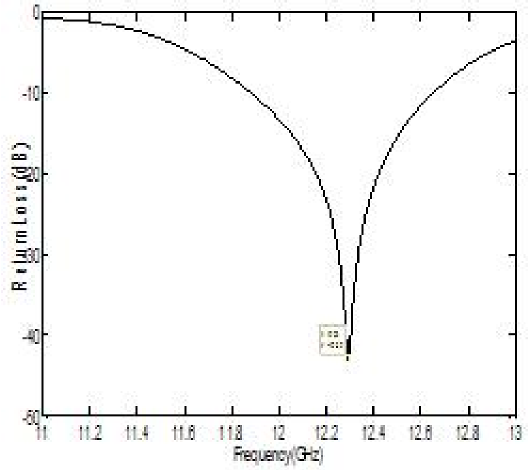

Figure 2: Return Loss of the linear array antenna

III. DESIGN OF H-PLANE POWER DIVIDER

A. *SINGLE H-PLANE Tee:*

High Frequency Structural Simulator is used to design single T-junction i.e. three port equal power divider. Septum parameters are obtained by proper optimization and repeated simulation resulting in converged solution. Through repeated iteration and optimization we could achieve the desired equal power values (-3dB) at the output ports and good input match over the operation frequency.

A three port equal power divider is designed with inductive windows to match the impedance at the input port and a septum to direct power and reduce reflections at the input port. It was observed that the side to which septum is moved gets less power than the opposite side. In order to make the real part of normalized impedance 1, the septum parameters were optimized and to nullify the imaginary part inductive windows were introduced.

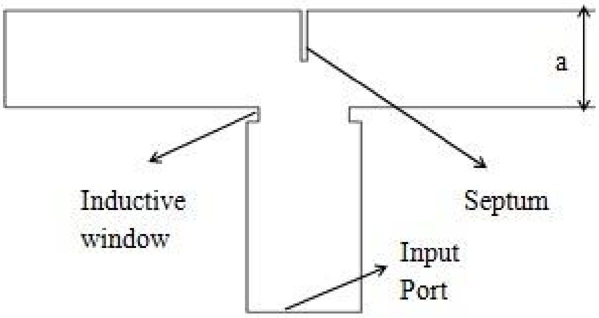

Figure 3: Schematic of the Tee Junction

The design was simulated in HFSS and obtained return loss is shown in Fig. 4 which is -44.89dB which indicates good impedance matching resulting in very less reflection at the input port. Fig. 5 shows coupled power in ports 2 and 3 which is almost -3 dB in both port indicating that power is equally divided amongst the two output ports.

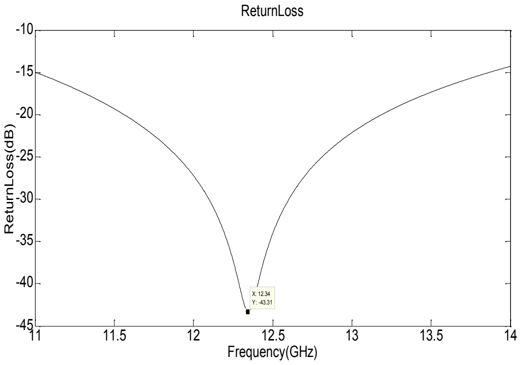

Figure 4: Return loss of a single Tee Junction

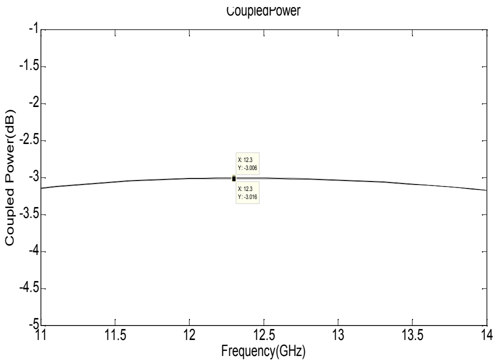

Figure 5: Coupled power to port 2 and port 3

B. 1:4 H-PLANE POWER DIVIDER

Now, a procedure to design a multiple-way power divider using T-junctions is presented [5] [6]. Fig. 6 shows the structure of a 1:4-way divider. T-junctions are spaced by half the guide wavelength in the feed waveguide. The window 1 is a matching T-junction which is a kind of reflectionless H-bend. In windows 2 to 5 the amplitude and the phase of the coupled power is controlled by the window width and position. Again septums are used to direct power and reduce reflections at the input port. Wave in the outer two ports travels $a+t$ (20.05mm) distance more in comparison to inner two ports which offers a phase difference of 227.41 degrees. Also bends, septum and width of the window affect the phase. Due to the combined effect the power in the outer two ports is out of phase with respect to the inner two ports.

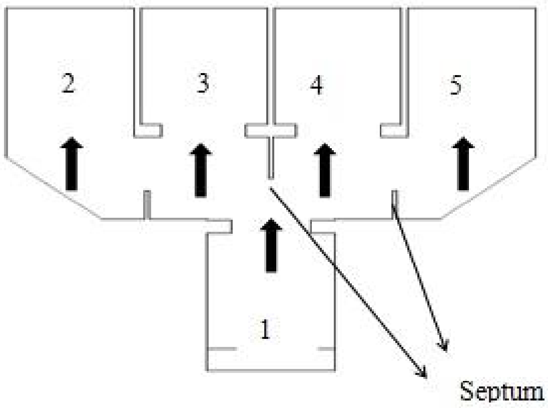

Figure 6: Schematic representing the cross-section of 1:4 power divider

The design was simulated in HFSS and obtained return loss as shown in Fig. 7, is -44.89dB at our frequency of interest which is indicative of good impedance matching and very less reflection at the input port. The post resonance is not perfect, it is of less concerned in present case for the antenna applications (It will important rather for filter applications). Figure 8 shows coupled power into the ports 2, 3, 4 and 5 which is almost -6 dB in all the port indicating that power is equally divided among all the output ports.

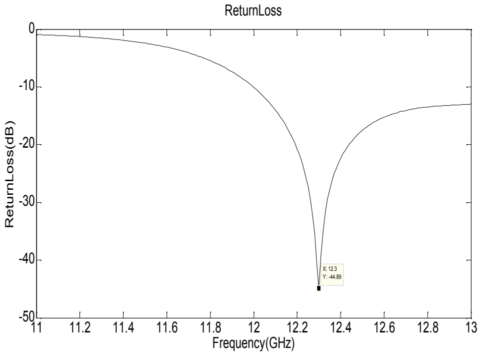

Figure 7: Return loss of 1:4 power divider

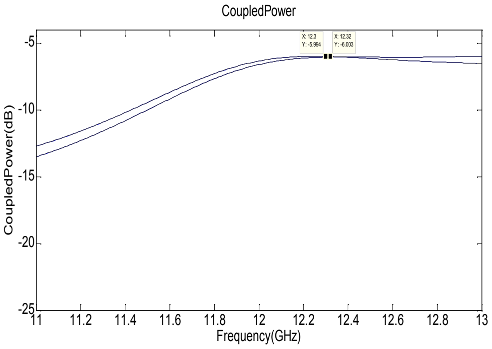

Figure 8: coupled power in the output port of the 1:4 power divider

IV. DESIGN OF PLANAR ARRAY

To design a planar array of 16 elements 4 linear arrays designed in previous section are united [4]. As already mentioned power in the outer two ports of the power divider is out of phase with respect to the inner two ports. Therefore to feed the 4x4 array in phase and to get the maximum directivity at the centre the outer two arrays are taken to be the mirror images of the inner two arrays and then the 4 linear arrays and power divider are united as shown Fig. 9. and simulated in HFSS. Figure 10 shows the simulated return loss of the combined structure.

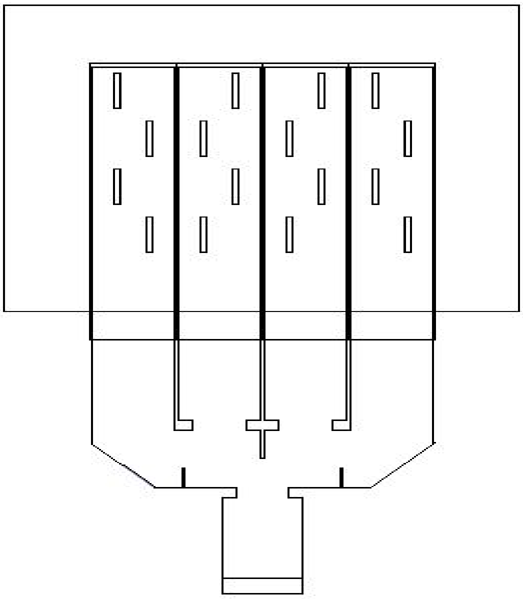

Figure 9: Cross-sectional view of the combined structure i.e., both the linear arrays and the power divider to form a planar array

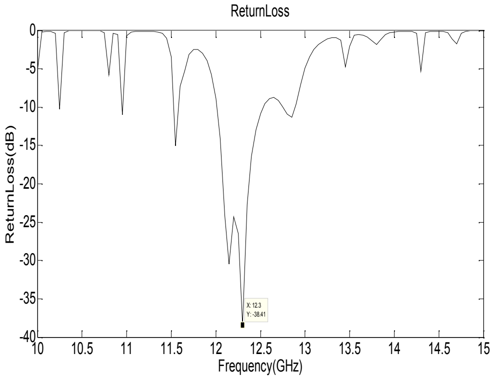

Figure 10: Return loss of the planar array structure

V. DIRECTIVITY OF THE PROPOSED ARRAY

Directivity is the radiated power density in the direction (θ, ϕ) divided by the radiated power density averaged over all directions i.e.

$$D = \frac{4\pi\alpha(\theta_o, \phi_o)\alpha^*(\theta_o, \phi_o)}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \alpha(\theta_o, \phi_o)\alpha^*(\theta_o, \phi_o)\sin\theta d\theta d\phi}$$

where α is the array factor as discussed in [1]. In our case of 4x4 uniformly spaced planar array

$$\alpha(\theta, \phi) = \left[\frac{\sin 4(kd_x \sin\theta\cos\phi)}{\sin(kd_x \sin\theta\cos\phi}\right]\left[\frac{\sin 4(kd_y \sin\theta\cos\phi}{\sin 4(kd_y \sin\theta\cos\phi}\right]$$

Using this concept a comparison graph is plotted with the simulation results and theoretical results which is shown in Fig. 11. Results obtained from theoretical analysis are well matched with those obtained from EM simulator.

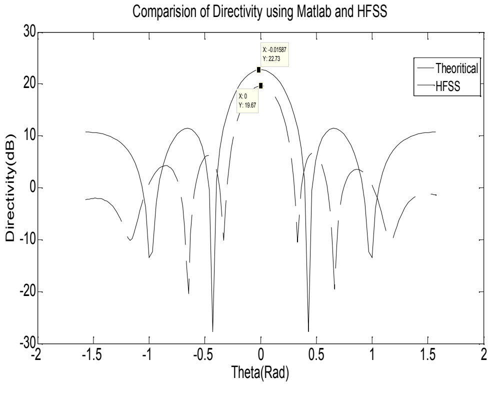

Figure 11: Comparison of directivity at phi = 0°

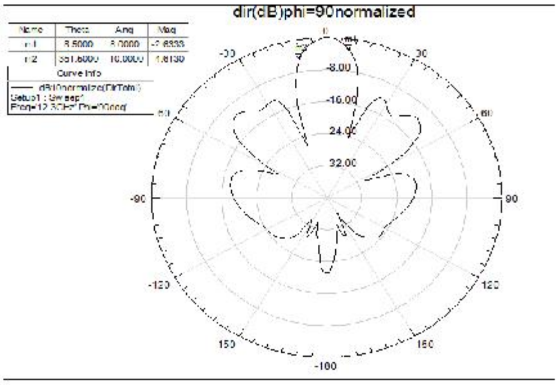

Figure 12: E-Plane polar pattern

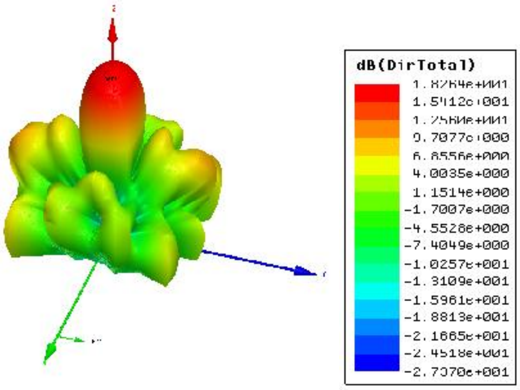

Figure 13: Three dimensional radiation pattern of the array

Figure 12 and 13 shows the E-plane radiation pattern of the proposed array showing highly directional nature in elevation plane and omnidirectionality in azimuth plane. The simulated HPBW is 17^0 implying that the antenna is very much directive. The antenna exhibits a cross-pole suppression of 43.969 dB over co-polar radiation.

CONCLUSION

A rectangular waveguide based slotted array antenna along with complete power divider driven feeding network is designed and simulated. The array is customized at centre frequency of 12.3 GHz with an impedance bandwidth of 949.4 MHz. A very good return loss of -38.1307 dB is obtained. Achieved gain of the overall system is 18.264 dB. Difference in the directivity of co-polarization and cross-polarization is 43.969 dB.

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