SLOT ARRAY EMPLOYING PHOTOETCHED TRI-PLATE TRANSMISSION LINES

Donald J. Sommers
Sanders Associates, Inc.
Nashua, N. H.

Abstract

Microwave printed circuit techniques are readily adapted to the construction of compact antennas ideal for flush mounting on high speed aircraft. This paper describes the development of a two-dimensional X-band array consisting of 16 slots fed by photoetched Tri-plate transmission line. The design of a unity coupled series slot and the resulting mode purity problems are discussed. Several power divider configurations are illustrated and data on the performance of some of these devices is presented. The construction of a 4 slot E-plane, a 4 slot H-plane and the combination 4x4 E-, H-plane array utilizing these power dividers is shown. Radiation patterns of each of these arrays were measured and a comparison of the individual and combination array patterns is made.

Introduction

A paper presented to you by Mr.Wild earlier in this symposium has acquainted you with Tri-plate, the shielded strip transmission line developed by Sanders Associates, Inc., of Nashua, N. H. You will recall that such a line is simply photoetched on the inside faces of two dielectric sheets which have copper foil bonded to both surfaces. The advantages of Tri-plate from the standpoints of light weight, compactness and economy of construction are quite obvious. But other advantages are equally important.

For example, I am going to describe and discuss the development of an X-band antenna which consists of a 4x4 array of slots etched in one of the two outer faces of a Tri-plate transmission line. The convenience of installation inherent in such antenna arrays enables them to be readily flush-mounted on the skin of a high speed aircraft. The 4x4 X-band slot array shown in Fig. 1 illustrates this very nicely. Here is a composite antenna array having a 4" square aperture and a total thickness of only 1/8". Such a device could be mounted simply by drilling a small hole in the aircraft's skin, a hole just large enough to allow the passage of a coaxial fitting or, in the case of this particular X-band array, a waveguide flange. It is, therefore, conceivable that any plane, whether already in operation or still in the design stage, could have a Tri-plate slot antenna installed without major structural change.

General Considerations

The possible applications of these flush-mounted antenna arrays are, in fact, so extensive that Sanders Associates,Inc., has investigated them at some length in conjunction with its study of the Tri-plate transmission line. Our principal objective in this work has been the development of a 4x4 slot array with in-phase signals of equal power fed to each slot. The 4x4 array was selected primarily because its size is about the minimum with which pattern asymmetry is distinguishable, and secondly because power splitters whose arms were in even numbers could be used. Power splitters having an odd number of arms are, of course, less convenient to use because the arms are not of equal length, which upsets the in-phase excitation of the slots they feed. This can, however, be remedied, as will be explained later.

Teflon fiberglas laminate was chosen as the dielectric material to be used in this development first because it was the only commercially available copper-clad dielectric with suitable electrical properties at microwave frequencies, and second because of its dielectric constant. The question of this dielectric constant merits some elaboration. Analysis of the problem shows that the ideal antenna for optimum broadside signal and mimimum "endfire" would have its slots spaced 1/2 wavelength apart in air and fed from a power divider whose arms are one wavelength apart in the dielectric being used. Unfortunately this ideal condition cannot be realized unless the dielectric constant of the material equals 4, because, since the principal mode of operation in Tri-plate is TEM, the wavelength varies as the square root of the dielectric constant. The dielectric constant of teflon fiberglas laminate - approximately 2.40 - was considered satisfactory for maintaining the proper phase relationship both in air and in the dielectric.

Finally a frequency of 9375 megacycles per second was selected for the study, primarily because of the availability of test equipment at that frequency.

Slot Design

The first step in the development of the 4x4 array was to design a satisfactory radiating element. A series slot, such as the one shown in Fig. 2, appeared to be the simplest and most natural type to excite from Tri-plate. It was not sufficient, however, just to etch the slot in one of the outside faces of a Tri-plate line. It was obvious that excitation could be accomplished in this manner because of the interruption of currents in the outer plate, but at the same time undesirable modes were set up as a result of the voltage unbalance introduced between the two outer plates by this asymmetrical device. Tests substantiated this. The first slot used in experiments - $1/2\,\lambda_0$ long and $1/20\,\lambda_0$ in width - showed appreciable lateral leakage from between the outer plates. It was evident that the parallel plate mode was present, and suppression of this mode was obviously essential to the proper operation of the radiating element. From previous experience with mode suppression techniques, it was determined that shorting pins along the center strip in the regions of the slot's input and output would maintain the proper voltage balance between the outer plates. Fig. 2 shows a typical shorting pattern.

While these pins effectively suppressed undesirable modes present in the line, they had considerable effect on the impedance of the slot around which they were installed. Because of the time involved in separating the true slot impedance from the parameters which affect it, it was decided to match this unity coupled slot solely by experimental means. (A study of slot impedance and the effect of these shorting elements is now in progress at Sanders Associates.) The final radiating element designed was a slot $3/5\,\lambda_0$ long and $1/20\,\lambda_0$ wide, in series with a 90 ohm Tri-plate line which terminated in an open circuit at a distance of $1/10\,\lambda_L$ from the slot center, λ_0 being the wavelength in air and λ_L the wavelength in the transmission line.

The small tab in the center of each slot of the 4x4 array of Fig. 1 adds capacity to the slot. Tuning is conveniently accomplished by trimming it to its proper length.

It is interesting to note the correlation between a series slot when coupled to air and the same radiator when coupled to waveguide. Fig. 3 illustrates a Tri-plate-to-waveguide transition using a series slot as the transformer. A slot matched under 1.1 VSWR to air at 9375 megacycles per second has a VSWR of 1.6 when coupled to a section of 1" x 1-1/2" waveguide with a matched termination. This is just about the same as the ratio of their characteristic impedances: 377 ohms for air and 235 ohms for waveguide at 9375 megacycles per second. Slot transitions of this sort have been used experimentally by Sanders Associates, Inc., with considerable success.

E- and H-plane Feed Systems

Having developed a suitable radiating element, it was then necessary to determine the best method for delivering energy of the correct magnitude and phase to an array of these elements. Because of its convenient form factor, Tri-plate can be shaped into an almost endless variety of power splitters. Those illustrated are merely suggestive of the multiplicity of designs which can be made.

The simplest power divider is a junction at which a line of characteristic impedance Z_0 divides into two parallel lines each having a characteristic impedance of $2Z_0$. Two possible configurations of this type are shown in Figs. 4(A) and 4(B). Fig. 4(A) is a Tee junction which is the Tri-plate counterpart of the coaxial "T". Fig. 4(B) illustrates an In-line junction which is more unique to strip type transmission lines. Comparing the shapes of these two junctions, it would seem that the In-line type would afford a much smoother transition than the Tee. This is borne out by the curves of Fig. 5, which are plots of VSWR vs Frequency over a 12% band centered at 9375 megacycles per second. The match of the In-line divider is under 1.10 over a 5% band, and under 1.18 over the entire 12% band, while the best match obtained with the Tee is only 1.22. It should be noted that the dips in the center of both curves are due, at least partially, to the fact that the loads are best matched in the center frequency region. However, the load VSWR's were less than 1.12 over the range covered.

A combination of three of these simple, two-way In-line junctions can be used to feed equal amounts of in-phase power to four separate lines. Fig. 6(A) shows such a device. Further steps in this power-splitting pattern should be made in multiples of two in order to preserve the power divider's equi-phase characteristic.

Considering the form factor of Tri-plate, it is obvious that a three-way equal power split can be accomplished easily by splitting a line of characteristic impedance Z_0 into three lines each having a characteristic impedance of $3Z_0$. It is apparent from the three-way power divider shown in Fig. 6(B) that the center arm in such a configuration is shorter than the outer two. This asymmetry, which upsets the equi-phase characteristic of the junction, can be overcome very simply by curving the center arm to make its length equal to that of the others. The power splitter shown in Fig. 6(B) has less than 0.3 db variation in power between the arms when measured over a 10% frequency band centered at 9375 megacycles per second.

Logically the next step in developing methods for feeding slot arrays was to make a power splitter which could divide power in any desired proportion. Such a device, which we shall refer to as a progressive power splitter, is illustrated on the left of Fig. 7 alongside the slotted array which it was designed to feed. This particular unit has been used successfully as an H-plane feed system for both the four-element H-plane array and the composite 4x4 array shown in Fig. 1. The input line to this system has a characteristic impedance of 22.5 ohms and feeds, through a three-to-one power division, two lines whose characteristic impedances are 30 ohms and 90 ohms. This 30 ohm line divides, in turn, into a 45 ohm line and a second 90 ohm line, giving in this case a two-to-one power split. Finally the power in the 45 ohm line divides equally into two more 90 ohm lines. All junctions of this power divider were designed to satisfy the fundamental parallel circuit equation; $1/Z_1 = 1/Z_2 + 1/Z_3$. Measurements taken on a progressive power divider of this type showed a maximum deviation of only 0.6 db over a 10% frequency band centered at 9375 megacycles per second.

You will recall that our objective has been to develop a 4x4 array whose slots, in the E-plane as well as the H-plane, were fed with signals which were not only of equal power but also in phase. The power divider shown on the left of Fig. 8 is a non-frequency sensitive device which excites all slots of the E-plane array beside it with in-phase signals. This is accomplished by virtue of the fact that all signals must travel along paths of equal length from the junction of the power divider to the slots which they feed. Equi-phase excitation in the H-plane, using the power divider of Fig. 7, will occur only at the frequency where λ_L equals the distance between the 90 ohm arms. Therefore, this distance was constructed to equal λ_L at 9375 megacycles per second, the design frequency.

The power divider system used to feed the final 4x4 slot array is shown in Fig. 9. Observe that this is a combination of the power dividers shown in Figs. 7 and 8. Here we have an assembly of four progressive power dividers, each of which feeds four H-plane coupled slots. Each of these progressive power dividers is coupled in phase to an arm of a four-way power splitter.

Radiation Patterns

Radiation patterns of the three antennae shown in Figs. 7, 8 and 9 were measured at the design frequency and are plotted in Figs. 10-13. The individual 4-slot H-plane and 4-slot E-plane arrays, each of which comprises a side of the two-dimensional array, were first constructed and individually tested in order to make a more complete analysis of the composite 4x4 array. The half-power beamwidth values for both of the four-slot linear arrays are very close to the predicted values. The H-plane array, with $1.92\lambda_0$ spacing between outside slot centers, has a 20° beamwidth, and the E-plane array, with $1.8\lambda_0$ spacing between slot centers, has a 23.5° beamwidth. The lower side lobes in the H-plane can be attributed to the voltage tapers at the end of the array.

Now, comparing the E- and H-plane patterns of the 4x4 array (Figs.12 and 13) with the corresponding individual array patterns (Figs. 10 and 11), we can see that the main lobes of both plots are identical. However, the side lobes in both planes of the 4x4 array are appreciably larger. The E-plane side lobe increased from approximately -12.5 db to -9.0 db, while the H-plane side lobe increased from approximately -15.2 db to -13.3 db. These higher side lobe intensities are due primarily to mutual coupling between diagonal slots. Diagonal slots are not, of course, present in the individual arrays.

This study of slot antenna arrays is being continued by Sanders Associates, Inc., to supplement the developments highlighted in this paper. Much work remains to be done. Yet even at this early stage, it is apparent that workable slot antennae and feed systems can be made easily and economically from Tri-plate transmission lines.

Acknowledgments

For sponsoring studies which have led to the development of the techniques and equipments discussed in this paper, grateful acknowledgment is made to the Bureau of Aeronautics, Industrial Planning Division; the Cambridge Air Force Research Center; and the National Bureau of Standards.

References

1. R. M. Barrett, "Etched sheets serve as microwave components," *Electronics*, vol. 25, p.114-118; June, 1952.

2. Sanders Associates, Inc. report "Photoetched Microwave Transmission Lines" of June 2, 1954, submitted under Contract CST-1365.

3. Sanders Associates, Inc. monthly progress letters to Cambridge Air Force Research Center under Contract AF19 (604) - 1154.

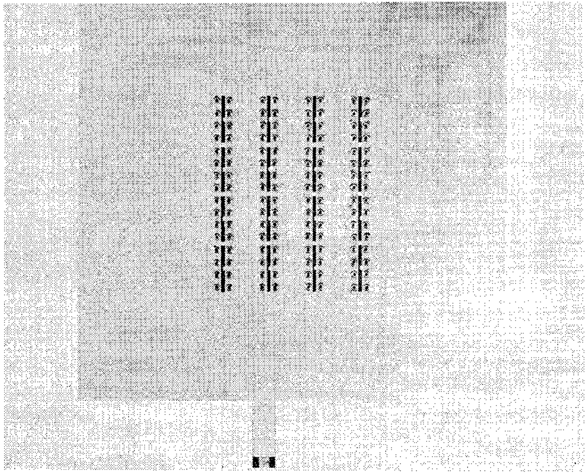

Fig. 1 - 4x4 slot array.

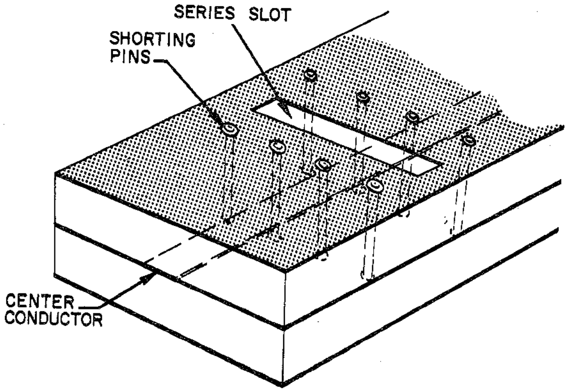

Fig. 2 - Series slot in tri-plate transmission line.

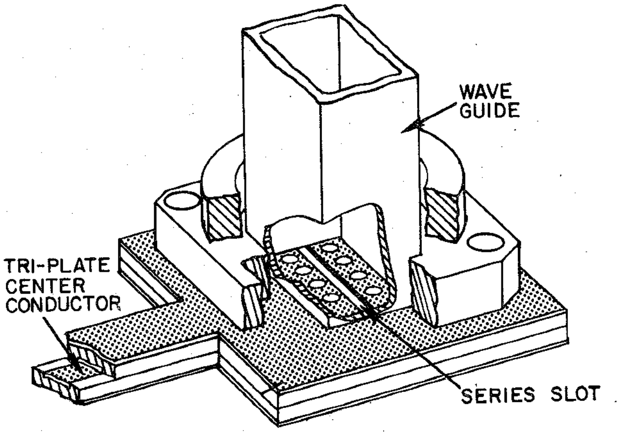

Fig. 3 - Cutaway view of tri-plate to waveguide transition.

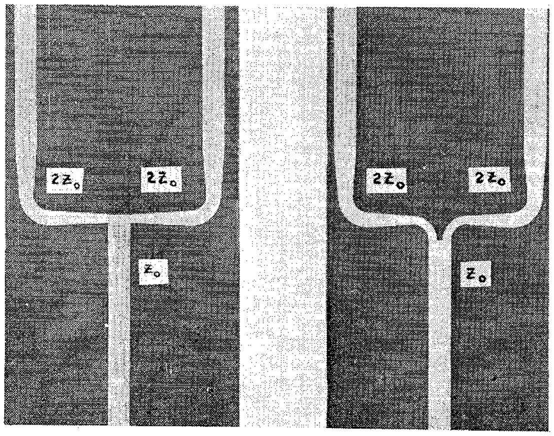

Fig. 4 - Two-way power dividers, tee (left), in-line (right).

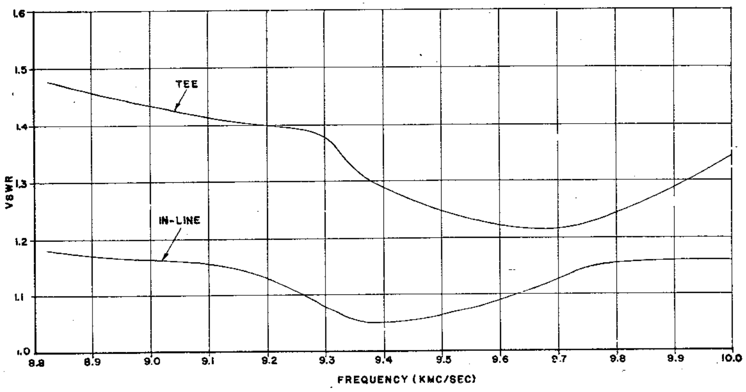

Fig. 5 - VSWR vs frequency curves of the junctions shown in Fig. 4.

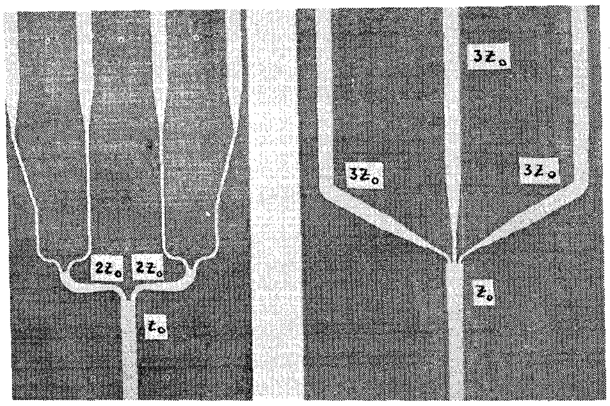

Fig. 6 - Four-way power divider (left), three-way power divider (right).

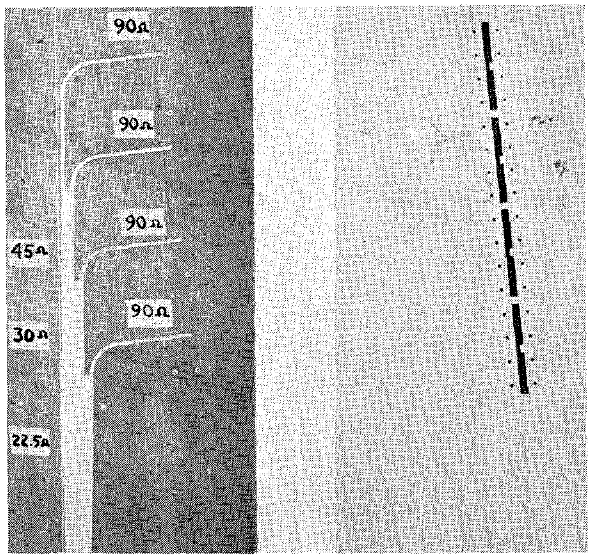

Fig. 7 - 4-slot H-plane array with progressive power divider feed.

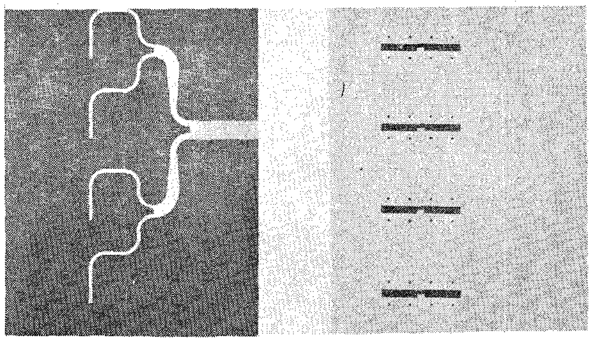

Fig. 8 - 4-slot H-plane array with four-way power divider feed.

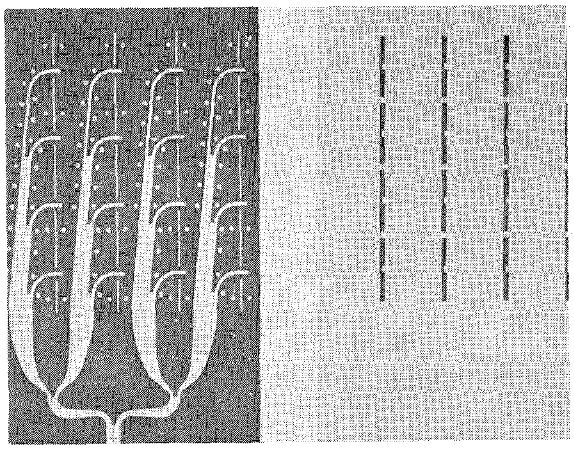

Fig. 9 - Composite 4x4 array with feed system.

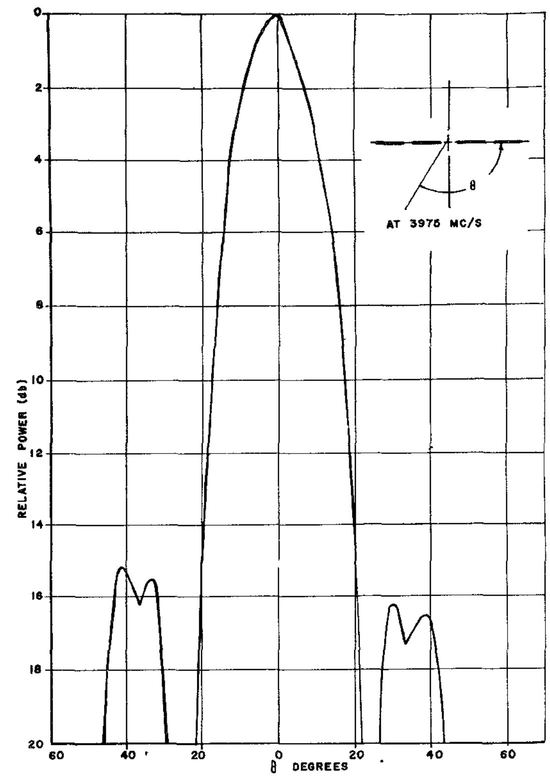

Fig. 10 - H-plane radiation pattern of 4-slot H-plane array in Fig. 7.

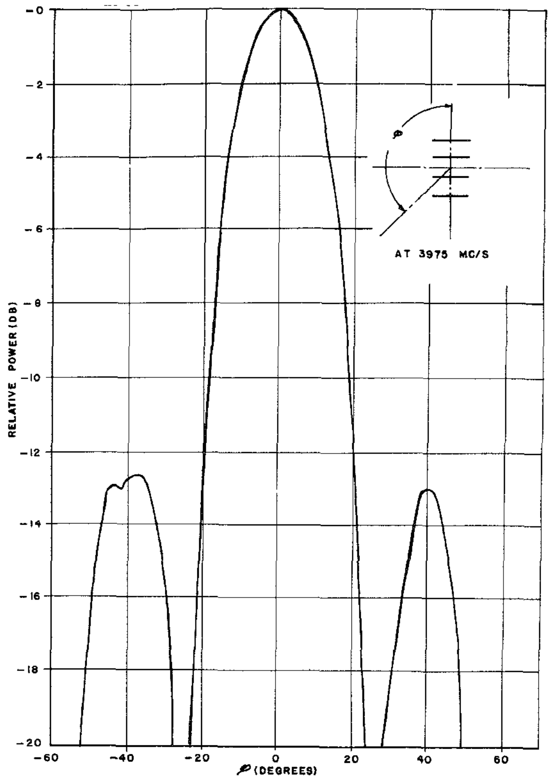

Fig. 11 - E-plane radiation pattern of 4-slot E-plane array in Fig. 8.

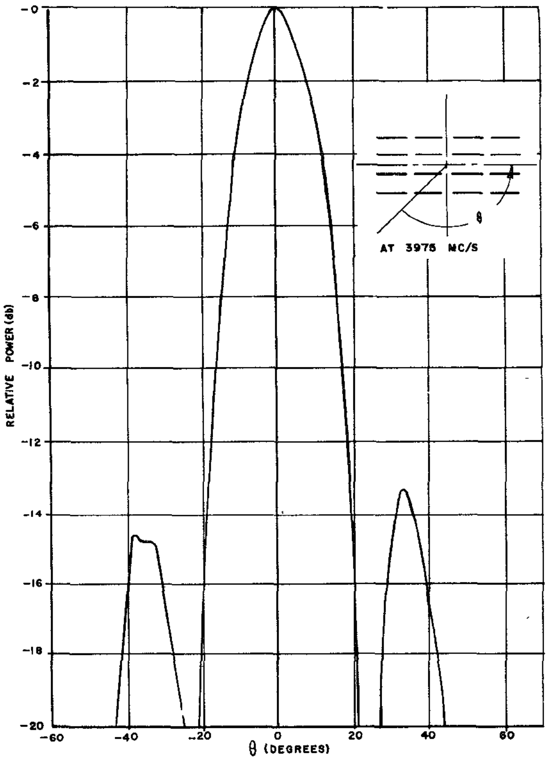

Fig. 12 - H-plane radiation patterns of 4x4 array in Fig. 9.

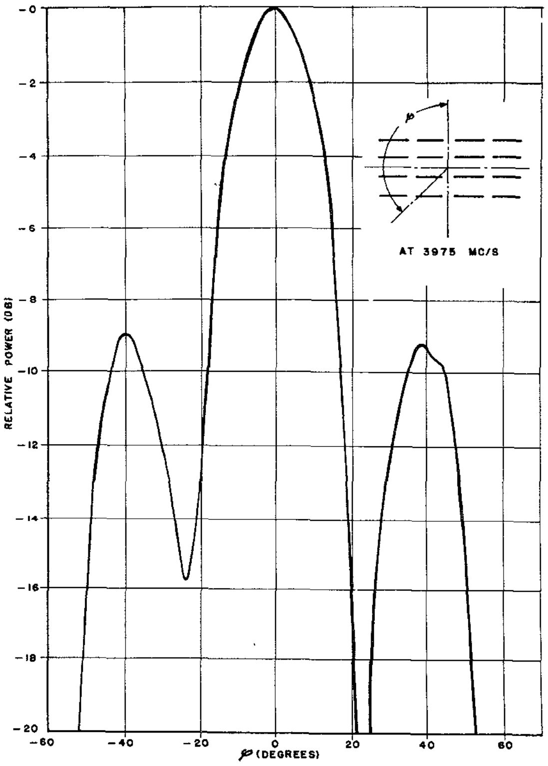

Fig. 13 - E-plane radiation patterns of 4x4 array in Fig. 9.