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Electromagnetic Coupling Reduction Techniques

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By

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FOREWORD

This report was prepared by The University of Michigan, Ann Arbor, Michigan, under the direction of Professor Ralph E. Hiatt and Professor John A. M. Lyon and on Air Force Contract AF 33(615)-3371 under Task No. 435709 of Project 4357 (U) "Electromagnetic Coupling Reduction Techniques". The work was administered under the direction of the Air Force Avionics Laboratory, Electronic Warfare Division, Research and Technology Division, Wright-Patterson Air Force Base Ohio. The Task Engineer was Mr. Olin E. Horton, the Project Engineer Mr. Herbert Bartman.

This report covers the period 15 November 1966 through 14 February 1967.

ABSTRACT

Progress is reported on several methods of obtaining increased isolation from one antenna to another. One of the methods is to use circumferential corrugations surrounding either one or both of the antennas involved. Such corrugations cause some changes in the radiation pattern of an antenna. The report indicates the extent of such changes as well as the amount of reduction of coupling which can be achieved.

Another method of mitigating coupling effects has been introduced in the form of a "fence" of thin wires erected vertically over the conducting plane between two antennas. Such a fence protrudes over the ground plane and would be objectionable for mounting over the skin surface of an aerospace vehicle. However, for wavelengths corresponding to the X-band of frequencies the actual extent of protrusion is not much for it corresponds to one-half of the wavelength used. Certainly for wavelengths corresponding to frequencies below the microwave regions, the protrusion from the surface might be a serious problem.

The use of a square cavity, surrounding an antenna, which is flush-mounted in the bottom surface of the cavity, has yielded data showing the reduction of coupling possible. This square cavity also has inserted in it, a series of corrugations. Large decoupling (30 db) was obtained over narrow frequency ranges. As much as 12 db was obtained over a 20 percent bandwidth.

Extensions have been made to the RF bridge reduction method. Very encouraging reductions of coupling have been achieved. The latest effort has been concentrated on improving the bandwidth over which such reductions are accomplished.

Results are presented on the near field coupling between two spirals. Data are shown, indicating a reduction of coupling as the frequency is increased on two spirals that are in adjoining positions. The coupling is most sensitive to spiral orientation when the spirals are operating at the low frequency end of the operating range. As frequency increases, it is shown that the coupling becomes independent of the sense of rotation of the spirals.

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I

INTRODUCTION

The first technical section of this report deals with the use of circumferential corrugations surrounding a slot antenna. Design details of the corrugations and the critical parameters are given. It is interesting that the use of corrugations results in some improvement of radiation pattern by the elimination of many of the undulations present for a slot mounted in a plane surface. Somewhat greater gain was obtained over the entire frequency range when a slot was modified by the use of surrounding corrugations. Preliminary experiments using dielectric or absorbing material in trenches, have been encouraging. In particular, the use of stepped or graded loading of dielectric has resulted in some improvement by making the reduction of coupling more uniform over a greater part of the frequency band. The use of corrugations around antennas was extended to the case of such corrugations around a monopole. It was found that the coupling from one antenna surrounded by corrugations to another without corrugations was reduced by 8 db.

One of the new methods of decoupling was that utilizing a fence consisting of thin wires erected vertically over the metal plane between two antennas. Such fences with elements of appropriate height were found to be very effective. A fence of thin wires closely spaced and of length of one half wavelength resulted in a decrease in coupling of 23 db over a forty percent bandwidth. Such fences may be useful in the cases of nonflush-mounted antennas. Except for microwave frequencies it appears that the fences would offer an objectionable protrusion for installations which would otherwise be entirely flush-mounted.

Another method of coupling reduction utilized a square recessed box with a slot antenna mounted in the bottom. Several rows of corrugations were placed in the box with the tops of the corrugations even with the surrounding metal ground plane and the bottoms of the corrugations corresponding to the bottom of the box. Coupling was measured between one such slot and another plain slot in the ground plane. Rather large amounts of decoupling were observed with this arrangement at specific frequencies. The decoupling was quite narrow banded.

A continuation of studies has been made utilizing the bridge link approach. Substantial effort has been put into modifications of the bridge arrangement so as to make the cancellation effect of such a bridge useful over a broad band of frequencies. These improvements have involved a detailed study of the various components of the X-band bridge used. To some extent it has been observed that results on a broadband basis have not been reproducible. In using a bridge to supply a cancelling signal, it has been found that 15 db of isolation over the entire X-band of frequencies can be obtained. However, it has been hard to reproduce the arrangement which provided this very desirable amount of coupling reduction. The current studies involve the balancing of the frequency dispersion characteristics of the two paths which exist in the bridge; one of these paths is the objectionable coupling path while the other path is the auxiliary path supplied through the bridge arrangement.

Other studies have concentrated on the near field decoupling of square Archimedian spirals. Further information has been gathered showing the usefullness of sense of rotation as a decoupling factor and also the variation of coupling with frequency. The variation of coupling with frequency can be considered as a means of changing from a near field coupling situation to a far field coupling situation. Even though, two square spirals are mounted with a minimum of spacing so that the outermost elements are almost touching, it has been found that as frequency is increased from the lowest operating frequency upward the coupling changes from a near field coupling to a far field coupling. This corresponds to the movement of the active region of the antenna from the outermost turn to those located nearer the center of the antenna. Such a change in position of the active region corresponds to changing the spacing of the antennas as far as near field coupling is concerned.

II

EXPERIMENTAL STUDIES

2.1 Circumferential Corrugations.

Corrugated surfaces have been used as an alternative to dielectric coating to produce an enhanced surface reactance (Barlow and Cullen, 1953). Such increased surface reactance was found to be desirable in order that high frequency energy could propagate along the interface of two different media without radiation. In this case a positive surface reactance is required.

By appropriate choice of the parameters involved, corrugations can also be used to create a negative surface reactance thus forcing the energy to radiate rather than propagate along the surface. This suggests a method to mitigate the coupling between two (microwave) antennas that are flush-mounted on a common metal surface. Once an appreciable amount of energy is allowed to be radiated from the modified surface the basic assumption of the theory of surface waves is no longer satisfied and such a model becomes incapable of explaining completely the antenna behavior. While a theory using a more accurate model is being developed certain results of the surface wave theory have been used to design corrugations to test experimentally the above assertions.

Two waveguide-fed slot antennas (2.3 cm x 1.0 cm) were used one of which was surrounded by flush-mount circumferential corrugations. The surface reactance of a corrugated metal surface is given to a first approximation by

$$X_s = \frac{b}{b+t} \sqrt{\frac{\mu_o}{\epsilon_o}} \tan kd \qquad (2.1)$$

where

b = trench width

t = wall thickness

d = trench depth

k = propagation coefficient

μ_o and ϵ_o = permeability and permittivity of free space

provided that there are at least three corrugations per wavelength along the surface. The frequency dependence of X_s imposes a restriction on the effectiveness of the method. However this disadvantage is offset to some extent by the fact that coupling is also frequency dependent. In the case where the antennas are so oriented that their respective E-planes coincide, the coupling is reduced at a rate of 6 db per octave of frequency while when the H-planes coincide the reduction is 12 db per octave provided that the distance between the two antennas is greater than one wavelength. The best choice is then to have maximum X_s (absolute) at the lower end f_1 of the frequency band over which increased isolation is desired, by choosing

$$kd \geqq \lambda_1/4 \ . \tag{2.2}$$

Two sets of corrugations have been constructed, having the following parameters:

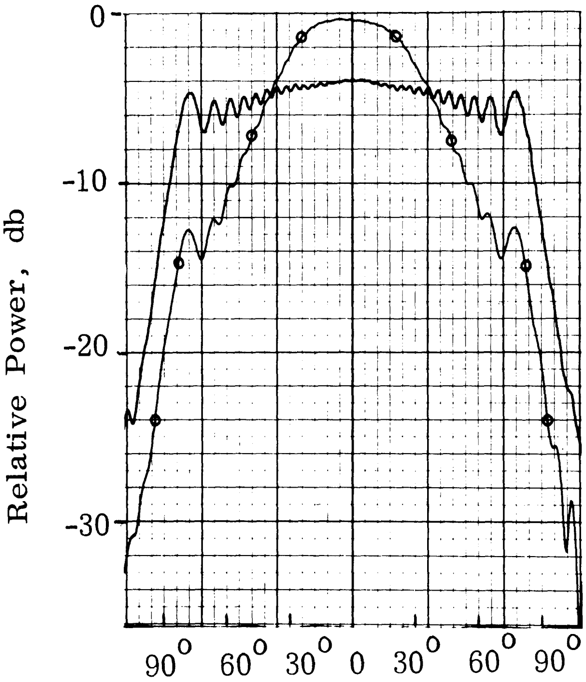
Set 1: d = 0.85 cm, b = 0.16 cm, t = 0.02 cm, 14 trenches

Set 2: d = 0.85 cm, b = 0.12 cm, t = 0.05 cm, 12 trenches.

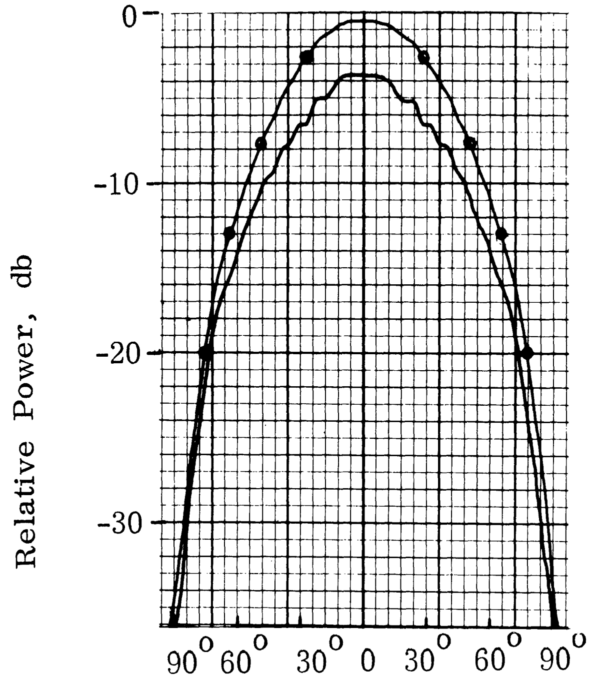
As expected from Eq. (2.1) Set "1" gave the best results. These results have already been presented (Lyon et al, 1966b). Set "2" reduced the maximum E-plane coupling observed in the frequency range 8.4 GHz to 12.4 GHz from - 29 db to - 37 db. Twice as much reduction would be expected if both slots were surrounded by similar corrugations.

The radiation patterns presented previously for a slot surrounded by corrugations (Set "1") were taken with the slot mounted on a large (12 feet square) ground plane. Since some of these antennas may be used on vehicles of considerably smaller dimensions and since the size of the ground plane does affect the pattern significantly, additional radiation patterns were taken using a rectangular ground plane 90 cm by 60 cm (Fig. 2-1) and an 11.1 cm diameter disc (Fig. 2-2) with the same set of corrugations. Two curves are presented superimposed in each case representing the radiation pattern of a plain slot and that when the slot is surrounded by corrugations. In each case the transmitter and receiver gains were left constant so that these figures provide also information about the effect of the corrugations on the antenna gain. The undulations present in the patterns of the plain slot are well known and have been explained by assuming additional radiation sources at the edges of the sheet. It is interesting to note that the corrugations virtually eliminate these undulations by preventing the propagation of a surface wave and thus reducing the diffraction from the ground plane edges. By orienting the slot for maximum gain and sweeping the frequency it was found that the modified slot has increased gain over the entire frequency range used. (Fig. 2-3).

Several attempts were made to increase the bandwidth of the corrugations. One possibility is to fill the trenches with a dielectric or absorbing material. One experiment has been completed using paraffin wax with Set "1". The paraffin has a dielectric constant of approximately 2 and a dissipation factor less than 0.0002 (both at 25^{o}C). By filling all trenches with paraffin it was noted that decoupling or isolation was generally reduced. Thus the amount of additional isolation, compared to the case of two plain slots, varied from 5 db at 8 GHz to zero at 12 GHz. This is due to the fact that the presence of the dielectric made the trenches look deeper in terms of wavelengths. More interesting was the case of graded loading where the amount of dielectric in a trench varied linearly with the radius, the innermost trench being empty and the outermost full. The E-plane coupling for this case is shown in Fig. 2-4. The



(a) E-Plane



(b) H-Plane

FIG. 2-1: E- AND H-PLANE RADIATION PATTERNS AT 10 GHz FOR A SLOT IN A 90 CM BY 60 CM METAL PLANE. (—) Plain Slot; (-θ-) Slot With Corrugations.

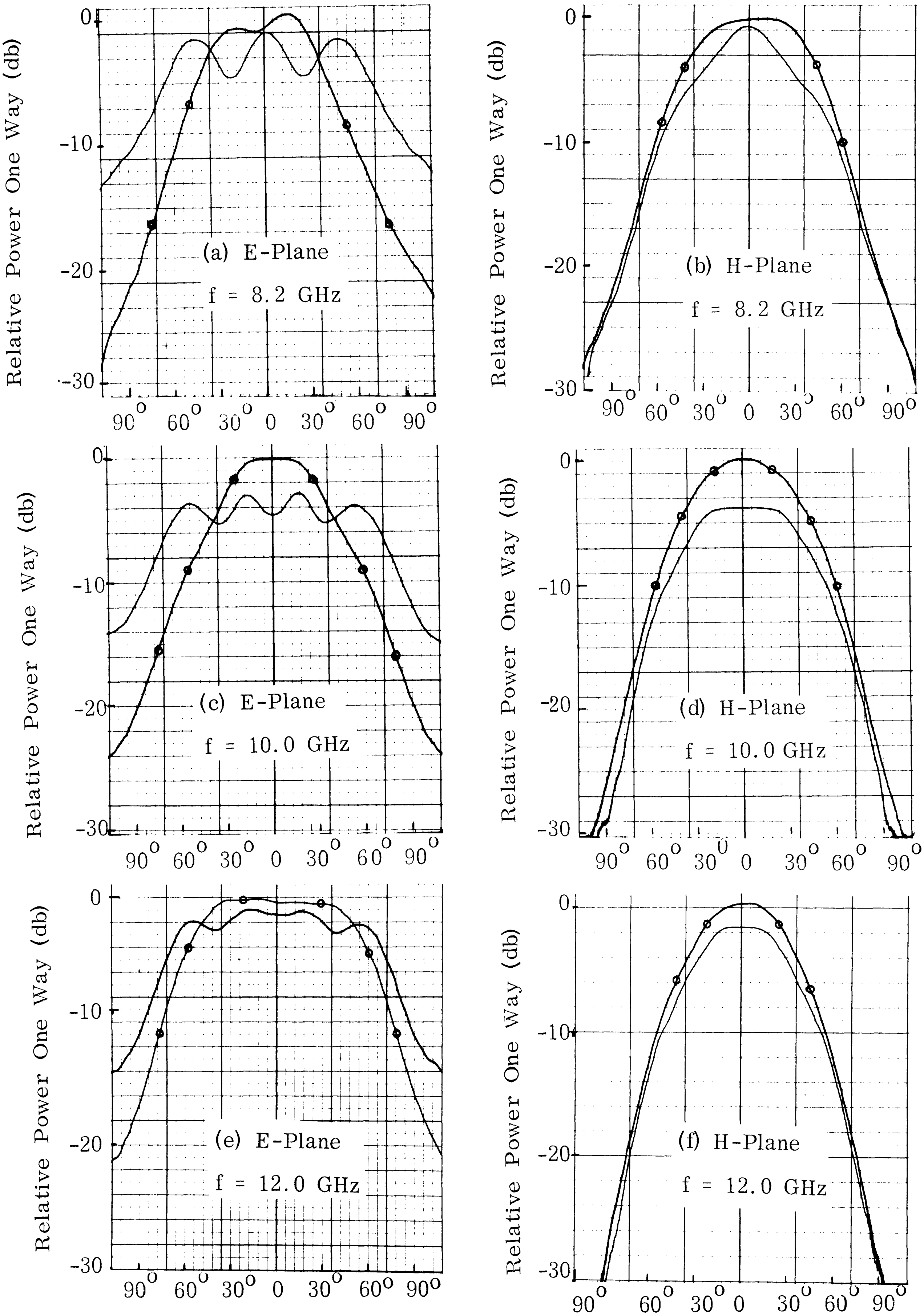


FIG. 2-2: E- AND H-PLANE RADIATION PATTERNS FOR A SLOT IN A METAL DISC OF 11.1 CM DIAMETER. (—) Plain Slot; (-θ-) Slot With Corrugations.

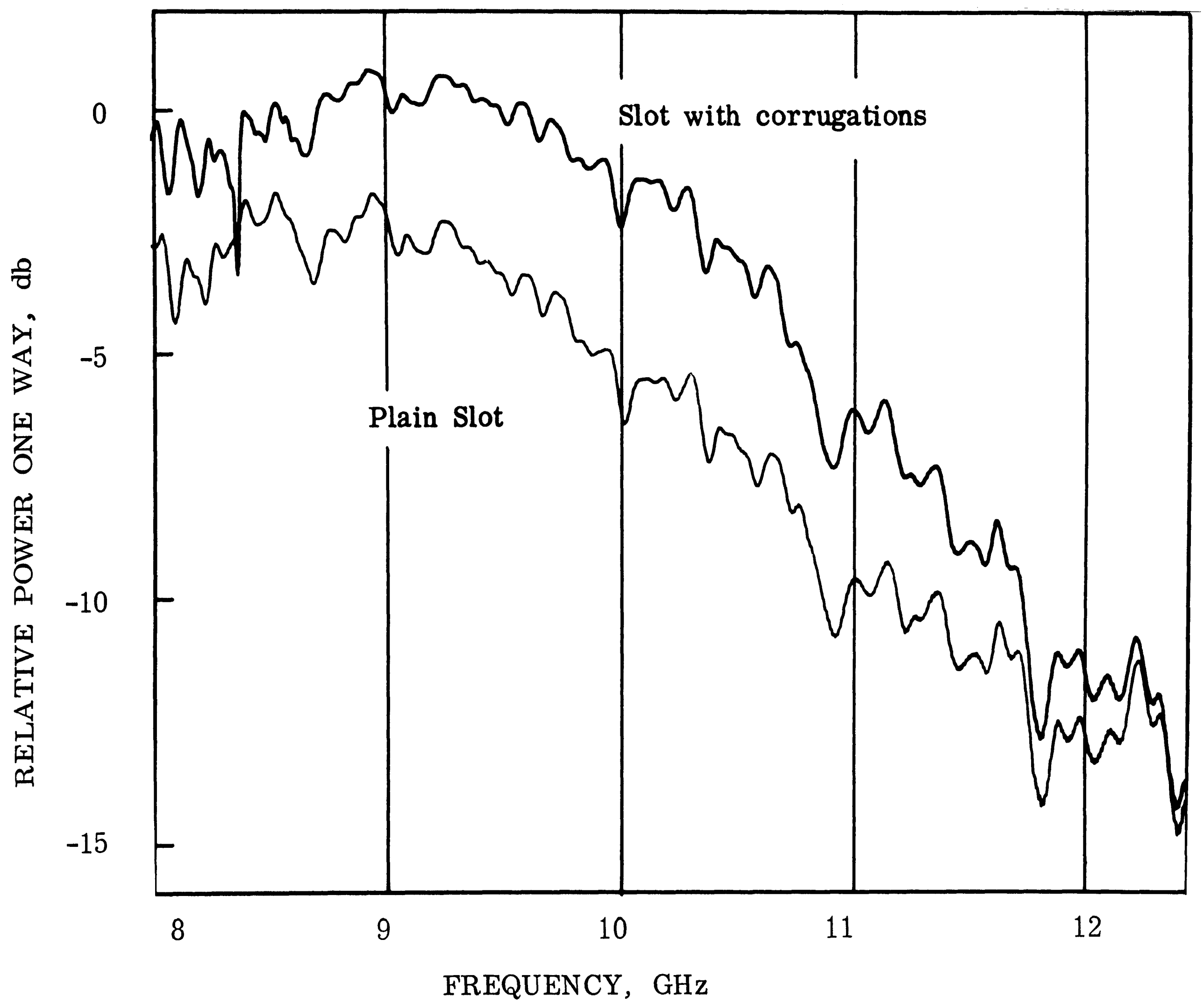


FIG. 2-3: MAXIMUM GAIN VS. FREQUENCY FOR A SLOT IN A METAL DISC OF 11.1 cm DIAMETER.

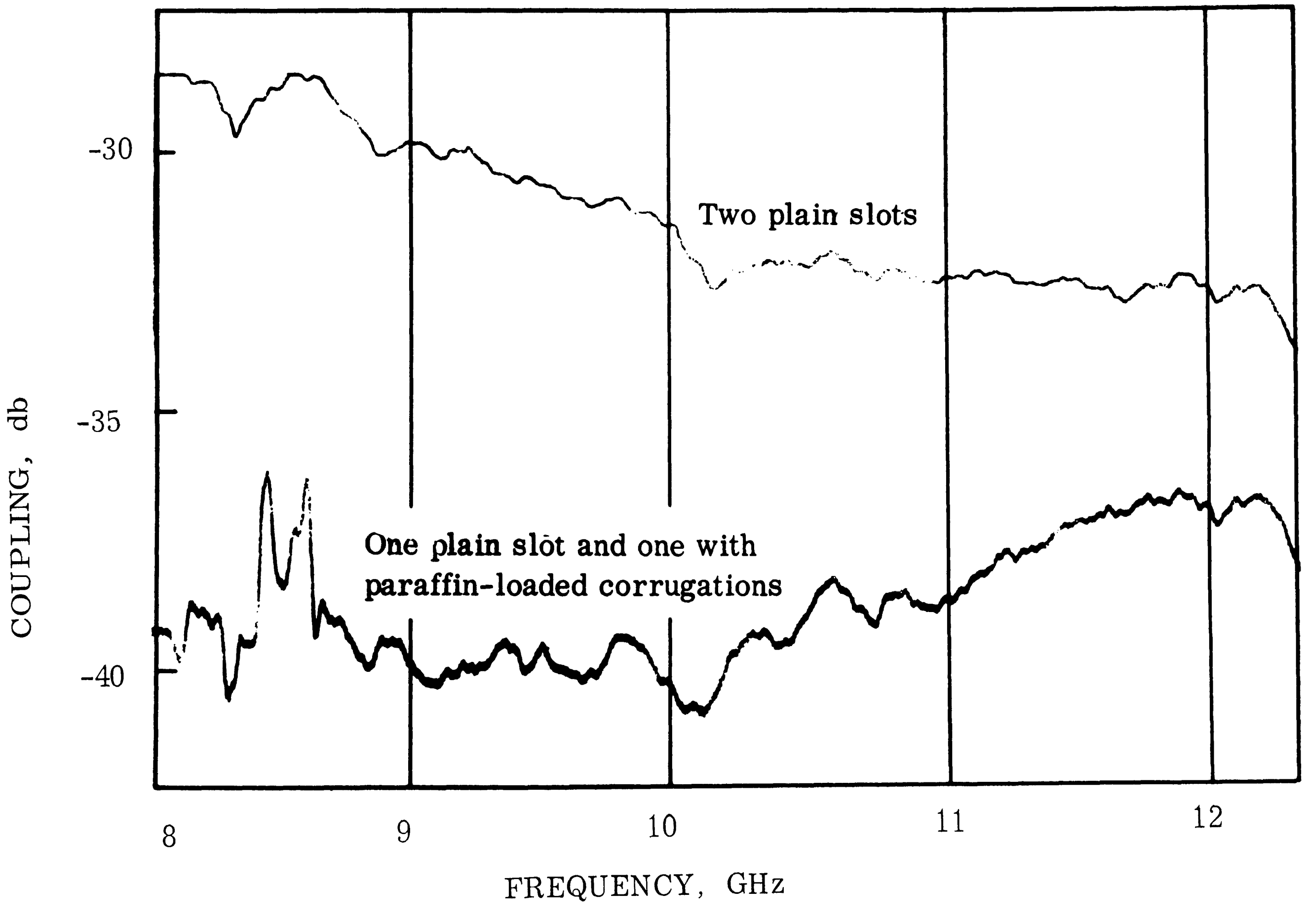


FIG. 2-4: E-PLANE COUPLING VS. FREQUENCY FOR TWO SLOTS SPACED 11.4 CM.

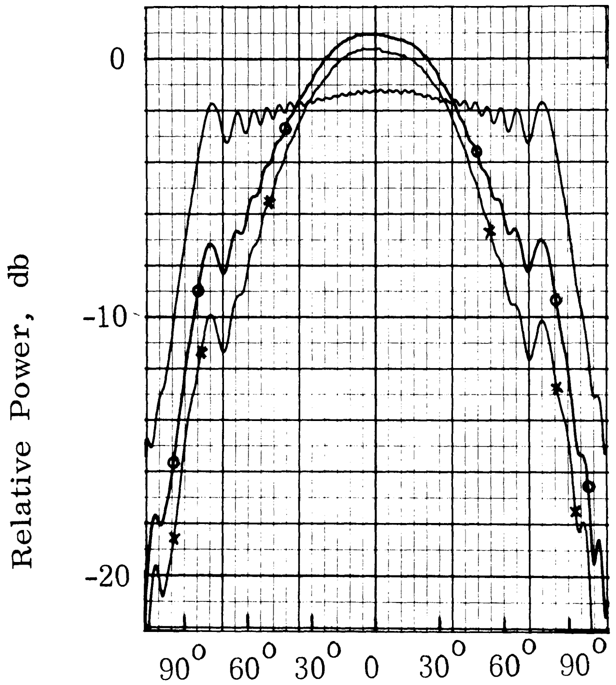
loading increases the coupling (compared with the case of empty trenches) by 1 db to 2 db in the higher part of the frequency band used, while it reduces greatly the large coupling variations occuring near 8 GHz when the trenches are empty. (Lyon, et al, 1966 b). This indicates that loading does offer some control over the behavior of the corrugations but more suitable materials will have to be tried.

In another experiment metal sectors were placed on top of the corrugations symmetrically located with respect to the H-plane of the slot. The objective was to isolate and eliminate portions of the trenches that may create undesirable radiation. By varying the angle of the sector (from 60° to 90° to 120°) it was found that sectors of 90° created a maximum additional reduction of the E-plane sidelobes (Fig. 2-5) which was accompanied by a reduction in coupling (Fig. 2-6).

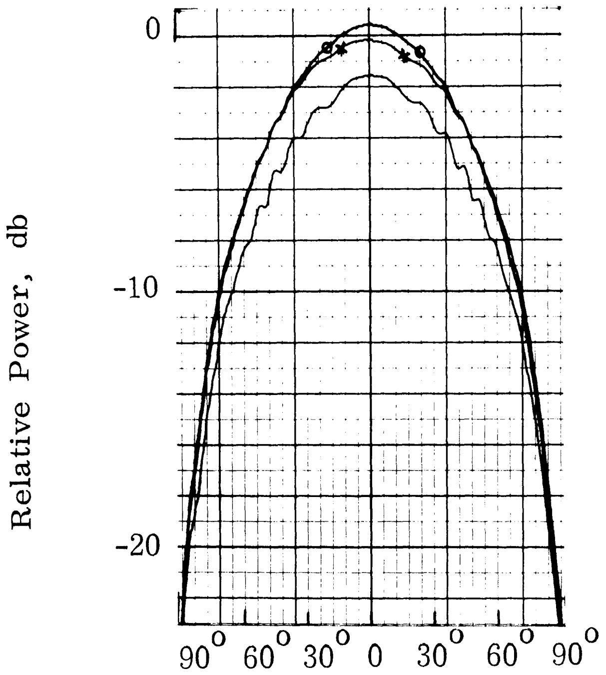
The field due to a, thin, half-wave slot in an infinite conducting plane (x-y plane) along the x-axis (defined as the intersection of the conducting plane and the E-plane of the slot) is given by:

$$\left.\begin{aligned} E_z &= j\,E_o\,\frac{e^{-jkr_1}}{\pi r}\,e^{j\omega t} \\ H_\phi &= -j\,\frac{E_o}{Z_o}\,\frac{e^{-jkr_1}}{\pi r_1}\,e^{j\omega t} \end{aligned}\right\} \qquad (2.3)$$

where r, r_1 are the distances of the point of observation from the center and the end of the slot respectively and Z_o is the characteristic impedance of free space. From these expressions it is seen that the field intensity varies as 1/r. Therefore it should be expected that the effect of the circumferential trenches diminishes with increasing distance from the center of the slot. This



(a) E-Plane



(b) H-Plane

FIG. 2-5: E-AND H-PLANE RADIATION PATTERNS AT 10 GHz FOR A SLOT IN A 90 CM BY 60 CM METAL PLANE. (—) Plain Slot; (-θ-) Slot With Corrugations; (-x-) Slot With Corrugations Partially Covered by 90° Metal Sectors in the H-Plane.

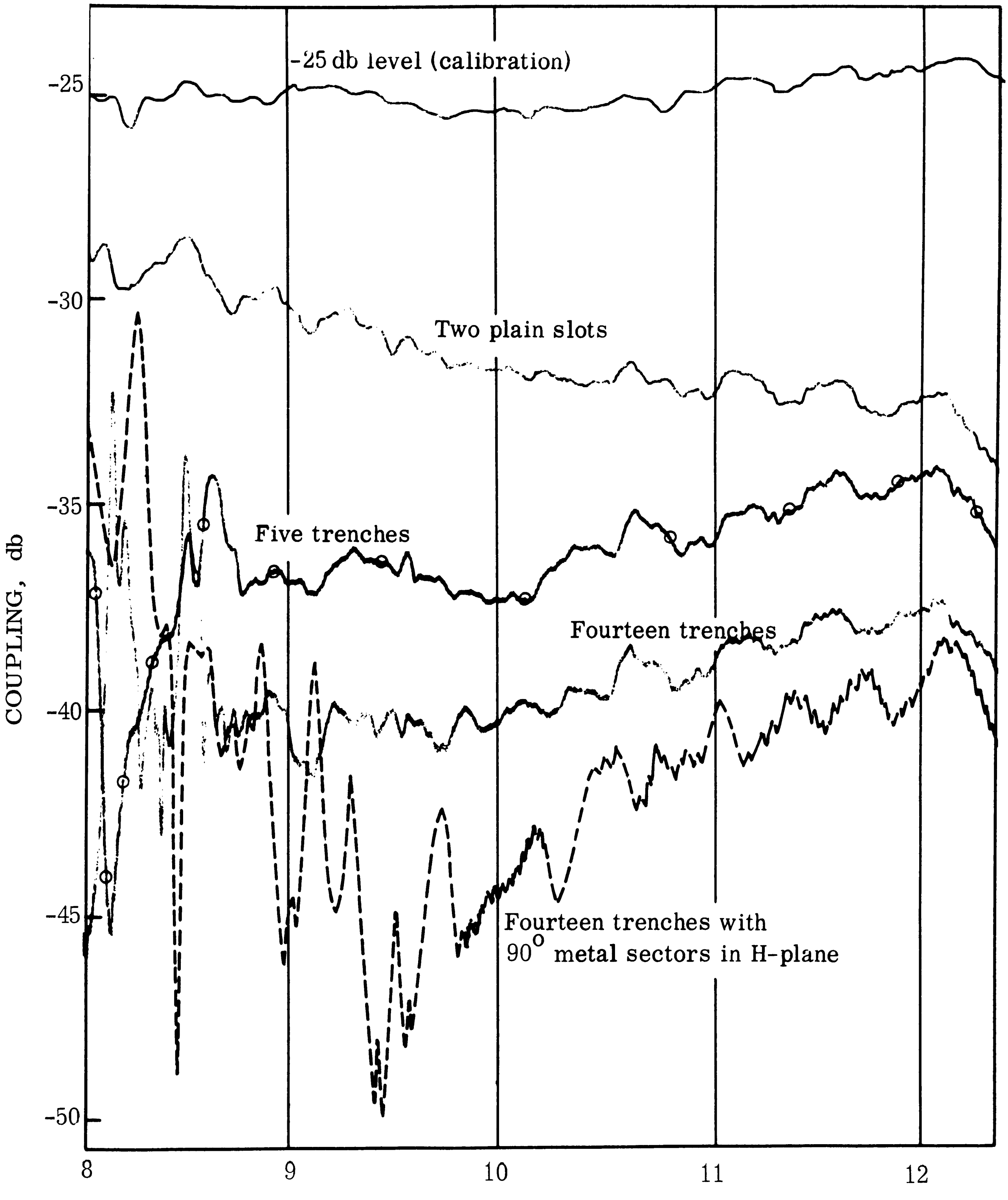


FIG. 2-6: E-PLANE COUPLING VS. FREQUENCY FOR TWO SLOTS SPACED 11.4 CM.

was verified experimentally by covering some of the trenches completely with metal foil and measuring the result on coupling (Fig. 2-6). It is seen that the first five trenches are responsible for more decoupling than the remaining nine at the lower frequencies. At the higher frequencies due to the dependence of the propagation coefficient in a trench upon the trench radius, the depth of the outer trenches is closer to being a quarter wavelength and therefore these trenches are more effective.

Studies were also made of the effect of the corrugations (Set 1) on the coupling between two monopole antennas. For this case two quarter-wavelength (at 9.0 GHz), thin monopoles were used in a large (12 feet square) metal plane. It was found that the coupling with one antenna only surrounded by corrugations was reduced by 8 db (Fig. 2-7). This was accompanied by a change in the standing-wave-ratio of the monopole as follows:

TABLE I

Monopole Standing Wave Ratio

Frequency, GHz	8	9	10	11
Plain Monopole	2.00	1.30	1.77	2.10
Monopole with corrugations	2.45	2.10	1.82	1.55

Radiation patterns were taken with the monopole mounted on a metal disc of 11.1 cm diameter (Fig. 2-8). Due to the small ground plane used in this case the radiation maximum for a plain ground plane occurs at 78^o from the monopole axis rather than 90^o as the theory predicts for the case of an infinite metal sheet. The modification of the ground plane by corrugations resulted

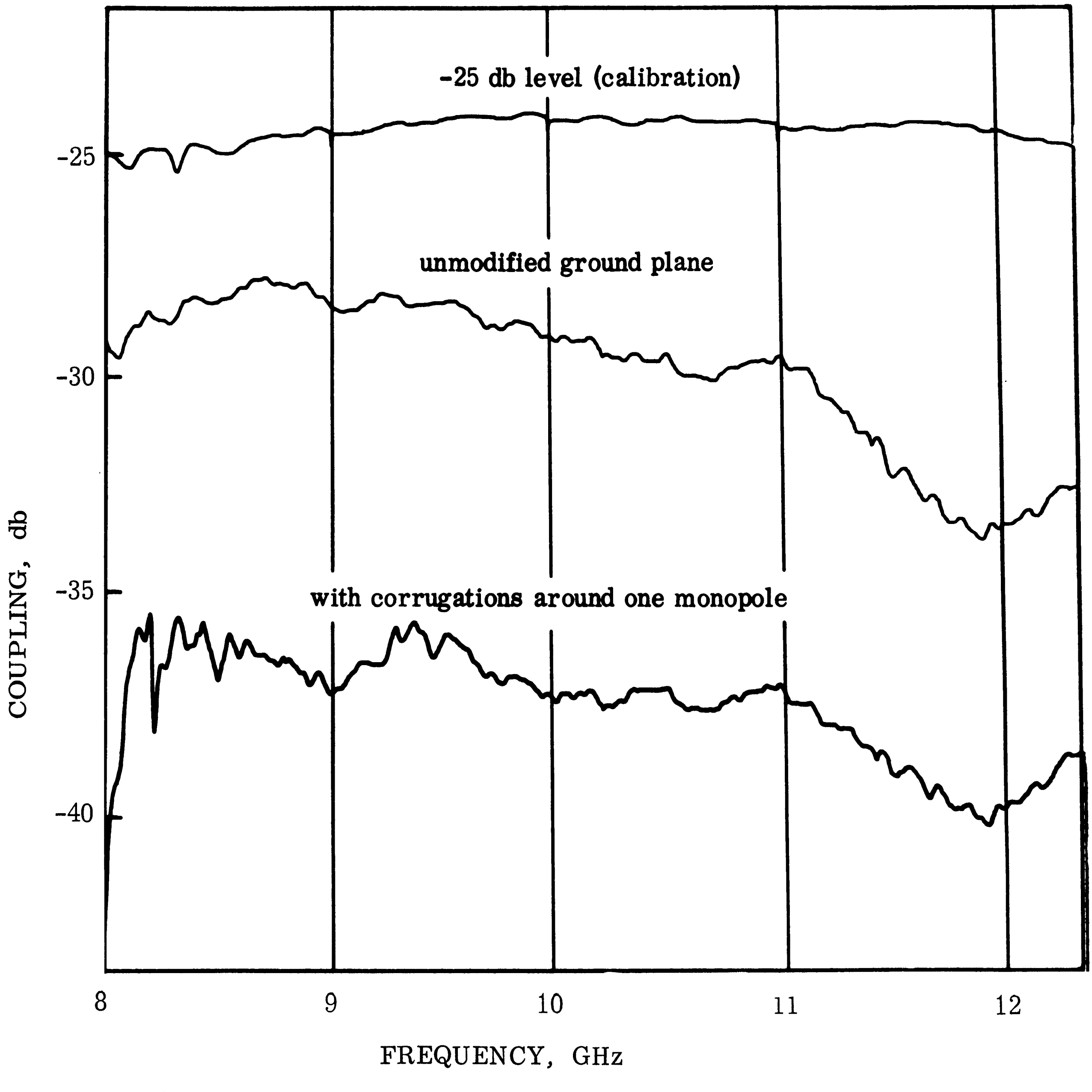
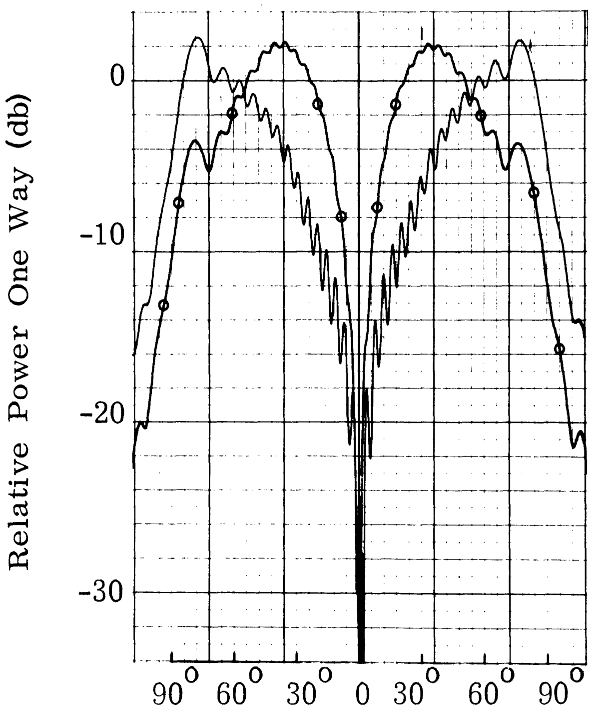
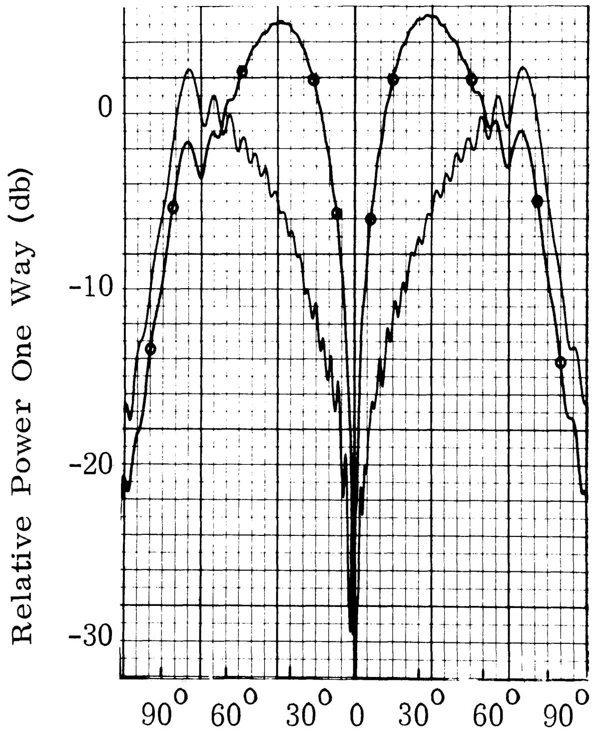


FIG. 2-7: COUPLING VS. FREQUENCY FOR TWO QUARTER-WAVE, THIN MONOPOLES (AT 9 GHz) SPACED 11.4 CM.



(a) f = 9.0 GHz



(b) f = 10.5 GHz

FIG. 2-8: RADIATION PATTERNS FOR A QUARTER-WAVE (AT 9.0 GHz), THIN MONOPOLE IN A 90 CM BY 60 CM METAL PLANE. (——) Plain Monopole; (-θ-) Monopole With Corrugations.

in a shift of the maximum to approximately 36° from the monopole axis. Simultaneously the ripple due to ground plane edge diffraction was greatly reduced.

2.2 Fences

A "fence" consisting of thin wires erected on the metal plane between two antennas was used to control the coupled power from one antenna to the other. Grids of wires with a spacing less than or equal to one-tenth of a wavelength are extensively used as reflectors in the vicinity of a transmitting antenna instead of a solid metal surface. Also the scattering properties of thin wires have been studied in the case of plane-wave incidence which means that the scattering object is at the far-field of both the transmitting and receiving antennas. The case considered here is different from that above in that (a) the spacing between adjacent wires is of the order of a quarter wavelength and (b) the fence is located in the near field of both transmitter and receiver.

The relative merits of a fence in decoupling were studied experimentally. The geometry of the two antennas with the fence is shown in Fig. 2-9. Different fences were used of the same number of elements (seven) and approximately the same spacing. In the frequency range 8.0 to 12.4 GHz the spacing was between $\lambda/4$ and $\lambda/2$. The height was a variable parameter with values between $\lambda/4$ and $\lambda/2$ at 9.0 GHz. It was found that a fence with a height near $\lambda/4$ at the center of the frequency band produced insignificant decoupling while a height near $\lambda/2$ gave the best results. The position of the fence to produce maximum decoupling was found to be a function of the positions of both transmitting and receiving antennas so that a fence may not be associated with a single antenna (as in the case of the grid reflector) but rather must be considered in relation to a pair of interfering antennas. Another experimental conclusion is that the frequency range over which decoupling is afforded is primarily a function of the fence parameters (height, spacing) rather than fence position on the ground plane.

The frequency sensitivity of a fence of the type described here may be desirable in a case where additional isolation is desired in a system of two antennas without any interference with a third nearby antenna operating at another frequency range.

A typical radiation pattern of a slot in a 90 cm by 60 cm ground plane in the presence of a fence is given in Fig. 2-10. The radiation pattern of the slot without the fence is also presented for comparison. Coupling curves for two slots on a common ground plane (12 feet square) with and without an intervening fence are shown in Fig. 2-11. It is seen that a fence of a very simple structure offers a considerable amount of additional isolation (20 db or more) over a forty percent bandwidth.

2.3 Effect of Square Cavity with Corrugations.

A square cavity was made with an X-band slot flush with the bottom surface of the cavity, see Fig. 2-12. The slot aperture was offset from the center to allow a space for the corrugations to be put between the two slots for measuring the effect on coupling, see Fig. 2-13.

Two sets of corrugations were studied experimentally.

Set A: Spacing between fins t = 2.1 mm; depth of the corrugations d = 9 mm; length of the corrugation ℓ = 6.5 cm; the number of fins is 10.

Set B: It has the same t, d, ℓ as set A but the number of fins is 15.

It was noticed from the experimental results for Set A of corrugations, Fig. 2-14 that the reduction of coupling reached at some points as high as 20 db. For the Set B coupling at some frequencies was reduced by more than 30 db and a reduction of over 12 db for approximately 20 per cent of the X-band (Fig. 2-15) was obtained.

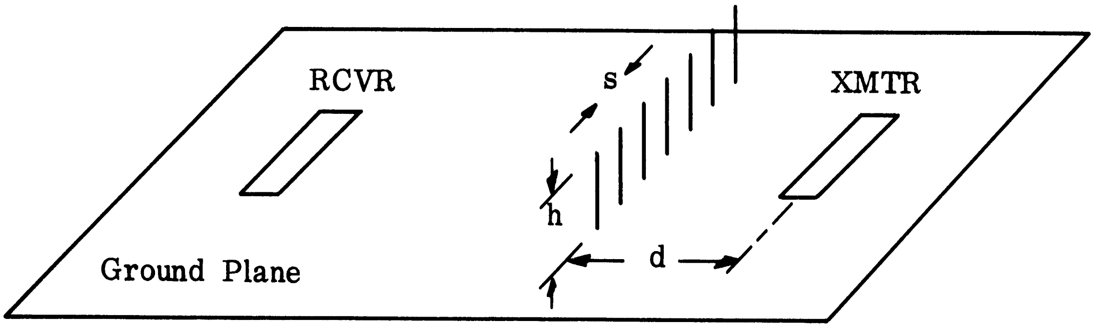


FIG. 2-9: GEOMETRY OF SLOTS WITH FENCE

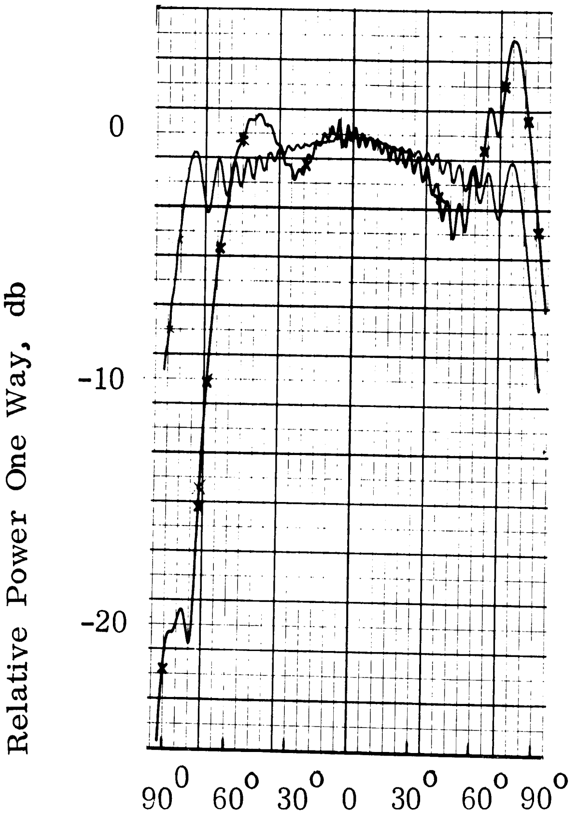
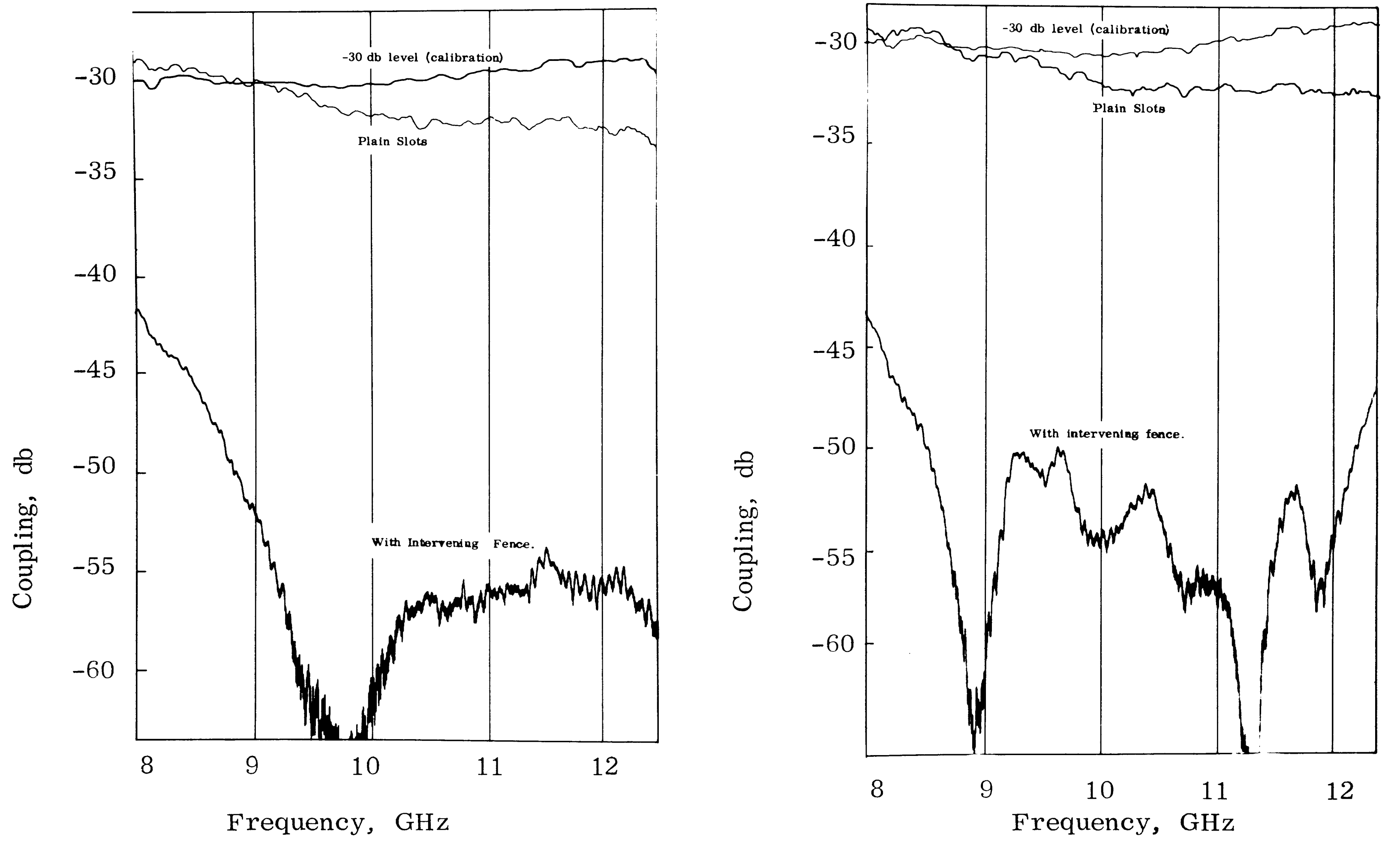


FIG. 2-10: E-PLANE RADIATION PATTERN AT 10 GHz FOR A SLOT IN A 90 CM BY 60 CM METAL PLANE IN THE PRESENCE OF A FENCE. (h = 1.7 cm s = 1.1 cm, d = 4.4 cm) (——) Plain Slot; (-x-) Slot with Fence.



(a) Fence: h = 1.5 cm, s = 1.2 cm, d = 2.6 cm

(b) Fence: h = 1.7 cm, s = 1.1 cm, d = 4.4 cm

FIG. 2-11: E-PLANE COUPLING VS. FREQUENCY FOR TWO SLOTS SPACED 11.4 CM WITH AND WITHOUT AN INTERVENING FENCE.

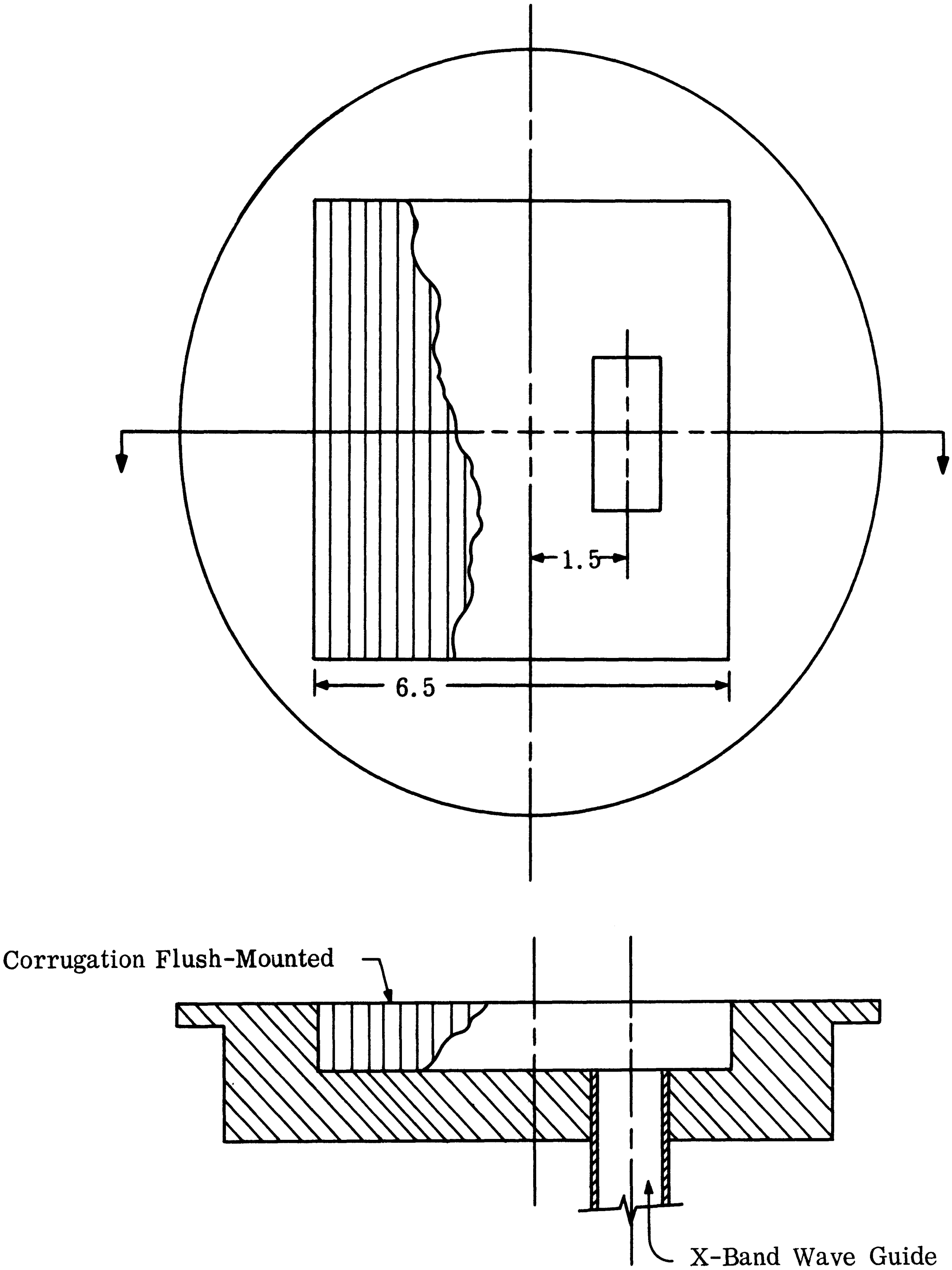


FIG. 2-12: THE CONFIGURATION OF SLOT ANTENNA WITH SQUARE CAVITY AROUND IT.

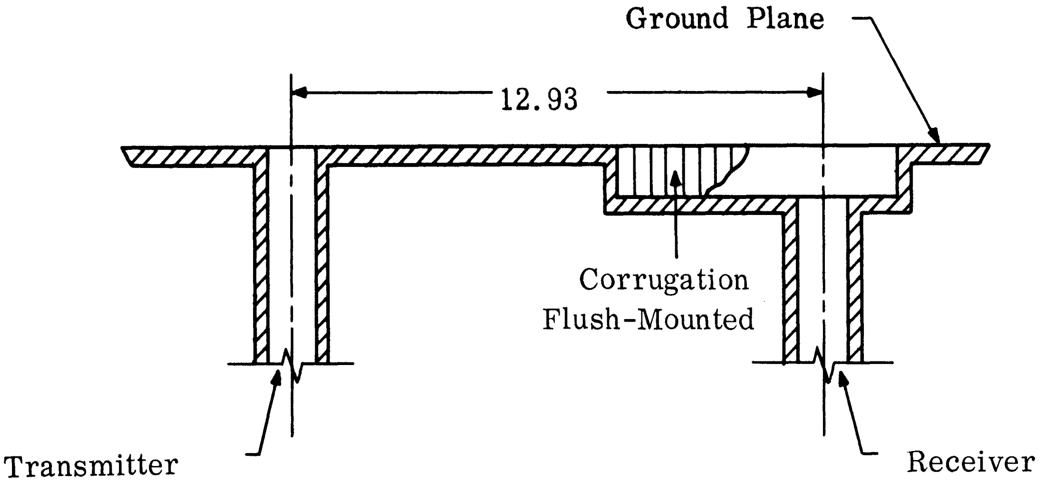


FIG. 2-13: THE ARRANGEMENT OF TRANSMITTER AND RECEIVER SLOTS AND CORRUGATIONS BETWEEN.

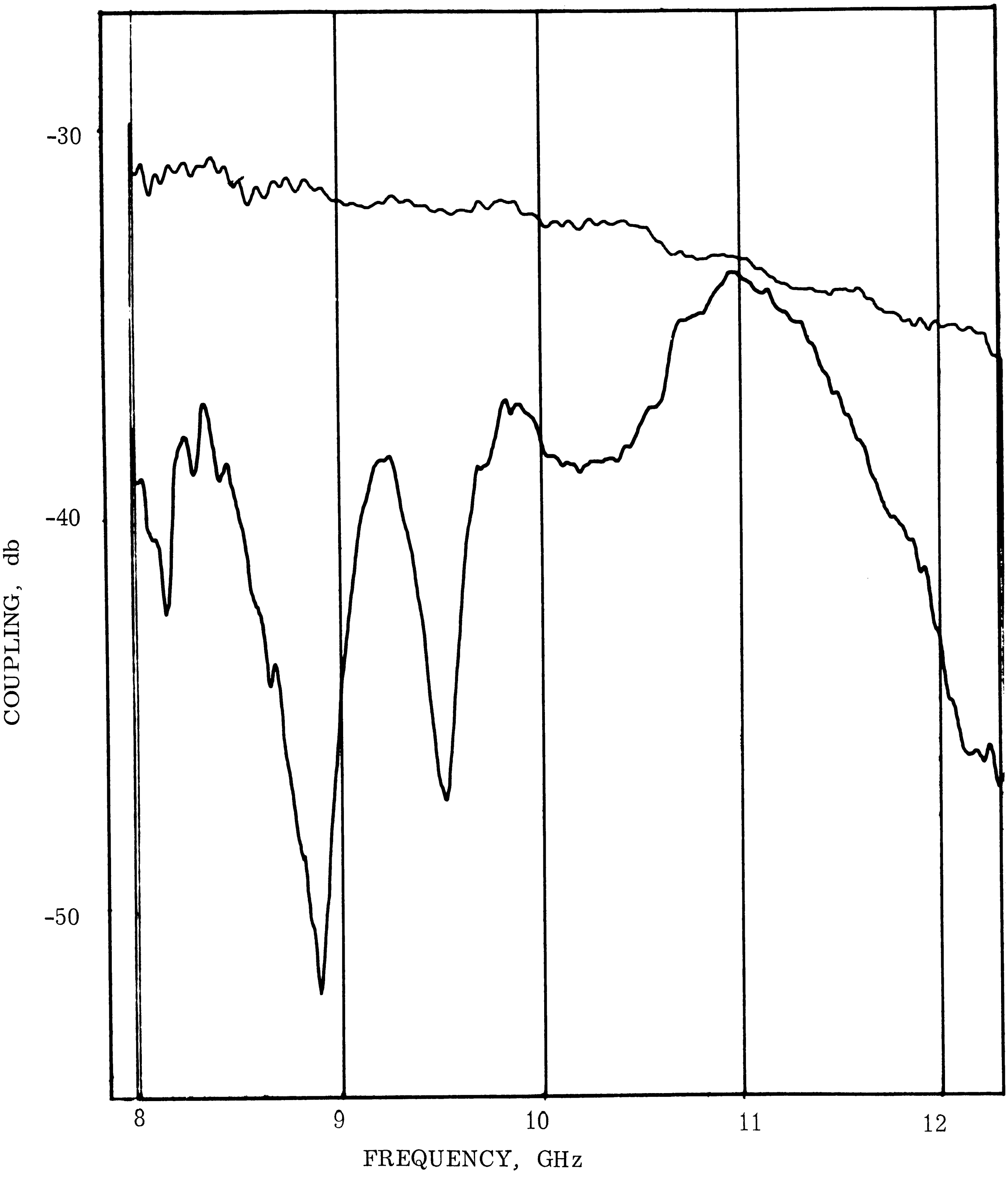


FIG. 2-14: E-PLANE COUPLING VS. FREQUENCY FOR SLOTS. The top curve is the coupling between two plain slots with 12.93 cm center-to-center spacing and lower curve is for Set A of the corrugations and arrangement as in Fig. 2-13.

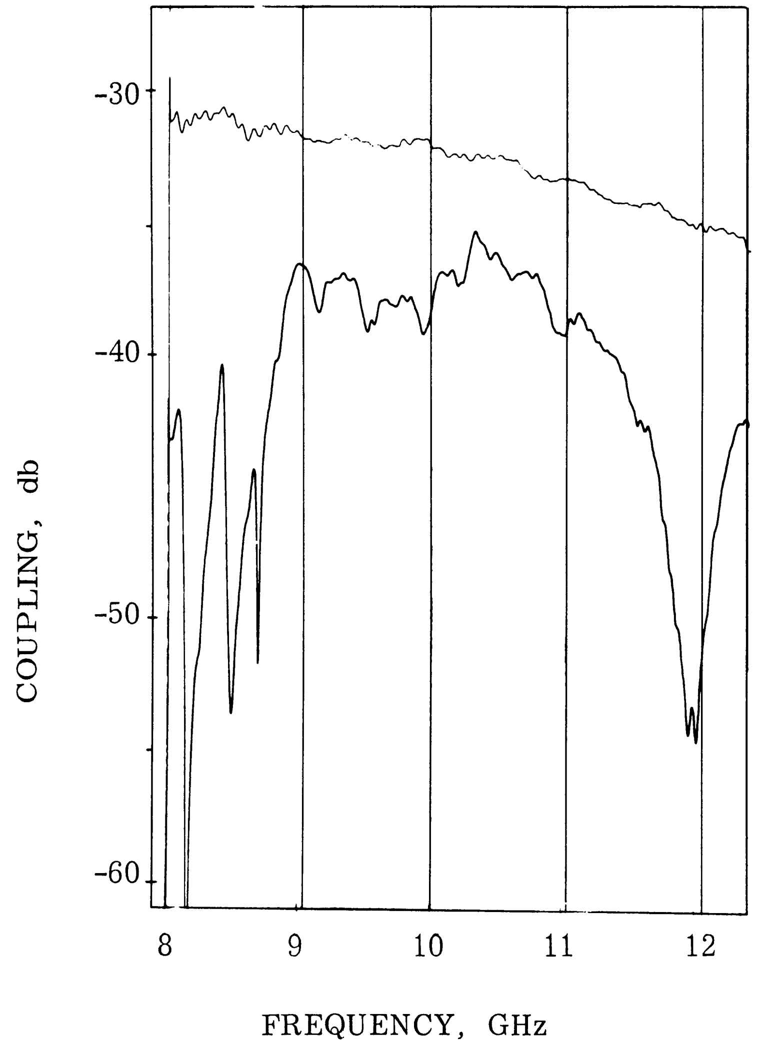


FIG. 2-15: E-PLANE COUPLING VS. FREQUENCY FOR SLOTS. The top curve is the coupling between two plain slots with 12.93 cm center-to-center spacing and lower curve is for Set B of the corrugations and arrangement as in Fig. 2-13.

It has been stated before (Lyon et al, 1966a, 1966b) that the depth of the corrugation d and separation t have a large effect on locating the position of lowest coupling, so by using a set of corrugations with various separations t and various depths d coupling levels can be lowered over a broadband. Also using corrugations next to both transmitter and receiver antennas would help in producing greater decoupling.

A set of experiments was performed on the square cavity with corrugations for measuring the E-plane (Fig. 2-16) and H-plane (Fig. 2-17) radiation patterns. It was noticed that the gain was increased by about 4 db in the case of E-plane radiation patterns.

Using an arrangement having the aperture of the slot flush-mounted with the bottom of the corrugations as is used in the case of the square cavity, but now with circumferential corrugations results in decoupling on a broadband basis. It was noticed from the E-plane radiation pattern that the side lobe level at 90^{o} has been reduced by approximately 17 db and the gain increased by about 2 db compared to a plain slot flush-mounted on a ground plane of the same dimensions (Fig. 2-18). Figure 2-19 shows the H-plane radiation pattern and also a comparison with a plain slot.

A set of experiments was performed to see the effect of recessing the slot aperture on both E-plane and H-plane coupling vs. frequency. A comparison is made with the unmodified case. From Fig. 2-20 it is seen that the top curve represents E-plane coupling vs. frequency for two plain slots separated 11.43 cm center-to-center and the curve in the middle represents the case of unmodified circumferential corrugations. The lower curve represents the effect of recessing the slot aperture to the base of the corrugations. It is noticed from Fig. 2-20 that the isolation has increased in the range between 8 GHz and 10.5 GHz. The decrease in coupling in the modified case reached 16 db over

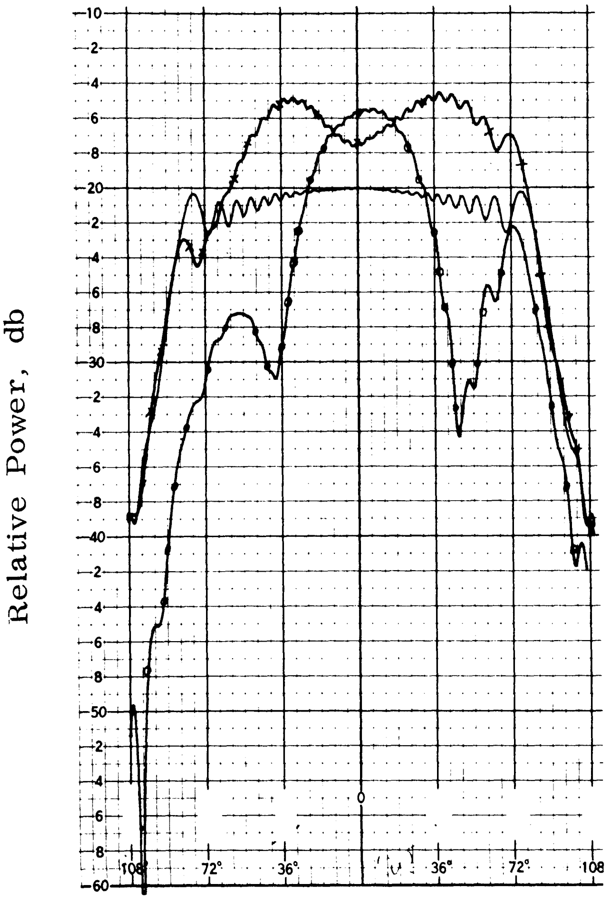


FIG. 2-16: E-PLANE PATTERNS FOR SLOTS AND MODIFICATIONS AT f = 9.0 GHz. (——) Slot flush with the ground plane; (-θ-) Set B of the corrugations is used as in Fig. 2-12; (-x-) Set A of corrugations is used as in Fig. 2-12.

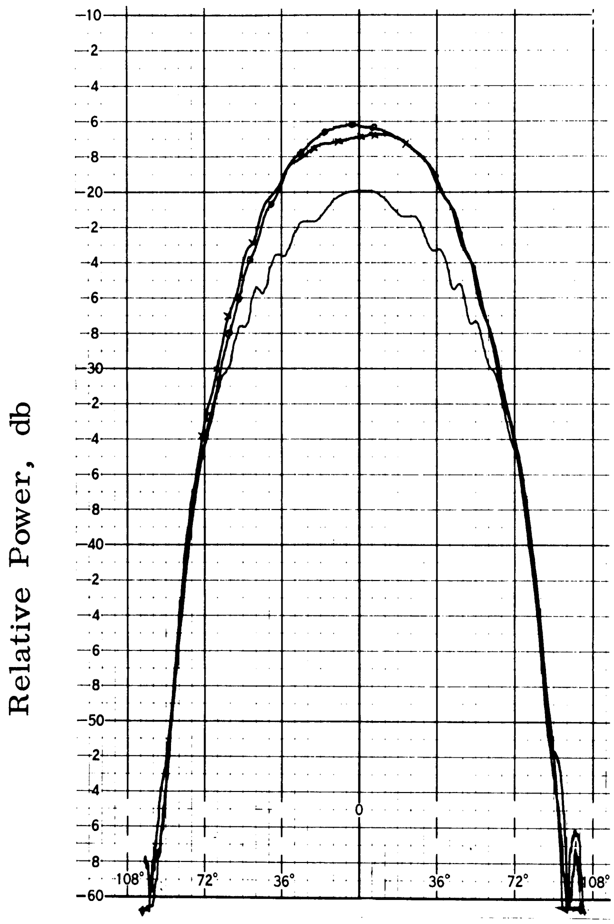


FIG. 2-17: H-PLANE PATTERNS FOR SLOTS AND MODIFICATIONS AT 9 GHz. (——) Slot flush with the ground plane; (-θ-) Set B of corrugations is used as in Fig. 2-12; (-x-) Set A of corrugations is used as in Fig. 2-12.

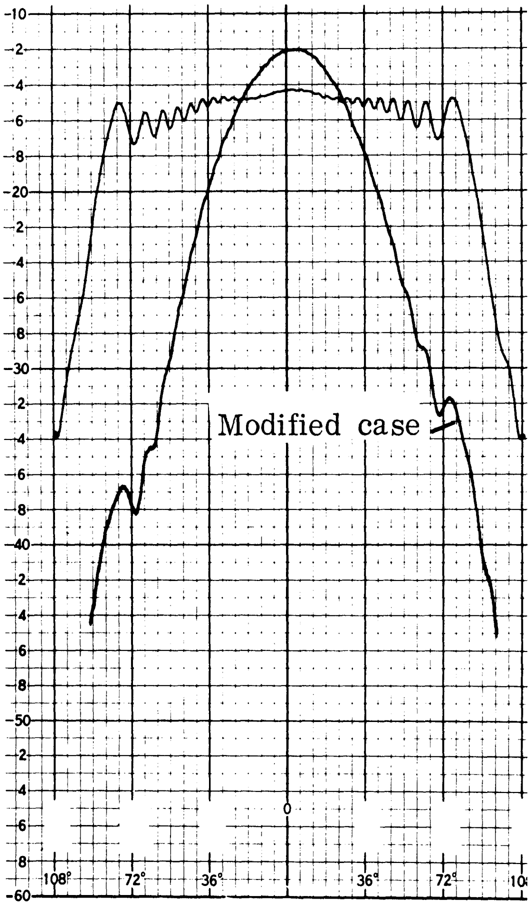


FIG. 2-18: E-PLANE PATTERNS FOR RECESSED SLOT APERTURE SURROUNDED BY CORRUGATIONS.

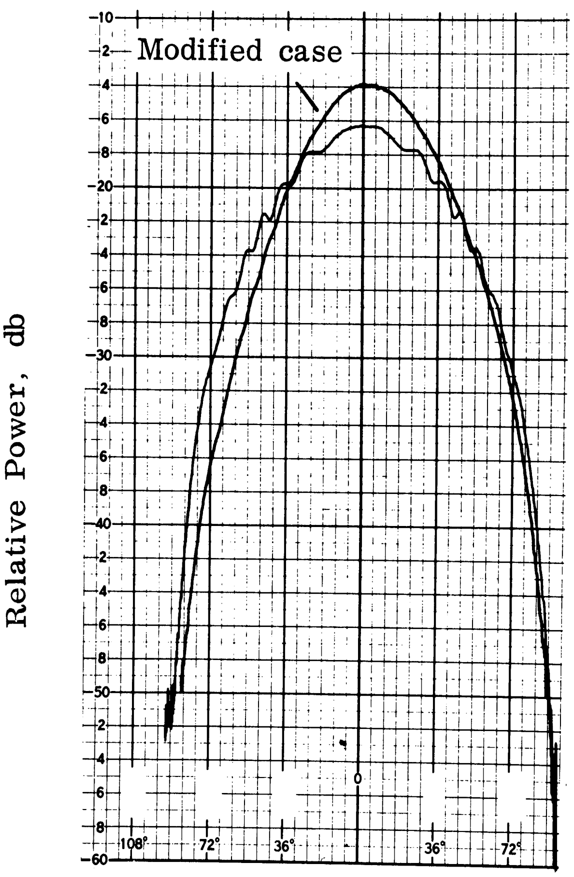


FIG. 2-19: H-PLANE PATTERNS FOR RECESSED SLOT APERTURE SURROUNDED BY CORRUGATIONS.

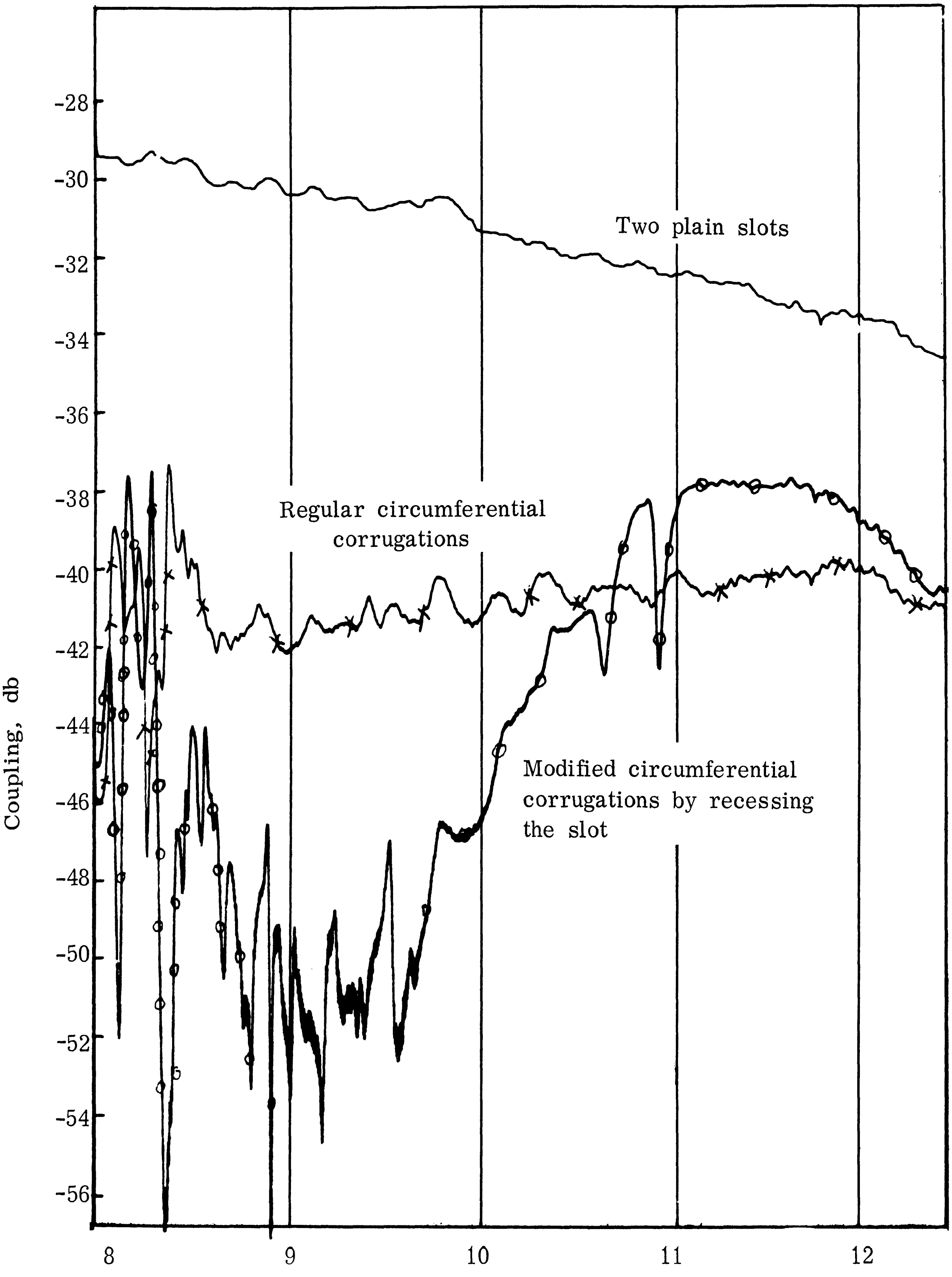


FIG. 2-20: E-PLANE COUPLING VS. FREQUENCY FOR CIRCUMFERENTIAL CORRUGATIONS AND MODIFICATIONS.

approximately half the X-band of frequencies. It is believed that by having various depths and separations the isolation can be improved over the whole X-band of frequencies. Also it was noticed for H-plane coupling that in the modified case greater isolation was obtained yielding a value of 64 db as shown in Fig. 2-21.

2.4 Decoupling of Two Antennas by Means of an RF Bridge

As suggested in Quarterly Report No. 4 (Lyon, et al 1966 b) under this contract, the X-band cancellation bridge was modified to decouple two rectangular slot antennas. The experimental circuit is shown in Fig. 2-22.

The swept input is fed into the H-plane of a magic tee, where it is divided. Power in the coupling path flows through a piece of RG-9 coax (L_2), through an isolator, through an attenuator (α_2), and couples through the slot antennas to the "majestic" tee. Power in the compensating path flows through an attenuator (α_1), through a piece of RG-9 coax (L_1), through an isolator, and into the "majestic" tee. The H-plane of the magic tee produces no relative phase shift, while the "majestic" tee produces 180^o relative phase shift. Thus, the output from the "majestic" tee is the difference of the two signals.

The two pieces of RG-9 coax are used to simulate the air or coupling path between the two antennas. The equivalent length of L_1 in wavelengths should be equal to the equivalent length of L_2 plus the air path between the two slots. This is done in an attempt to match the dispersion versus frequency characteristic of the compensating path with the coupling path.

The attenuators α_1 and α_2 are used to equalize the relative power levels in the two paths. There is approximately 30 db decoupling between the two slot antennas. Note that α_2 is not strictly needed. It is included, however, to match the dispersion characteristic of the other attenuator.

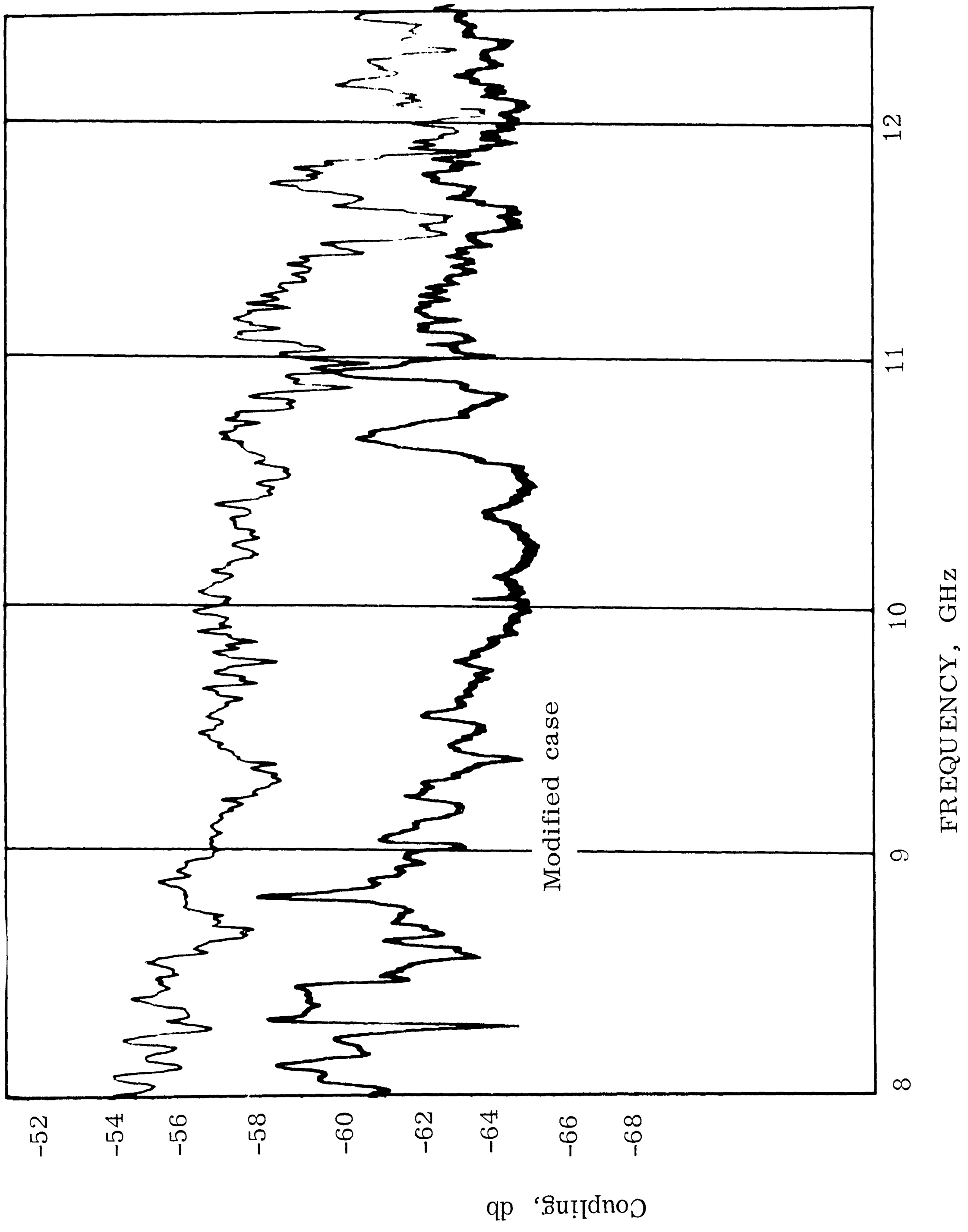


FIG. 2-21: H-PLANE COUPLING VS. FREQUENCY FOR MODIFIED CIRCUMFERENTIAL CORRUGATION.

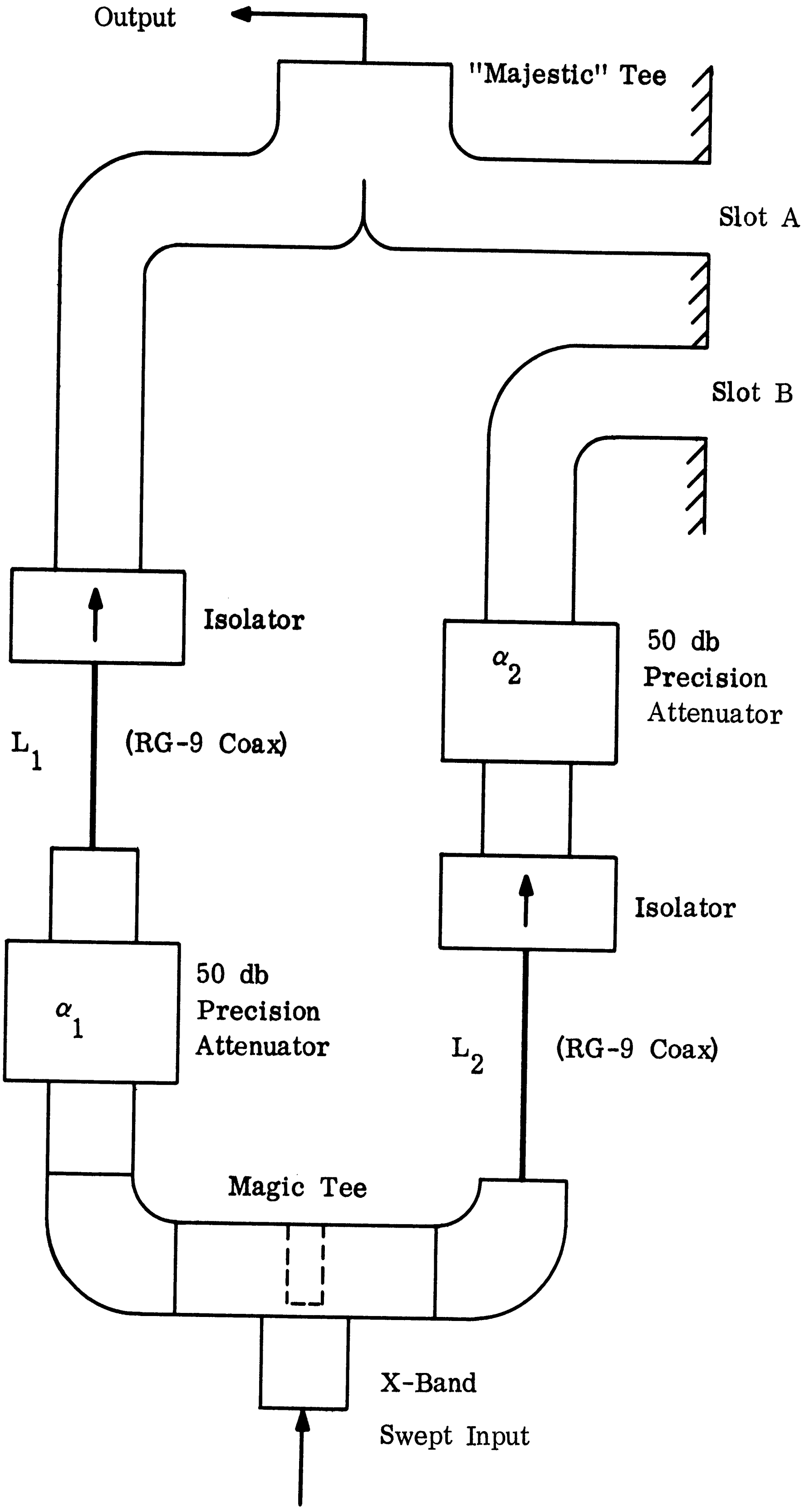


FIG. 2-22: X-BAND MAJESTIC TEE BRIDGE

The best decoupling obtained with this majestic tee bridge is shown in Fig. 2-23. The antennas are decoupled over the entire X-band, with at least 15 db of isolation. Unfortunately, it has been impossible to duplicate this chart in later experiments. There is a possibility that the wrong pieces of RG-9 coax were used in later tests. In any event, there were problems with this circuit. The transmitted power level, as mirrored by the coupling curve in Fig. 2-23, falls sharply at the high frequency end of X-band. This was traced to using the H-plane of the magic tee as the bridge feed. Also, there was trouble in adjusting the path lengths. Recall that the compensating path and coupling path must be the same electrical length for broadband, optimum decoupling. The only method available at X-band is to use discrete "spacers", or small pieces of waveguide. It would be desirable to have a means of continuous path length adjustment at X-band similar to that afforded by an S-band trombone.

An X-band line stretcher was devised from a movable short and a cross-guide directional coupler, see Fig. 2-24. Power enters port 1 and most of it flows out port 2 into the matched load. However, an attenuated signal is coupled to port 3. The strength of this signal depends upon the type of coupler used. Since the compensating path requires an attenuated signal, this coupler attenuation is useful. The signal leaving port 3 is reflected by the adjustable short and most of it comes out port 4. Since the position of the short is variable, a continuous adjustment of line length is achieved. Note that the reflection from the short causes a 180^o phase shift. Thus, the H-plane of the magic tee can no longer be used. An adaptation to an E-plane feed is necessary. This solves the problem of power loss at high frequencies in X-band.

A preliminary cancellation bridge was constructed using an E-plane magic tee feed and "majestic" tee to add the two signals. One path contained the X-band line stretcher, an attenuator, and an isolator. The other path con-

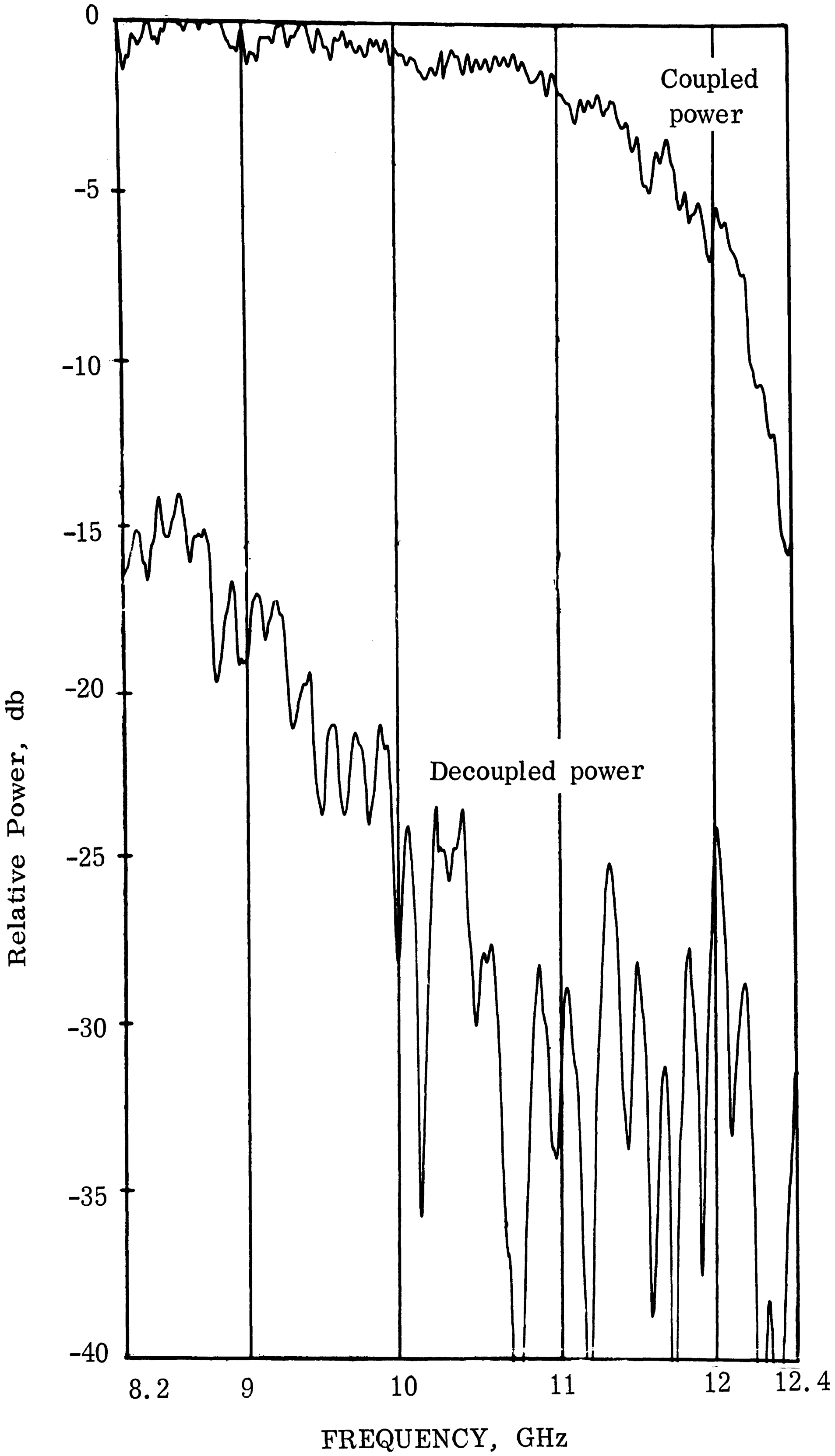


FIG. 2-23: SLOT ANTENNA DECOUPLING BY MAJESTIC TEE BRIDGE.

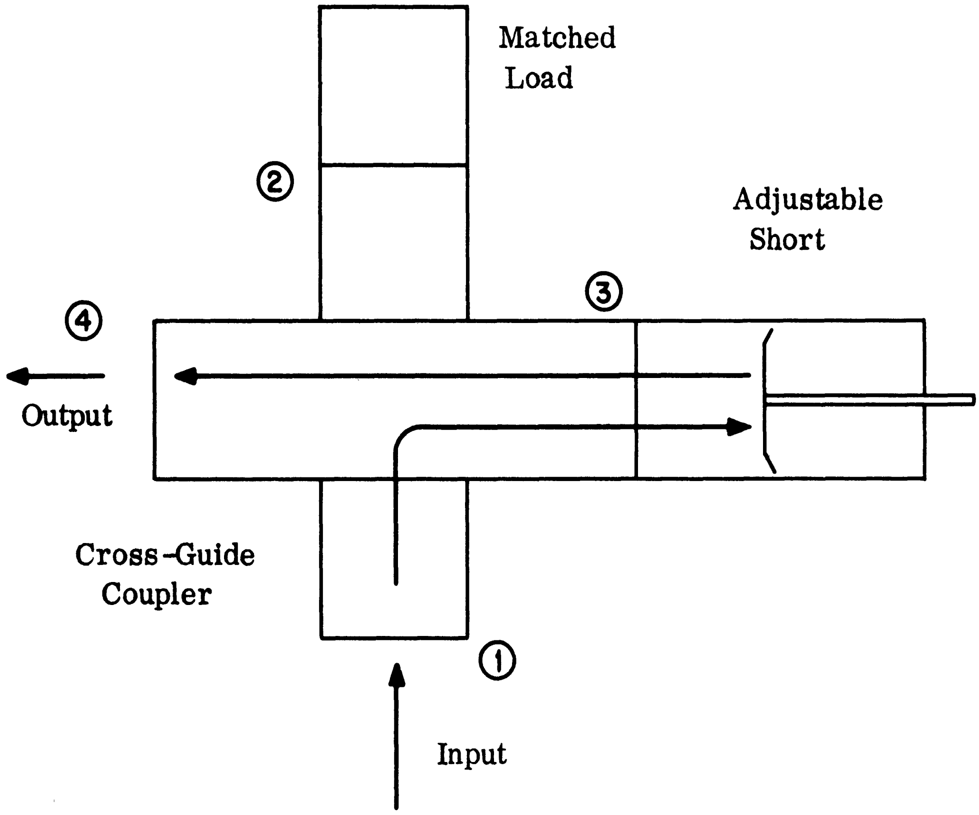


FIG. 2-24: X-BAND LINE STRETCHER.

tained an attenuator, an isolator, and enough wave-guide to make the two paths approximately the same length. It was found to be very easy to critically adjust the path length for optimum cancellation using the line stretcher. Also, the power loss at high frequencies was eliminated, see Fig. 2-25. Since an E-plane feed can be used, a "majestic" tee could be used in place of the magic tee. A "majestic" tee has far superior properties compared to a magic tee. This change should improve performance.

2.5 Near Field Decoupling of Square Spirals.

It was reported before that the far field coupling between two spirals is independent of the sense of rotation of the spirals. It was also pointed out that this might not be the case with the near field coupling. The last report contained coupling patterns of two square spirals at a center-to-center separation of 11.43 cm at 2.2 GHz and other frequencies. It was found that even at this close spacing, 0.84λ at 2.2 GHz, the coupling was still independent of the sense of rotation of the spirals. More recently, coupling data for two square spirals in a common ground plane were obtained for two cases, first with two left-hand spirals, then with one left-hand spiral and one right-hand spiral. The center-to-center distance between the spirals for the above cases is 5 cm or λ/3 at f = 2.0 GHz. The results are shown in Fig. 2-26. This figure shows the coupling versus frequency in the above mentioned two cases as frequency varies from 1.75 GHz to 1.90 GHz. It is seen that the coupling between two left-hand spirals is generally weaker than that between a left-hand spiral and a right-hand spiral. Above 2 GHz, there is not much difference in coupling between the two cases. Coupling data below 1.75 GHz were not obtained, due to the limitation imposed by the range of the signal generator. However, it was found later that the S-band spirals used do not work below 1.6 GHz. It should be pointed out that although the range 1.75 GHz to 1.90 GHz is not in

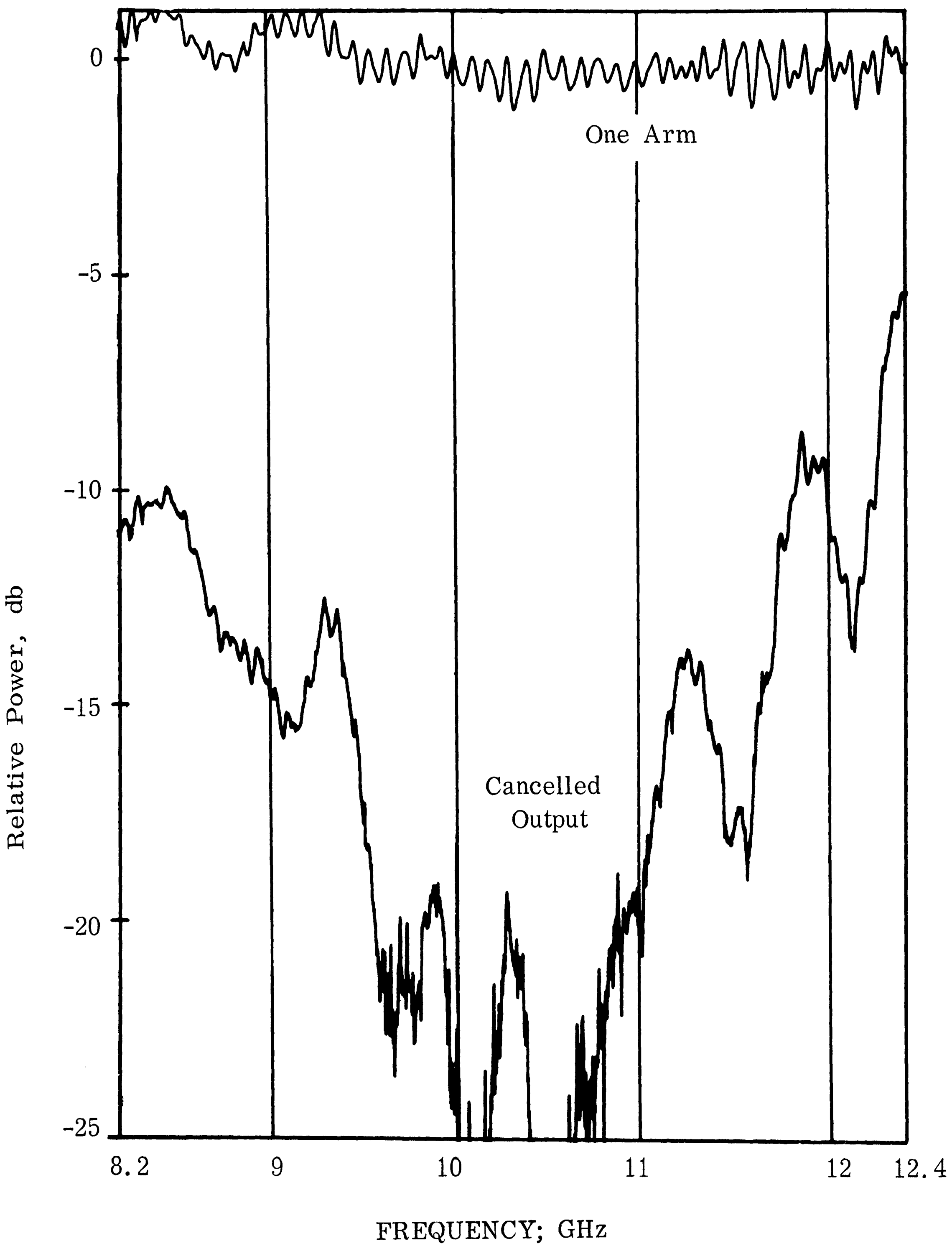


FIG. 2-25: PRELIMINARY CANCELLATION BRIDGE, E-PLANE FEED.

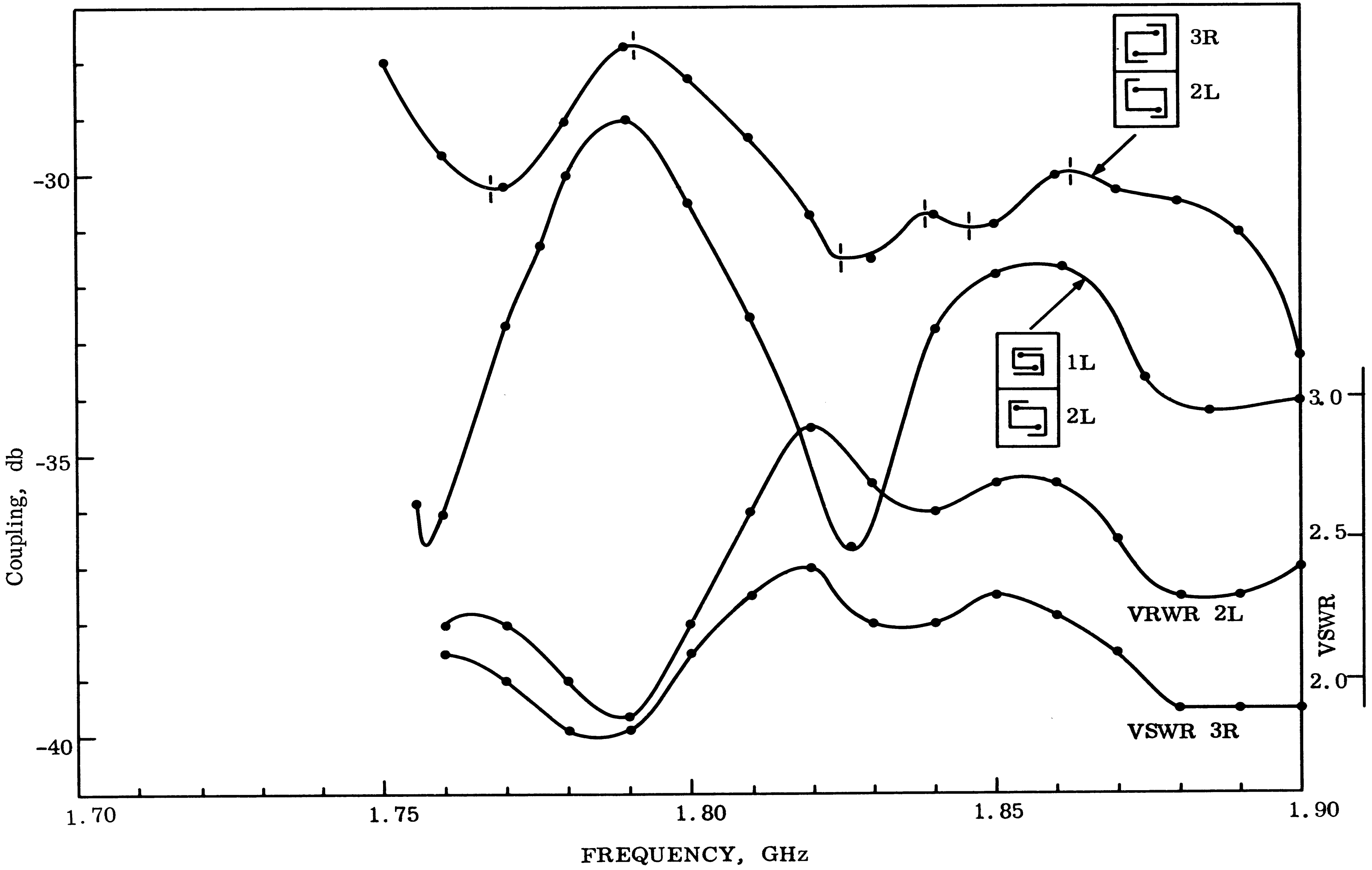


FIG. 2-26: COUPLING BETWEEN TWO CLOSE-PACKED SPIRALS AND VSWR OF SPIRALS 2L AND 3R.

the S-band, the fairly low SWR indicates that the spirals used are still efficient radiators.

2.6 Asymmetrical Spirals for Decoupling

It is thought that a spiral with asymmetrical geometry would have an asymmetrical coupling pattern on the ground plane and hence can be used to achieve decoupling. One thinks naturally about a regular spiral first. Refer to Fig. 2-27 and consider a rectangular loop in the ground plane, i.e., the x-y plane in this case with long sides of length ℓ_1 and short sides of length ℓ_2. The coupling between this antenna and any other antenna, say a monopole, on the ground plane will depend on the angle ϕ. It is expected that the field is mainly determined by the two long sides when $\ell_1 >> \ell_2$. One drawback concerning the rectangular spiral is the difficulty in maintaining the prerequisite $\ell_1 >> \ell_2$. Beginning with ℓ_1 and ℓ_2 for the innermost turn of a rectangular spiral, one would have $\ell_1 + (n - 1)d_1$ and $\ell_2 + (n - 1)d_2$ for the nth turn. It is not hard to see that to maintain the same $\ell_1 : \ell_2$ ratio for all turns, one would have to have $\ell_1 : \ell_2 = d_2 : d_1$. This leads to an impractically small d_1 if many turns are to be constructed. A hexagonal spiral with two long sides and four short sides as shown in Fig. 2-28 does not have the above difficulty for a rectangular spiral and was made for a first try.

Figure 2-28 shows the face of the hexagonal spiral as made. It was 1 3/4 turns for each of the two windings and is designed to operate at 1.6 GHz. It is backed by a cavity with a depth of about 1 1/4", inside of which an S-band balun is used to provide the transition from the antenna to a coaxial cable. Radiation patterns at 1.4, 1.6 1.8 and 2.0 GHz and coupling patterns with a monopole at these frequencies were taken. Figure 2-29 presents the patterns at 1.6 GHz showing the radiation is mainly axial in direction. The patterns at 1.4 and 1.8 GHz were similar to the ones shown here for 1.6 GHz. The

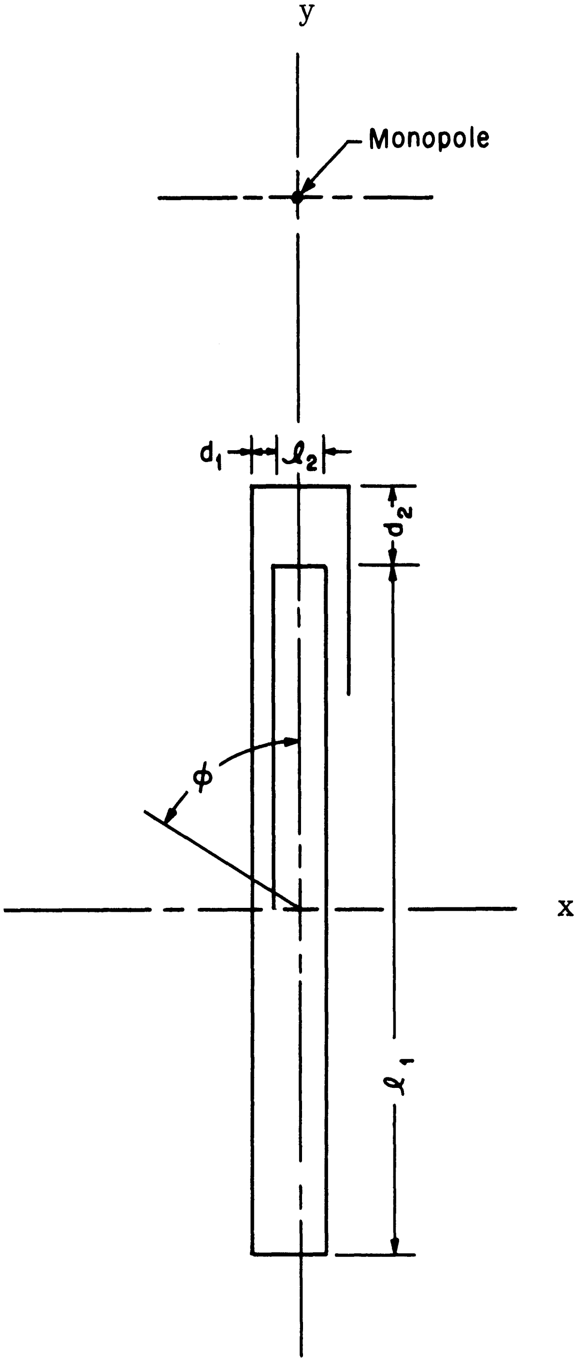


FIG. 2-27: GEOMETRY OF COUPLING BETWEEN A RECTANGULAR SPIRAL AND A MONOPOLE ON A GROUND PLANE.

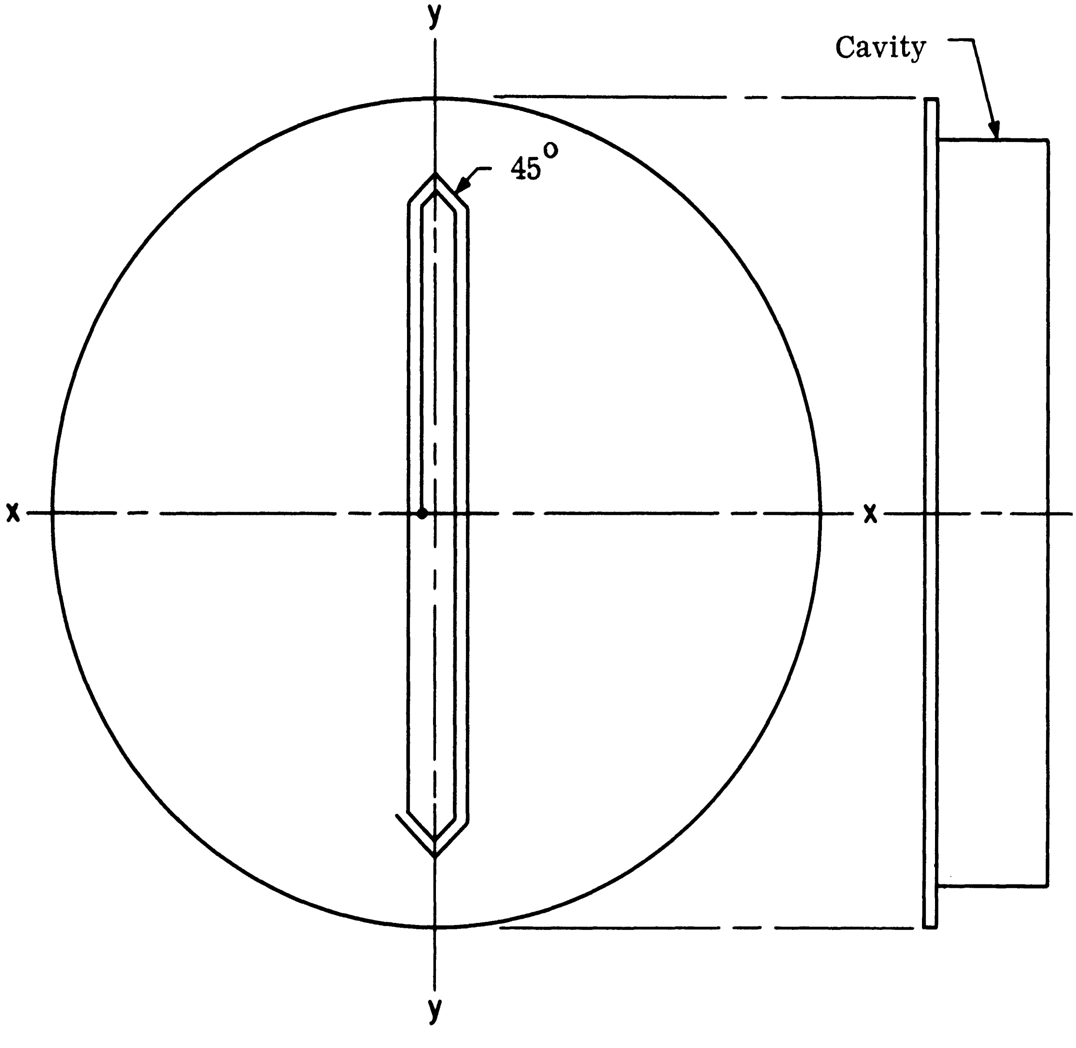
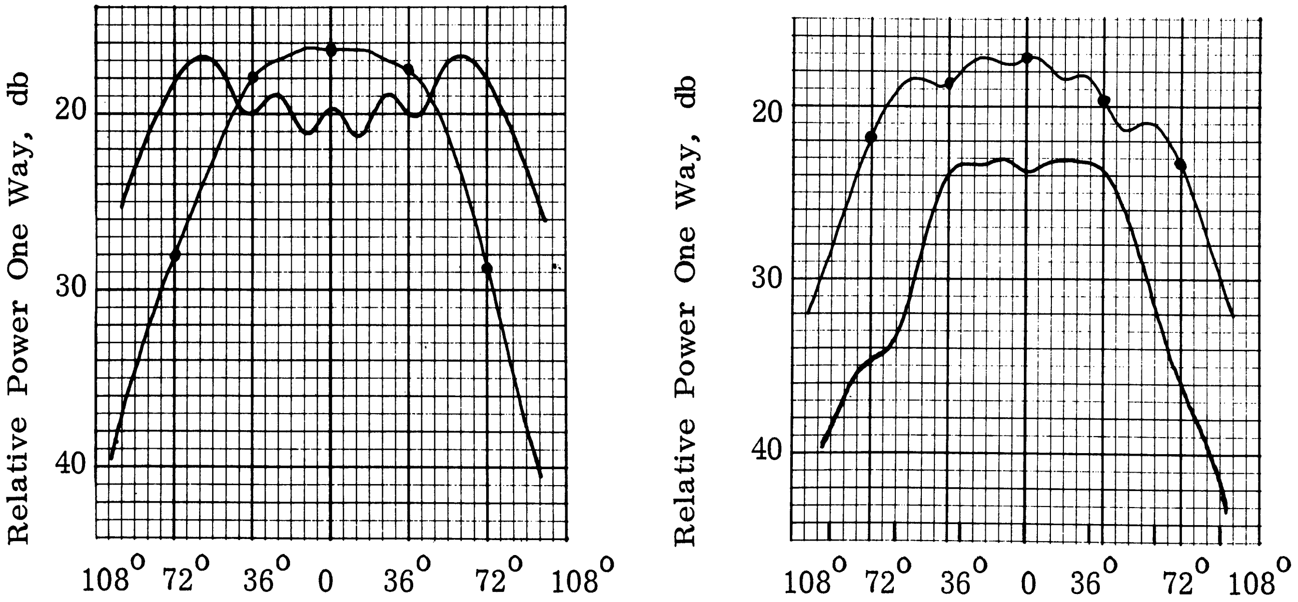


FIG. 2-28: THE HEXAGONAL SPIRAL. Only one of the two symmetrically developed windings are shown here.



(a) Pattern about y-y axis in Fig. 2-28.

(b) Pattern about x-x axis in Fig. 2-28.

FIG. 2-29: RADIATION PATTERN OF THE HEXOGONAL SPIRAL ON TWO MUTUALLY PERPENDICULAR PLANES USING A LOG PERIODIC ANTENNA AS RECEIVING ANTENNA. (-♦-) When elements of the receiving antenna are parallel to the long sides of the spiral; (——) When elements of the receiving antenna are perpendicular to the long sides of the spiral.

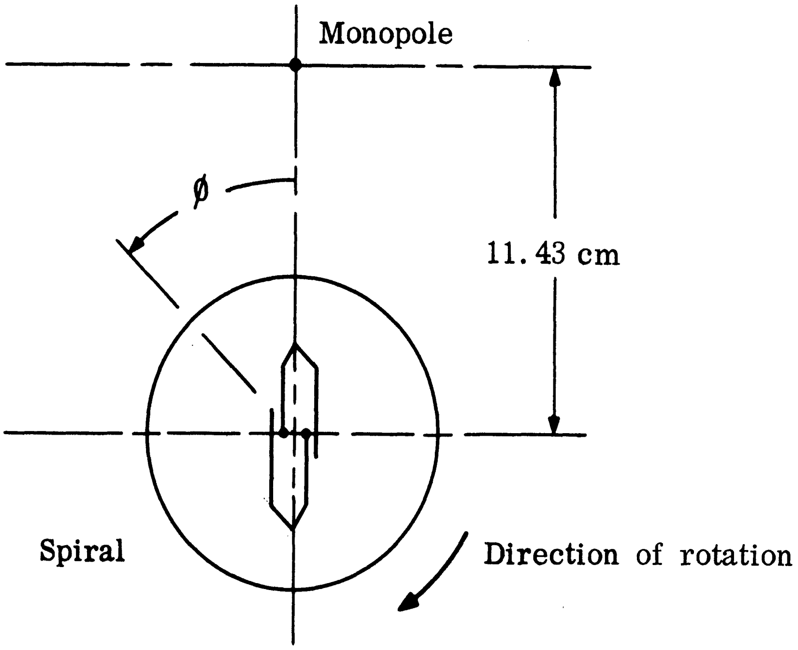
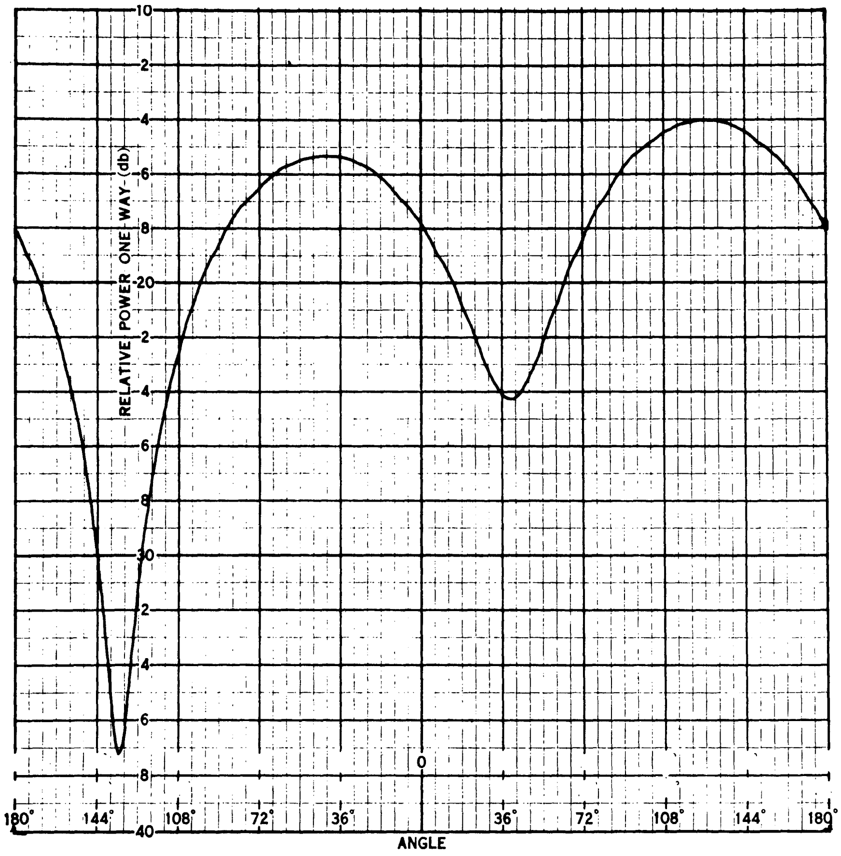


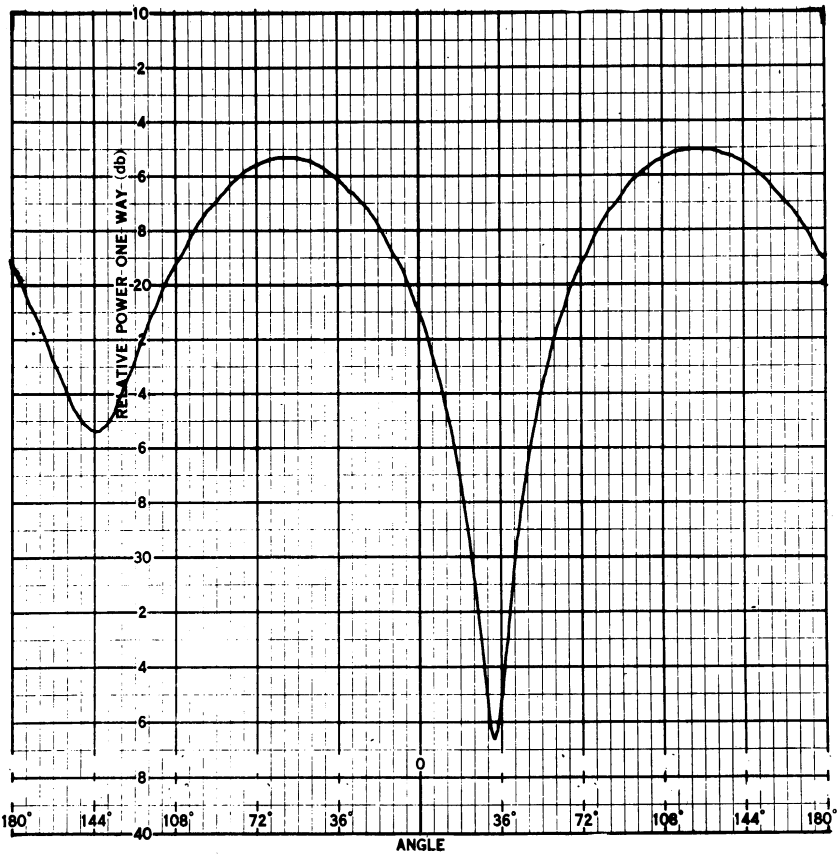
FIG. 2-30: COUPLING MEASUREMENTS OF A MONOPOLE AND A SPIRAL ON THE SAME GROUND PLANE.

patterns at 2.0 GHz have two large lobes indicating that more turns will be needed if the spiral is to function at this frequency. Figure 2-30 illustrates the arrangement of the spiral-monopole coupling measurement. The result is shown in Fig. 2-31. The direction for minimum coupling seems to be along the $\phi = 144^o$ and 324^o axis for f = 1.6 GHz and is about 22 db below the maximum coupling. The lack of complete symmetry at both ends of the spiral explains partly why the minimum coupling is not along the $\phi = 0^o$ and 180^oaxis. The data suggest that a broadband antenna whose ground plane coupling pattern depends on orientation is possible.



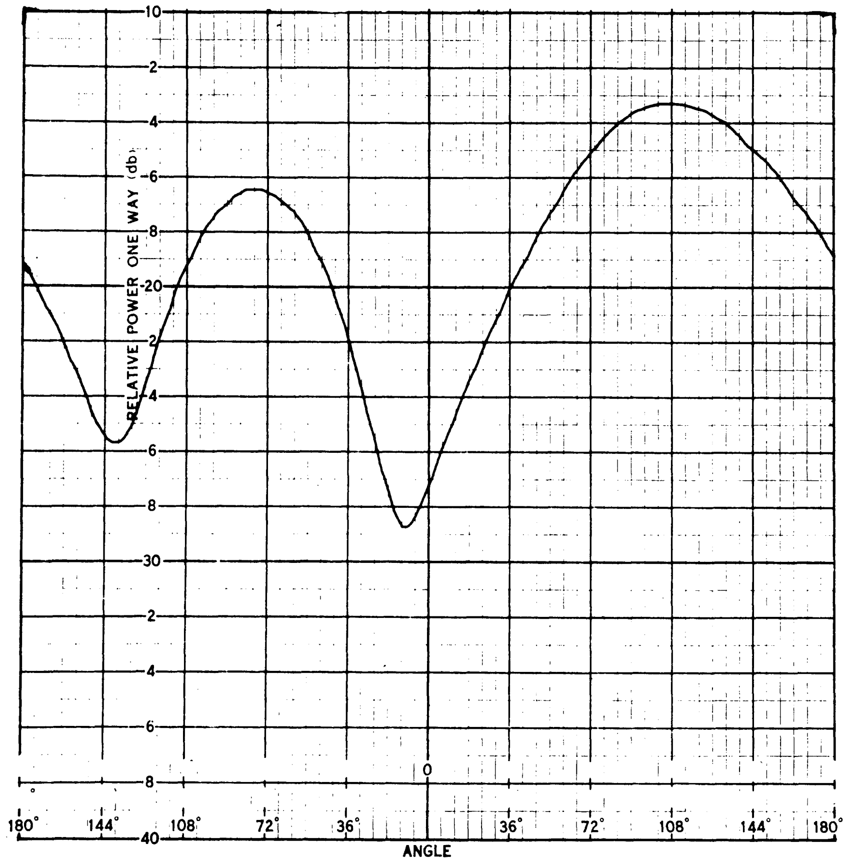
(a) f = 1.4 GHz

FIG. 2-31: COUPLING BETWEEN A MONOPOLE AND THE HEXAGONAL SPIRAL VS. ORIENTATION.



(b) f = 1.6 GHz

FIG. 2-31: CONTINUED



(c) f = 1.8 GHz

FIG. 2-31: CONTINUED.

III

CONCLUSIONS

The studies to date have afforded a good deal of insight as to methods which are useful and practical for the reduction in coupling frequently necessary for the proper operation of systems in close proximity.

The use of corrugations surrounding either rectangular slots or monopoles has proved an effective means of reducing coupling. To date the reductions of coupling have not been as broadbanded with respect to frequency as seems desirable.

A method using fences of metal pins protruding from the ground plane has been very successful in providing a high degree of reduction of coupling over a broadband of frequency. So far this method does not seem appropriate for systems that are flush-mounted.

A method of mounting a slot antenna in a recessed cavity with the recessed cavity partially filled with corrugations parallel to the long sides of the slot has proved effective at certain points in the frequency spectrum. A moderate amount of coupling reduction has been obtained over a 20 percent bandwidth.

Adaptation of the cancellation bridge to decouple two slot antennas has proved to be successful. Substantial reduction in coupling over the entire X-band of frequencies has been achieved. The ultimate limitation of this method seems to be in matching the frequency dispersion characteristics of the two paths.

The study of the decoupling of spirals has shown very clearly that the coupling changes from a near field phonomenon to a far field phenomenon as the frequency changes from the lowest permitted operating frequency to higher frequency. As the coupling becomes a far field phenomenon, it is apparent that the coupling level becomes independent of the orientation or rotation of the two antennas.

The study of near field decoupling for spirals has been extended to the use of asymmetrical spirals. Asymmetrical spirals refer to those which have a minor axis substantially different in length from a major axis. Such unconventional spirals are being used to study the effects that the exaggerated form of these spiral windings have on the coupling.

IV

FUTURE EFFORT

It is now contemplated that an extension will be made to the study of the use of corrugations for increasing isolation by the further use and placement of materials in such corrugations. The broadbanding of isolation is an important objective for this work. Further, an analytical study is commencing on the radiation characteristics of slots or monopoles in the presence of corrugated structures.

An early effort is planned on the study of antennas with the phase center varying with the operating frequency. This type of study is apparently basic to much of the coupling and decoupling work done to date on this project. A scimitar antenna is being constructed for this purpose. Also, a flush-mounted design of an antenna consisting of a slot array where the phase center shifts is also being planned.

Because of the observed decoupling which has been accomplished through bridge methods, further extensions of such methods are being contemplated. A major modification of the bridge in order to make it even less frequency sensitive has been designed and construction awaits delivery of vital component parts.

Additional effort of near field coupling of spiral antennas is planned. A significant amount of effort will be devoted to the detailed study of the effects of terminal matching on the ends of spirals. Although there have been some studies on such terminations none of them heretofore have been directed toward the mitigation of unwanted coupling.

ACKNOWLEDGMENT

Mr. D. R. Brundage of The University of Michigan Institute of Science and Technology obtained most of the experimental data in this report.

REFERENCES

Barlow, H. M. and A. L. Cullen (1953) " Surface Waves", Proc. IEEE, (London), Pt, III, Vol. 100, pp. 329-341.

Lyon, J. A. M., et al (1966 a) "Electromagnetic Coupling Reduction Techniques", The University of Michigan Radiation Laboratory Report No. 7692-2-Q.

Lyon, J. A. M., et al (1966 b) "Electromagnetic Coupling Reduction Techniques", The University of Michigan Radiation Laboratory Report No. 7692-4-Q.

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13. ABSTRACT Progress is reported on several methods of obtaining increased isolation from one antenna to another. One of the methods is to use circumferential corrugations surrounding either one or both of the antennas involved. Such corrugations cause some changes in the radiation pattern of an antenna. The report indicates the extent of such changes as well as the amount of reduction of coupling which can be achieved.

Another method of mitigating coupling effects has been introduced in the from of a "fence" of thin wires erected vertically over the conducting plane between two antennas. Such a fence protrudes over the ground plane and would be objectionable for mounting over the skin surface of an aerospace vehicle. However, for wavelengths corresponding to the X-band of frequencies the actual extent of protrusion is not much for it corresponds to one-half of the wavelength used. Certainly for wavelengths corresponding to frequencies below the microwave regions, the protrusion from the surface might be a serious problem.

The use of a square cavity, surrounding an antenna, which is flush-mounted in the bottom surface of the cavity, has yielded data showing the reduction of coupling possible. This square cavity is also has inserted in it, a series of corrugations. Large decoupling (30dh) obtained over narrow frequency ranges. As much as 12db was obtained over a 20 percent bandwidth.

Extensions have been made to the RF bridge reduction method. Very encouraging reductions of coupling have been achieved. The latest effort has been concentrated on improving the bandwidth over which such reductions are accomplished.

Results are presented on the near field coupling between two spirals. Data are shown, indicating a reduction of coupling as the frequency is increased on two spirals that are in adjoining positions. The coupling is most sensitive to spiral orientation when the spirals are operating at the low frequency end of the operating range. As frequency increases, it is shown that the coupling becomes independent of the sense of rotation of the spirals.

14. KEY WORDS	LINK A		LINK B		LINK C	
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ANTENNA						
COUPLING						
DECOUPLING						
ISOLATION INCREASE						

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