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Design and Development of Ultralow Sidelobe Antenna

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ABSTRACT

This paper describes the design and development of an airborne ultralow sidelobe level antenna, starting from the design of individual linear arrays and the power divider network. The antenna employs radiating slots on broadwall of rectangular waveguide and is of traveling wave type. The various stages involved in the design process are described briefly. The experimental results including the far-field patterns, voltage standing wave ratio, and power division ratios are discussed in detail.

1. INTRODUCTION

The literature on microwave antennas is in abundance, with a variety of configurations like reflectors, printed antennas, slotted arrays[1], dipole arrays, etc. The applicability of a particular antenna is determined by the pattern requirements, operating environment, etc. Many microwave communications and radar antenna systems employ slotted waveguide planar arrays because of their high radiating efficiency, excellent control of the sidelobe levels and the precise alignment of main beam that does not require calibration. Waveguide arrays are ideally suited for the generation of ultralow sidelobe levels with pencil main beam. They are preferred in radar applications because of their high power handling capability when compared to printed arrays. For airborne applications where the stress is on ultralow sidelobes, high gain, low losses and low cross-polarisation, the slotted arrays score overtheir counterparts like the reflector antennas and the printed antennas.

Slotted waveguide antennas can be divided into two types, (i) resonant, and (ii) non-resonant arrays. In a resonant array, the aperture has equiphase distribution and the beam is at boresight. One disadvantage of this type of array is its limited bandwidth which can only be enhanced by sub-arraying the aperture requiring a complicated feeder arrangement. In a non-resonant array, a matched load is put at the load end, thereby giving rise to progressive phase taper across the aperture. The main beam can be placed from endfire to within one beamwidth from boresight. It is well-known fact that the non-resonant array gives larger bandwidth compared to equivalent resonant array. This paper describes in detail, the various stages involved in the design of slotted array antenna.

2. THEORY

The design of ultralow sidelobe slotted array demands accurate analysis of the radiating slots, power divider network, non-resonant array design methodology, etc. The input impedance of the array depends on the accuracy with which the slot characterisation and the array design has been done.

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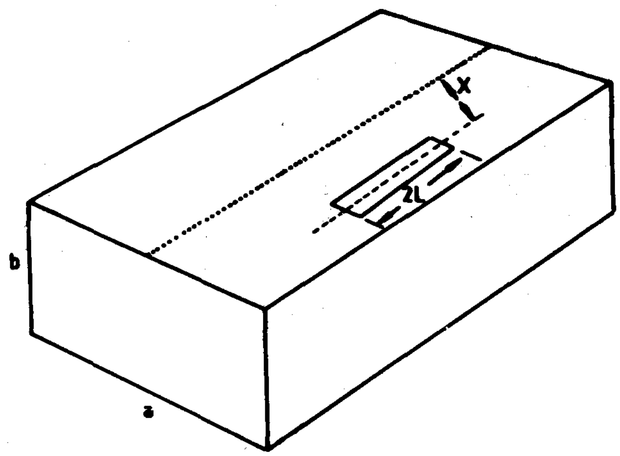

Figure 1. Slot cut on top of rectangular waveguide showing basic element used in the planar array.

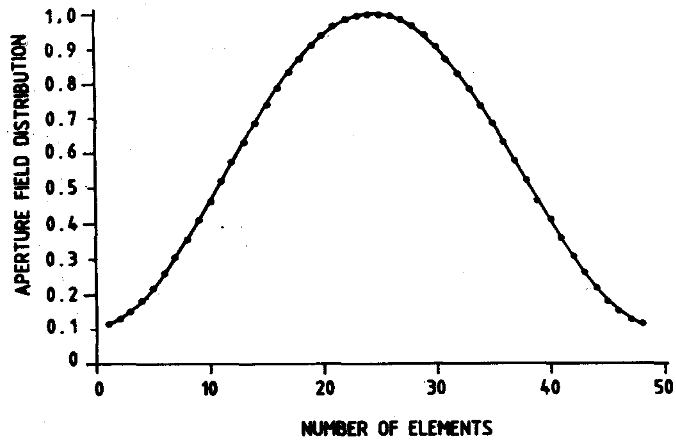

Figure 2 (a). Aperture voltage distribution in the azimuth plane.

The entire design procedure may be divided into six stages: (i) radiating slot characterisation, (ii) synthesis of aperture distribution, (iii) power dissipated in the load, (iv) design of non-resonant linear arrays, (v) power divider network, and (vi) fabrication and testing of planar array. Each of these stages are briefly described below:

2.1 Radiating Slot Characterisation

Figure 1 shows a slot cut on the broad wall of the rectangular waveguide. It serves as a basic radiating element. The amplitude and phase at the slot aperture is controlled by changing the offset and the length of the slot, which in turn changes the admittance offered by slot to the waveguide. An analysis of the broad wall radiating slots for various offsets from the centre line of a rectangular waveguide is carried out. Pertinent integral equations, taking into account finite wall thickness, have been developed and solved for the slot aperture *E*-field using method of moments (MoM)[2-3]. A menu-driven software package has been developed based on the MoM analysis. The results have been validated by comparison with the published data. The numerical results for the scattering from slots can be computed over a range of offsets, frequencies and waveguide dimensions.

2.2 Synthesis of Aperture Distribution

Proper choice of aperture distribution is essential to satisfy the pattern requirements in an optimum way. Furthermore, the aperture distribution has to be realisable. Taylor distribution is chosen for providing the aperture voltage amplitudes and phases. Its features are that the first $\bar{n}$ sidelobes are at same level (peak sidelobe level) and the far off sidelobes fall-off as $1/u$, where u is a parameter of sin θ space. Taylor distribution can easily be realised in waveguide-slotted arrays without exceeding the limits on the slot offsets. Aperture distribution has been synthesised for a sidelobe level of - 40 dB with $\bar{n}$ = 5. Figure 2(a) shows the aperture distribution of the 48-element array. Elevation distribution is a -35 dB Taylor with $\bar{n}$ = 5, spread over 14 elements and is shown in Fig. 2(b). The array employs a separable aperture distribution.

2.3 Power Dissipated in the Load

A matched load is placed at the load end of the non-resonant array, leading to dissipation of some fraction of the input power in the load. This power-to-load (PWL) effects the gain and the input match of the antenna significantly. The percentage of power to be delivered to load has to be decided from the overall length of the antenna, aperture distribution, the limits on the slot offsets, and the power handling capability of the matched loads. For long waveguides, the admittance variation from slot-to-slot is not high and a lower limit of 4 per cent PWL can be achieved comfortably.

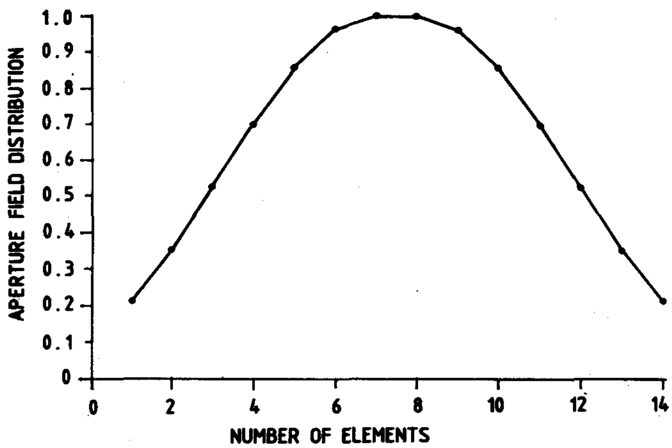

Figure 2 (b). Aperture voltage distribution in the elevation plane.

2.4 Design of Non-Resonant Linear Arrays

The array antenna is designed in the S-band. To keep the main beam at 5° and to avoid the second-order beams, the slots are displaced in alternate directions on either side of the centre line of the broad wall of the waveguide. This avoids the complication of adjacent slots overlapping each other. The uniform progressive phase along the array becomes $\beta d-\pi$. Since, it is advantageous to keep the beam between the broad side and the forward endfire, the spacing between the slots has to be chosen, such that $\beta d > \pi$. Under this circumstance, the spacing between slots for the required beam squint is computed as follows:

$$d = \frac{\lambda/2}{\frac{\beta}{\kappa_o} - \cos\theta_o} \tag{1}$$

where

β Waveguide dominant mode propagation constant

θ_o Main beam pointing angle

κ_o Free space propagation constant.

The overall length of antenna and hence the number of slots in the array are obtained from the beamwidth requirement. Next step is to compute the conductance to be offered by each of the slots. Under the assumption that the slots are not severely loading the waveguide, the aperture of the array antenna can be thought of as a continuous aperture and the concept of conductance per unit length can be brought in. Let, some representative component in the waveguide be expressed as a decaying wave, such that power present at any cross-section is given by:

$$p(z)=B^2 \exp[-2 \int_0^z \alpha(\zeta)\, d\zeta] \tag{2}$$

where B is the original field amplitude and α is the rate of attenuation.

Following Eqn 2, the point equation relating the power present and the attenuation rate can be written as

$$\frac{1}{p(z)} \frac{dp(z)}{dz} = -2\alpha(z) \tag{3}$$

Let the aperture distribution be given by $A(\zeta)\, e^{-j\beta\zeta}$, then the power present at cross-section z is

$$p(z)=P_{in} - \int_0^z |A(\zeta)|^2\, d\zeta \tag{4}$$

where P_{in} is the total input power to the waveguide.

Let P_{load} be the power to be delivered to load for an array of length L. Let f be the fraction of the input power that is delivered to load. Then, it follows from the above equations that

$$P_{load} = f\, P_{in}$$

$$P_{in}(1-f) = \int_0^L |A(\zeta)|^2\, d\zeta$$

and

$$p(z)=\frac{1}{1-f} \int_0^L |A(\zeta)|^2\, d\zeta - \int_0^z |A(\zeta)|^2\, d\zeta$$

From the above equation and Eqn 3, it follows that

Figure 3. Non-resonant planar slotted array

$$\alpha(z) = \frac{0.5|A(z)|^2}{\frac{1}{1-f}\int_0^L |A(\zeta)|^2 d\zeta - \int_0^z |A(\zeta)|^2 \cdot d\zeta} \quad (5)$$

By definition, normalised conductance per unit length

$$g(z) = -\frac{1}{p(z)}\frac{dp(z)}{p(z)} = 2\alpha(z) \quad (6)$$

therefore

$$g(z) = \frac{|A(z)|^2}{\frac{1}{1-f}\int_0^L |A(\zeta)|^2 d\zeta - \int_0^z |A(\zeta)|^2 d\zeta} \quad (7)$$

Following Eqn. 7, the normalised conductance of a given slot of the array can be obtained as a product of g(z) and the slot spacing d.

2.5 Power Divider Network

The power divider network was a 1:14 unequal divider which feeds the elevation plane of the planar array. The aperture distribution of the planar array has been achieved by using unequal power divider in elevation plane and by linear array design in azimuth plane. The 1:14 network was made up of two 1:7 waveguide power dividers, each feeding

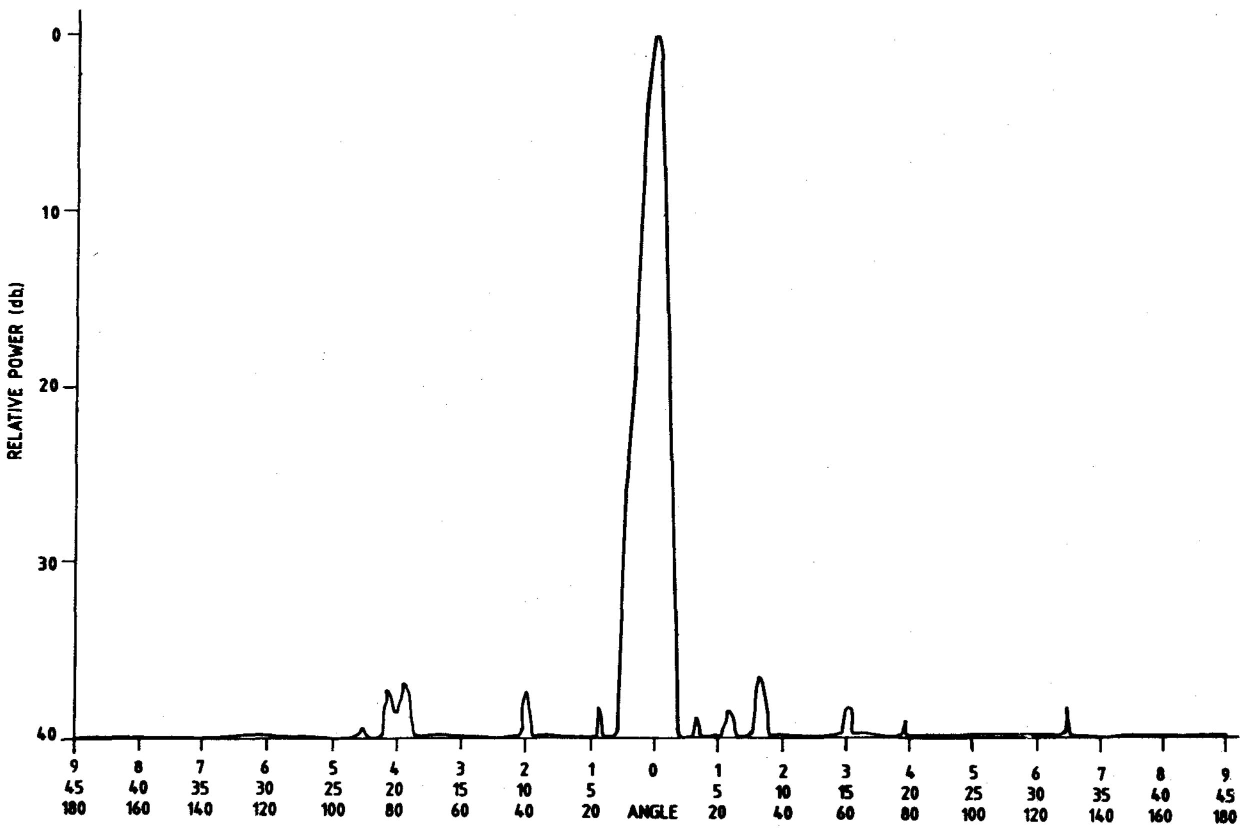

Figure 4 (a). Radiation pattern of the planar array in azimuth plane

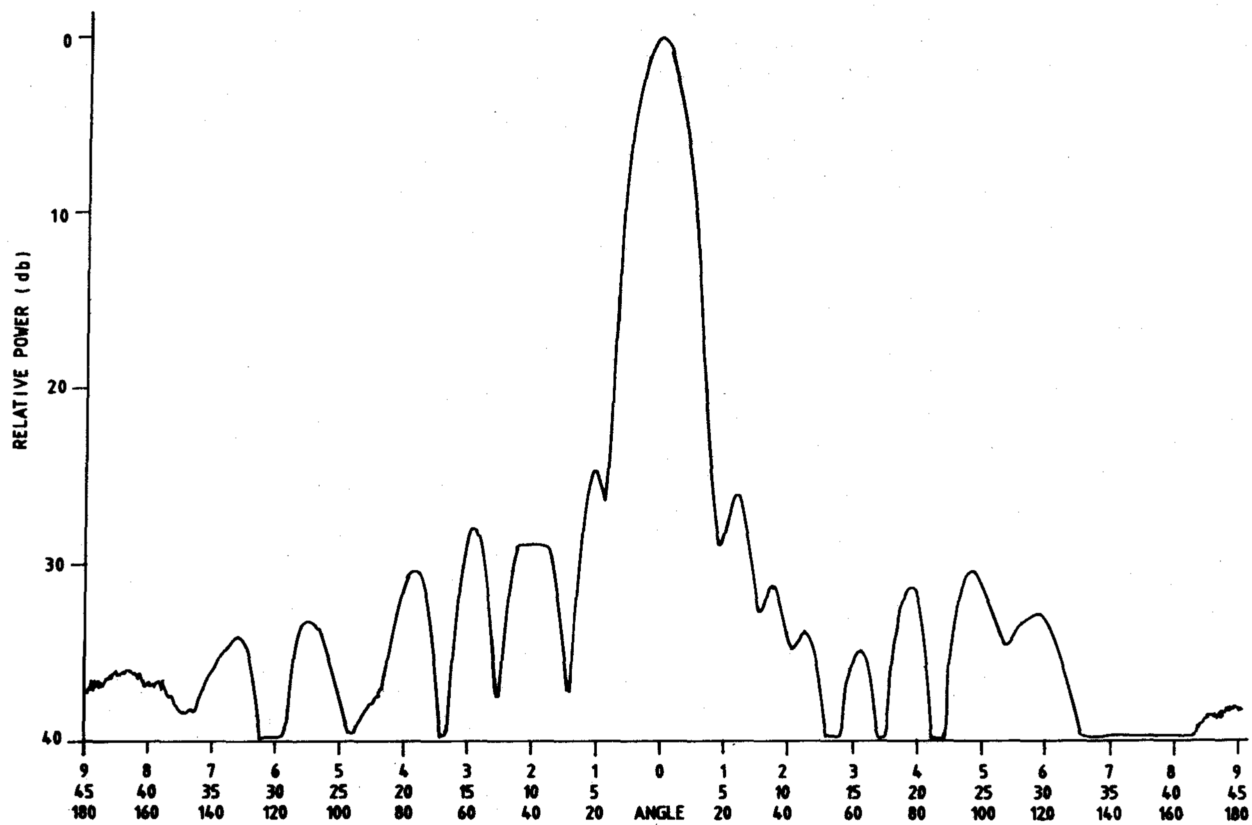

Figure 4 (b). Radiation pattern of the planar array in elevation plane

one-half of the elevation plane of the planar array. These two 1:7 power dividers were united by a magic tee to provide the elevation difference and the sum channels. Metal septems were employed inside the waveguide network to phase match the output ports and to get proper amplitude distribution. Each 1:7 power divider was designed using high frequency system simulator (HFSS) software package on Sun Sparc workstation. The 1:14 power divider was fabricated and tested. It was found to give an amplitude accuracy of within 0.25 dB and a phase accuracy of within 7°.

2.6 Fabrication & Testing of Planar Array

Radiating slots were machined on the top broad wall of each of the 14 waveguides. Each of the 14 linear arrays were tested for the input reflection coefficient, transmission coefficient and the radiation pattern. The linear arrays were designed for 5 per cent to PWL at design frequency and after fabrication, they were found to be having 5.5 per cent PWL which is quite close to design value. All the radiating waveguides were kept on the fixture side by side (linear arrays showing good performance were placed at the centre) to form the planar array. Suitable mechanical fixing and adhesives were used to stick the waveguides to the support structure. The power divider was fixed behind the planar antenna and it was connected to the antenna by phase-matched low insertion loss cables. The radiating surface of the array was covered with Tedlar dielectric sheet. A photograph of the planar array before sticking the dielectric cover is shown in Fig. 3. The array was operated as a vertically-polarised antenna.

The planar array was tested for voltage standing wave ratio (VSWR) using HP-8510 network analyser. The input match is found to be better than -17 dB over the frequency range of interest. An extensive radiation pattern measurement was carried out at an outdoor test range. The results of the azimuth and elevation far-field patterns at the design frequency are shown in Fig. 4. The peak sidelobe level is found to be

-36 dB in azimuth and -25 dB in elevation at the design frequency. The lowest sidelobe level achieved was -36.5 dB in azimuth and -25.6 dB in elevation. The average sidelobe was found to be -49 dB and the median was - 48.5 dB. The antenna was found to exhibit better than 32 dB gain over the frequency region of interest.

3. CONCLUSION

The design, analysis, fabrication and testing of ultralow sidelobe slotted waveguide non-resonant array for airborne radar applications involve sophisticated electromagnetic modelling and careful mechanical approach. Based on the results obtained from MoM and HFSS analyses, a large planar array has been designed, fabricated and tested successfully. An ultralow sidelobe level of the order of -35 dB and better has been achieved over a large frequency range. This is the first ultralow sidelobe antenna designed and developed in the country.

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