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Slotted Waveguide Shaped Beam Antenna at Ku Band

ROBERT V. McGAHAN

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1. Consolidated Design Results

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Slotted Waveguide Shaped Beam Antenna at Ku Band

1. INTRODUCTION

This report describes work performed under Project 86820602, later changed to Project 46001601. In the course of developing the Phase Derived Navigation System (Project 46001601), a microwave landing system, the need arose for six identical beacon antennas. These beacon antennas are used to delineate the boundaries of the landing zone (runway) in question, in order that a cockpit display may be generated.

The requirement was for an antenna to produce a cosecant pattern in elevation and an omni-directional pattern in azimuth. The frequency of operation was to be 15.84 GHz. Linear polarization was desired. Since the units were to be mounted in a field environment on portable transmitters, both weight and ease of mounting were considerations.

The necessity for a shaped beam in one plane indicated either a phased array or a specially shaped reflector. This, along with the aforementioned weight and mounting problems, led to adoption of an array of slots in a waveguide.

The shaped beam desired requires a non-linear progressive phase across the array. Since equi-spaced longitudinal shunt slots can produce only linear phase distributions they were deemed inappropriate. The requirement that each

(Received for publication 16 June 1977)

slot have independently controllable phase and amplitude led to utilization of a method discussed by Maxum.¹

This method allows the phase and amplitude of each slot to be controlled independently by inclining and displacing it appropriately. Plotting the equation describing the fields in the waveguide as a function of displacement and inclination allows a graphical solution for the position of each slot. This method is discussed in detail in Section 3.

2. SYNTHESIS OF ELEMENT CURRENTS

Before discussing the design of the slots, a description of the method used to determine the element currents will be presented. Since the cosecant elevation pattern was to be synthesized by an array of discrete radiators it was decided to use Schelkunoff's Method.^{2,3} In this method, the desired farfield pattern is expanded in a Fourier series of M terms, where M is the number of elements in the array, and the current on the mth element is then associated with the coefficient of the mth term in the series.

Letting M = 2N+1, the synthesized pattern can be written as a sum of terms

(1)

(2)

$$\mathbf{F}_{\mathbf{D}}(\mathbf{u}) = \sum_{n=-N}^{N} \mathbf{A}_{n} \mathbf{e}^{jkn\delta u}$$

where δ is the element spacing, k is the wave number $\frac{2\pi}{\lambda}$, and $u = \cos \theta$. The various coefficients are

$$A_n = \int_{-1}^{1} F_D(u) e^{-jkn\delta u} du$$

where F_{D} is the pattern to be synthesized.

Applying this to the specific case of a linear array of uniformly spaced elements, M = 21 and $\delta = \lambda/2$, using the geometry of Figure 1,

- 1. Maxum, B.J. (1960) "Resonant Slots with Independent Control of Amplitude and Phase" IRE T-AP Vol. AP-8, 4:384.
- Schelkunoff, S.A. (1943) "A Mathematical Theory of Linear Arrays," BESTJ, Vol. 22, 1:80-107.
- Collin, R.E. and Zucker, F.J. (1969) <u>Antenna Theory</u>, McGraw-Hill, New York, Part 1, Chap. 7, "Antenna Pattern Synthesis."



 A_n is complex, with magnitude a_n and phase α_n . Denoting the region of interest as extending from u_1 to u_2

$$A_{n} = \int_{u_{1}}^{u_{2}} \frac{1}{u} e^{-jn\pi u} du = Ci(n\pi u_{2}) - Ci(n\pi u_{1}) - j[Si(n\pi u_{2}) - Si(n\pi u_{1})].$$
(3)

Solving for 21 elements over the region $u_1 = .2$, $u_2 = .7$, corresponding to the angular range $12^\circ \le \theta \le 45^\circ$, yields the element currents listed in Table 1. Theoretical farfield patterns have been computed using these currents and are discussed in Section 4.

EL No.	Relative Magnitude a	Relative Phase ct [deg]	r	 ¥	∆x [inch]	θ [deg]	Resonant Length L [inch]
1	.160	82.91	0.00303	1.048	002	3.0	.36
2	.144	28.92	.00246	.944	.013	- 1.3	.36
3	.104	4.91	.00129	.628	010	.15	.36
4	.176	347.87	.00370	1.157	.017	.7	.361
5	.256	295.19	.00788	1.689	011	- 4.0	.361
6	.256	239.15	.00794	1.696	013	4.0	.361
7	.192	211.81	.00449	1.275	.016	- 1.8	.36
8	.352	196.55	.01532	2.355	033	1.8	.361
9	.648	139.92	.05476	4.453	.051	8.1	.363
10	.904	71.45	.11928	6.572	.031	-17.5	.364
11	1.000	0	.17090	7.866	125	0	.373
12	.904	- 71.45	.16234	7.666	.037	20.6	.365
13	.648	-139.92	.09100	5.740	.066	-10.8	.362
14	.352	-196.55	.02759	3.161	045	- 2.5	.362
15	.192	-211.81	.00828	1.731	.022	2.5	.36
16	.256	-239.15	.01494	2.325	018	- 5.5	.361
17	.256	-295.19	.01516	2.343	015	5.8	.361
18	.176	-347.87	.00722	1.617	.023	- 1.0	.36
19	.104	- 4.91	.00253	.956	014	2	.36
20	.144	- 28.92	.00487	1.328	.018	1.8	.36
21	.160	- 82.11	.00605	1.480	003	- 4.0	.36

Table 1. Consolidated Design Results

3. SLOT DESIGN PROCEDURE

The design of the slots was carried out according to the method described in Section 1. This method consists of four parts, once the synthesis of element currents is completed.

First the percentage of input power to be radiated is chosen and a coupling coefficient gamma (γ) is computed for each element in the array. The gammas account for the loss in total power as one proceeds along the array and are used to determine the displacement of each slot from the center line of the waveguide. The coupling coefficients are given by

$$\gamma_n = \frac{a_n^2 P_r}{K_M - K_n P_r} ,$$

(4)

where P_r is the percent power radiated (expressed as a decimal), K_n is the running sum of the a_n^2 :



and a_n is found from the complex element excitation

$$A_n = |A_n| e^{j\alpha n} = a_n e^{j\alpha n}$$

As in Section 2, M = 2N+1 and thus

$$K_{M} = \sum_{-N}^{N} a_{n}^{2}.$$

Once the coupling coefficients are determined, the ratio of the slot voltage to the amplitude of the dominant mode in the waveguide can be determined by

$$\left|\frac{V}{A}\right|_{n} = \sqrt{Ck_{o}k_{g}\frac{b}{a}\gamma},$$
(5)

where k_0 and k_g are $2\pi/\lambda_0$ and $2\pi/\lambda_h$, respectively, and have units of radians/ meter, a and b are the inside dimensions of the waveguide, and C is a constant. The value of C depends on the units of k_0 and k_g ; for the given case C = 8.22x10⁻³, while in Maxum's paper [1], C = 12.74, due to the fact that therein the units of k_0 and k_g are rad/inch.

The next step in the design procedure is to determine θ , the angle of inclination, and Δx , the displacement, for each slot. The complex excitation for a slot can be expressed as a function of θ and x, where θ and x are as designated in Figure 2:

(6)

$$\frac{\mathbf{V}}{\mathbf{A}} = \left| \frac{\mathbf{V}}{\mathbf{A}} \right| e^{j\alpha} = \frac{8 \cdot 1}{a} \left[\operatorname{Be}^{\frac{j\pi \mathbf{x}}{a}} + \operatorname{De}^{\frac{-j\pi \mathbf{x}}{a}} \right]$$

where

$$\mathbf{B} = \frac{\cos{(\frac{\pi}{2}\cos{(\mathbf{i}-\theta)})}}{\sin{(\mathbf{i}-\theta)}} \ , \ \mathbf{D} = \frac{\cos{(\frac{\pi}{2}\cos{(\mathbf{i}+\theta)})}}{\sin{(\mathbf{i}+\theta)}}$$





and i is the frequency dependent angle of incidence of the propagating wave in the guide given by $i = \sin^{-1}(\lambda_0/2a)$. The phase α is found from the element excitation, while the magnitude ratio |V/A| is determined from the coupling coefficient.

When Equation 6 is plotted, curves relating slot excitation (magnitude and phase) to slot orientation result, as in Figure 3. How well a given slot, when constructed, will perform depends on two things, the machining tolerances and the actual orientation of the slot. Slot excitations with large V/A ratios and large inclination angles are relatively insensitive to machining errors because of the steepness of the curves in these regions, but these slots are near the limits of validity of the design method. Slots with small V/A ratios and inclination angles are well within the design limitations but are much more sensitive to machining errors.

Examination of Figure 3 indicates that the range of excitation phases extends only from 0° to 90°. However any phase in the range $-180^\circ \le \alpha \le 180^\circ$ can be obtained. Use is made of the fact that the phase of the field inside a waveguide can be changed by 180° by crossing the center line perpendicularly or by moving along the guide to a point $\lambda_g/2$ away. Thus a slot excitation can be put into the proper phase range ($-180^\circ \le \alpha \le 0$ or $0 \le \alpha \le 180^\circ$) by moving a multiple of $\lambda_g/2$ along the guide from some reference, and crossing the center line if necessary. The proper quadrant can then be selected by choosing the sign of the inclination angle.

Using the conventional formulation of wave propagation in the positive z direction, and the geometry of Figure 2, a method of determining which of the



Figure 3. Design Curves Relating Δx and θ to Slot Excitations

four possible slot orientations will put the slot excitation phase in the proper quadrant follows. Examination of the fields within the waveguide shows that a negative Δx and a positively increasing θ produce phases which vary from 0° to +90°. This first quadrant condition is taken as the reference. A slot with negative Δx and negatively increasing θ can have phase variations from 0° to -90°. Positive Δx and positively or negatively increasing θ produce phase variations 180° to 90° (second quadrant) or -180° to -90° (third quadrant) respectively. The foregoing are applicable for a slot at the same z as the reference slot. When one moves along the guide, as in constructing an array, one must account for the n(180°) phase shifts incurred thereby. These conditions are summarized in Figure 2.

The fourth and final step in the design of the slots is to determine their lengths. Maxum measured the resonant lengths of slots for various combinations of Δx and θ , and interpolated the results to obtain a family of curves. Maxum's curves give slot length (1) vs Δx and θ , where 1 and Δx are in inches, for WR90 waveguide at 9.375 GHz. It was reasoned that these curves could be normalized to wavelength and used at 15.84 GHz for WR62 guide and, indeed, experimental





Figure 4. Curves of Resonant Slot Length as a Function of Δx and θ Normalized to Wavelength

4. RADIATION PATTERNS

The synthesized element currents listed in Table 1 were used to compute theoretical farfield patterns. These patterns were computed assuming an array of collinear dipoles. The length of each dipole was $\lambda_0/2$, and the center-to-center separation was $\lambda_g/2$, where λ_o and λ_g are the free-space and guide wavelengths, respectively, as depicted in Figure 5.

The element pattern used was that of a slot in a ground plane.⁴ When the long axis of the slot is parallel to the z-axis this pattern becomes:

$$I(\theta) = \frac{\cos{(\frac{\pi}{2}\sin\theta)}}{\cos\theta}$$

(7)

where θ is measured from the positive y-axis as in Figure 6. Figure 6 also shows the comparison between this element pattern and that of $\cos \theta$ over the same range.

 Fante, R.L. and Mayhan, J.T. (1970) "Bounds on the Electric Field Outside a Radiating System - II," IEEE T-AP Vol. AP-18, 1:64.



Figure 5. Geometry Used to Analyze the Slot Array



Figure 6. Element Pattern for a Slot.

Although the slots were inclined, rather than parallel to the long axis of the waveguide, and were, in general, shorter than $\lambda_0/2$ due to changes in resonance conditions, as well as being offset from the center line by varying amounts because of the magnitude requirements, these deviations were small. Therefore, they were ignored in computing theoretical farfield patterns and a common axis was assumed. The resulting pattern for the region of interest is shown in Figure 8.

The method outlined in Section 3 was used to design an array of 21 slots to produce the cosecant pattern synthesized in Section 2. The center element was



Figure 7. Ku Band Slotted Waveguide Antenna, WR62 Waveguide, Total Length = 31 cm.

chosen as the reference. A value of 50% was chosen for the power radiated. As noted in Section 1, the frequency of operation was 15.84 GHz.

The resulting values of Δx , θ and 1 are listed in Table 1 along with the synthesized element excitations, coupling coefficients (γ) and |V/A| ratios. One of the antennas so constructed is shown in Figure 7.

The farfield patterns of the experimental antennas were measured in an anechoic chamber. The source was a Gunn Diode Oscillator feeding a small horn. The receiver was a phase-locked microwave measurements receiver using a bolometer as the square-law device.

The guide wavelength is 2.36 cm, thus the aperture (D) of the array is 24.8 cm. The farfield condition $(2D^2/\lambda_0)$ for this antenna is 6.5 m, thus the chamber length of 9 m was sufficient to insure being in the far field.

A typical measured pattern*, taken at 15.84 GHz, is shown in Figure 9.

Seven identical units were ultimately constructed by a machinist. The first unit was made with a makeshift jig and had poorer performance than the remaining six. These six had patterns which were identical to within one dB.



Figure 8. Theoretical Radiation Pattern of Slot Array. Frequency = 15.84 GHz



Figure 9. Measured Radiation Fattern of Ku Band Slotted Waveguide Antenna. Frequency = 15.84 GHz

5. CONCLUSIONS

This slotted waveguide antenna was designed to fill a current need. The slot orientations and resonant lengths were taken directly from curves designed by Maxum and adapted to the required frequency and waveguide size. The first models built performed so well that no further attempt was made to refine the theory, since the object was to produce working antennas rather than do novel research. Thus the deviations of the measured patterns from the theoretical can only be discussed on a qualitative basis.

A comparison of Figures 8 and 9 shows that the theoretical pattern has a first sidelobe of -19.1 dB while the measured sidelobe is -19.8 dB. The remaining measured sidelobes exhibit random behavior with an average noise level of approximately 24.3 dB. Examination of the element currents (Table 1) shows that the average (least mean square) phase slope is 58° per element. The deviations of the actual phases from the linear tilt correspond to an effective number of elements of 10.27. The machining tolerances and the graphical inaccuracies in the design indicate a mean square phase error of 12° per element. These values are consistent with the observed -24 dB average sidelobe level.

The measured gain of the experimental model was 12 dB. Assuming an elevation element pattern as in Section 4, Equation 7, and a cartiod azimuthal pattern $(1+\cos \omega)$, a theoretical gain of 12.8 dB was calculated. The calculated gain assumed that all slots were resonant and that 50% of the input power was radiated. In fact, the slots may well not be resonant, since the a/b ratio of WR90 waveguide is not the same as that for WR62 waveguide, and the normalization made on Maxum's graph did not account for this. The cross polarization pattern was measured to be -20 dB.

This report demonstrates that the method of inclining and displacing slots to obtain independent control of phase and amplitude is a viable way of constructing a shaped beam antenna. The design frequency of 15.84 GHz and power radiated of 50% significantly increases the range of validity of the method beyond the previously published limits.¹

METRIC SYSTEM

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Quantity	Unit	SI Symbol	Formula
eneth	metre	m	
ness	kilogram	kg	
ime	second	•	
lectric current	ampere	٨	
hermodynamic temperature	kelvin	ĸ	
mount of substance	mole	mol	***
uminous intensity	candela	cd	
SUPPLEMENTARY UNITS:			
lane angle	radian	red	
olid angle	steradian	st	
DERIVED UNITS:			
Acceleration	metre per second squared		m/s
ctivity (of a radioactive source)	disintegration per second	and succession of the	(disintegration)/s
ngular acceleration	radian per second squared		red/s
ngular velocity	radian per second		red/s
rea	square metre		m
lensity	kilogram per cubic metre		kg/m
lectric capacitance	fared	F	A-s/V
lectrical conductance	siemens	S	AN
lectric field strength	volt per metre		V/m
electric inductance	henry	н	V-s/A
lectric potential difference	volt	v	W/A
electric resistance	ohm		VA
electromotive force	volt	V	W/A
nergy	joule		N-m
entropy	joule per kelvin		J/K
orce	newton	N	kg-m/s
requency	hertz	Hz	(cycle)/s
lluminance	lux	lx	lm/m
uminance	candela per square metre		com
uminous flux	lumen	lm	cosr
nagnetic field strength	ampere per metre		A/m
magnetic flux	weber	Wb	V-B
nagnetic flux density	tesia		wom
magnetomotive force	ampere	^ .	
power	watt	W	1
pressure	pascal	Fa	A
quantity of electricity	coulomb		Nm
quantity of heat	joure		Wier
radiant intensity	watt per steradian		Wka.K
specific heat	joule per kilogram-keivin	 Da	N/m
stress	pascal		W/m.K
inermal conductivity	watt per metre-keivin		m/s
velocity	metre per second		Part
viscosity, dynamic	pascal-second		min
viscosity, kinematic	square metre per second	v	WA
voltage	volt		m
volume	cubic metre		(wavel/m
work	ioule	ï	N·m
SI PREFIXES:			
Multiplicati	on Factors	Profix	SI Symbol

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