ACTIVE CONTROL OF RADAR SCATTERING

by

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Final Report

on

Purchase Order No. 978902 dated 8/10/84

to

Northrop Corporation E171/3E
8900 E. Washington Blvd.
Pico Rivera, CA 90660

Attn: Dr. Jerrold S. Shuster

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1. Introduction

This is the final report describing the results of a 13 week study carried out for the Northrop Corporation E171/3E under Purchase Order No. 978902 dated 8/10/84. The objectives were to study techniques for the active control of radar scattering cross sections, and since the physical displacement of part of the target's surface was not regarded as a viable technique, attention focussed on modifications to the impedance presented by some or all of the surface.

In principle at least, there are several ways in which this might be accomplished. We could, for example, break up the surface into electrically isolated elements or patches whose impedances could be individually controlled, and the reflectivity of the resulting surface should then vary according to the impedances presented. As discussed in Chapter 2, this approach has several progenitors, and the particular realization that we chose to consider evolved from our present work on patch antennas. The data presented in Chapter 2 suggests that the concept does have some merit.

It would also be possible to change the microwave reflectivity of a surface if one or more of the electromagnetic constants characterizing the material of which the surface is composed could be changed by application of a biassing or control signal. There are certain materials for which this might be feasible. For example, by changing the preferred orientation of the axes of a thin layer of a crystalline material, the reflectivity and transmittivity could be changed for any given polarization of the incident field, and yet another parameter of interest is the conductivity. To this end, we undertook a literature search for information about the microwave properties of semiconducting materials with particular reference to their possible use as surfaces whose scattering could be controlled. An annotated list of the references is given in Chapter 3, but because of the limited time available, we have so far obtained only a few of the more accessible publications. A discrete realization of this type of approach is to use PIN diodes and in Chapter 3 we indicate a number of experiments that could be performed to determine the variation in cross section that might be achievable.

For specular or near-specular scattering from a surface many wavelengths in dimension, it is necessary to change the impedance over a substantial fraction of the surface to have any significant effect on the scattering, but there are circumstances in which it should be sufficient to modify only a small portion of the surface. A case in point is a thin (or planar) surface at near glancing incidence for H polarization, where the backscattering is primarily due to a traveling wave. To interrupt the wave using a localized variable impedance could then have a major effect on the scattering over a small range of angles, and to test this idea, a few numerical experiments were performed using an available computer code. The results of this limited study are described in Chapter 4.

Although none of these ideas have been pursued to the stage where definitive conclusions are possible, the preliminary results that have been obtained are reasonably encouraging. It seems certain that, to a limited degree at worst, active control of scattering is an achievable goal, and the use of semiconductors, localized or distributed, and tunable patches are all worth more detailed study.

2. Array Concepts

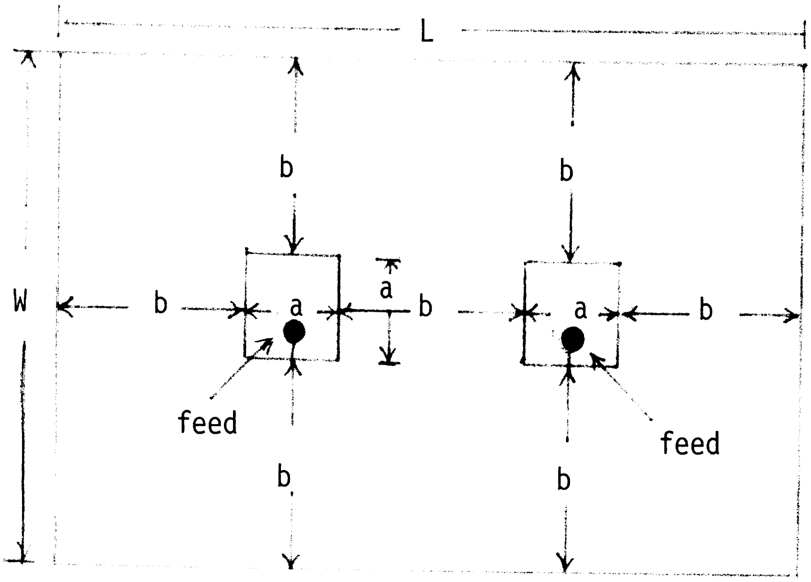
If a surface is broken up into electrically isolated elements or patches whose impedances can be individually controlled, it is evident that the reflectivity of the resulting surface will change according to the impedances presented. This type of approach has several progenitors and it is of interest to examine the application of antenna array concept in order to determine the most effective realization of the surface. If we start from the concept of a patch antenna and conceive of the surface as an array of these patches, the impedances presented by the individual patches can be changed to modify the resulting scattering. With this approach, the techniques of adaptive array antennas become applicable, and if a surface could be constructed in this manner, we would have the ability to exercise considerable control over the scattering.

Consider a thin dielectric substrate one side of which is in contact with a plane conducting surface, with the other having an array of rectangular patches. The patches are designed to resonate at a given frequency, and we note that the resonant frequency can be changed by introducing passive metallic posts within the input region of each patch [1]. (If desired, this tuning can be accomplished using PIN diodes.) We remark that the electronics necessary to control the reflectivity via the inputs to the patches is similar to that used in adaptive arrays and can be placed behind the conducting surface.

To assess the feasibility of antenna array concepts to control the electromagnetic reflecting characteristics of certain structures, the scattering properties of single and dual patch antennas have been measured at the X-band frequencies (f = 8.0 - 10.0 GHz; λ = 1.47 inch to 1.18 inch) under various conditions. The following sections describe the measurements, results and significant findings.

2.1 Test Configurations. Three test antenna configurations referred to as single patch, dual patch 1 and dual patch 2 were fabricated using a plane dielectric substrate consisting of a 5880 Duroid sheet of thickness 0.02 inch and having a nominal dielectric constant of 2.2. A sketch of the dual patch configuration is given in Fig. 1 which shows the two square patches, each of dimension a x a, located symmetrically on the front surface of the dielectric substrate of dimension L x W. Two separate dual patch configurations were fabricated. For the dual patch 1 the entire back surface of the substrate was metallized and for the dual patch 2 only the portions of the back surfaces (each equal to the patch area) lying opposite to each patch were metallized. The single patch configuration consisted of one patch antenna with the patch, substrate and the ground plane having the same surface size.

Each patch was fed from the back with the help of a coaxial probe attached to a point on the edge of the patch as shown in Fig. 1. Using the available theoretical expressions [2], the individual patches were designed to resonate at about 9.0 GHz (λ ≅ 1.31 inch). The location of the exciting probe was chosen so that the impedance of each patch was 50 Ω [3]. Various dimensions of the three test configurations are given as follows:



a = 0.40 inch, b = 1.18 inches, L = 4.34 inches, W = 2.76 inches

Fig. 1: Sketch of a typical dual patch antenna configuration.

Single Patch: patch, substrate and ground plane are of the same size 0.4 inch x 0.4 inch.

Dual Patch 1: patch size 0.4 inch x 0.4 inch
(Fig. 1) substrate size 4.34 inch x 2.76 inch
ground plane 4.34 inch x 2.76 inch
b = 1.18 inch

Dual Patch 2: patch size 0.4 inch x 0.4 inch
(Fig. 1) substrate size 4.34 inch x 2.76 inch
two separate ground planes; size of each 0.4 inch x 0.4 inch
b = 1.18 inch.

2.2 Results. The resonant frequency of each of the antenna configurations described above is defined to be the frequency where the minimum input reflection (or VSWR) occurs. Therefore, it is apprppriate to describe first the results of input reflection measurements.

Input Reflection

Figures 2(a) and 2(b) show the amplitude of the measured input reflection coefficient (Γ) vs frequency for dual patch 1 with one patch terminated in its load and short-circuited, respectively; similar results were obtained with one patch open circuited, but are not shown. As can be seen from the results, the resonant frequency is 8.7 GHz and is not affected by the termination of the patch. Similar results obtained with the dual patch 2 with one patch terminated in its load are shown in Fig. 3, which indicates that the

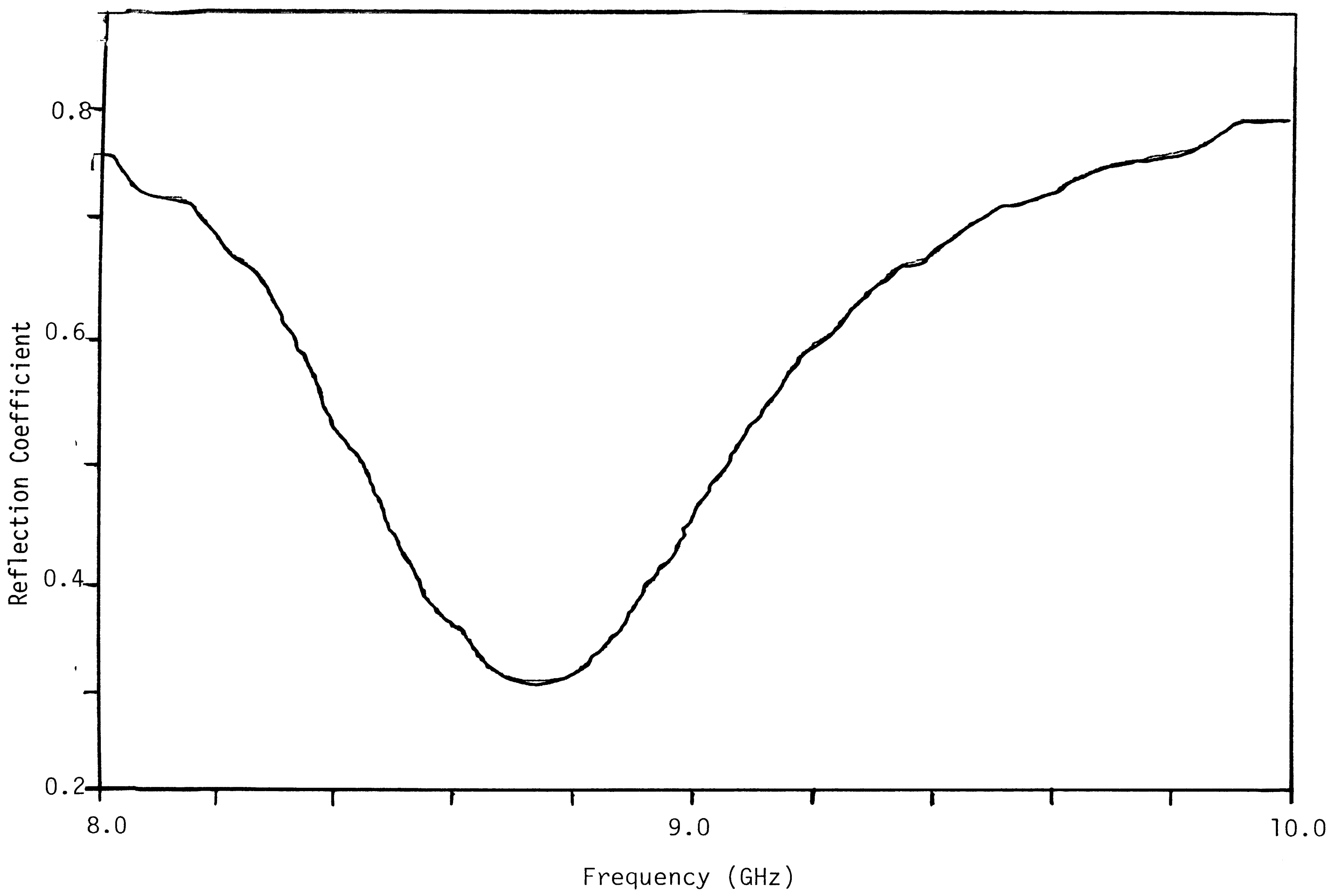


Fig. 2(a): Amplitude of the input reflection vs. frequency for the dual patch 1 with one patch terminated by 50 ohms.

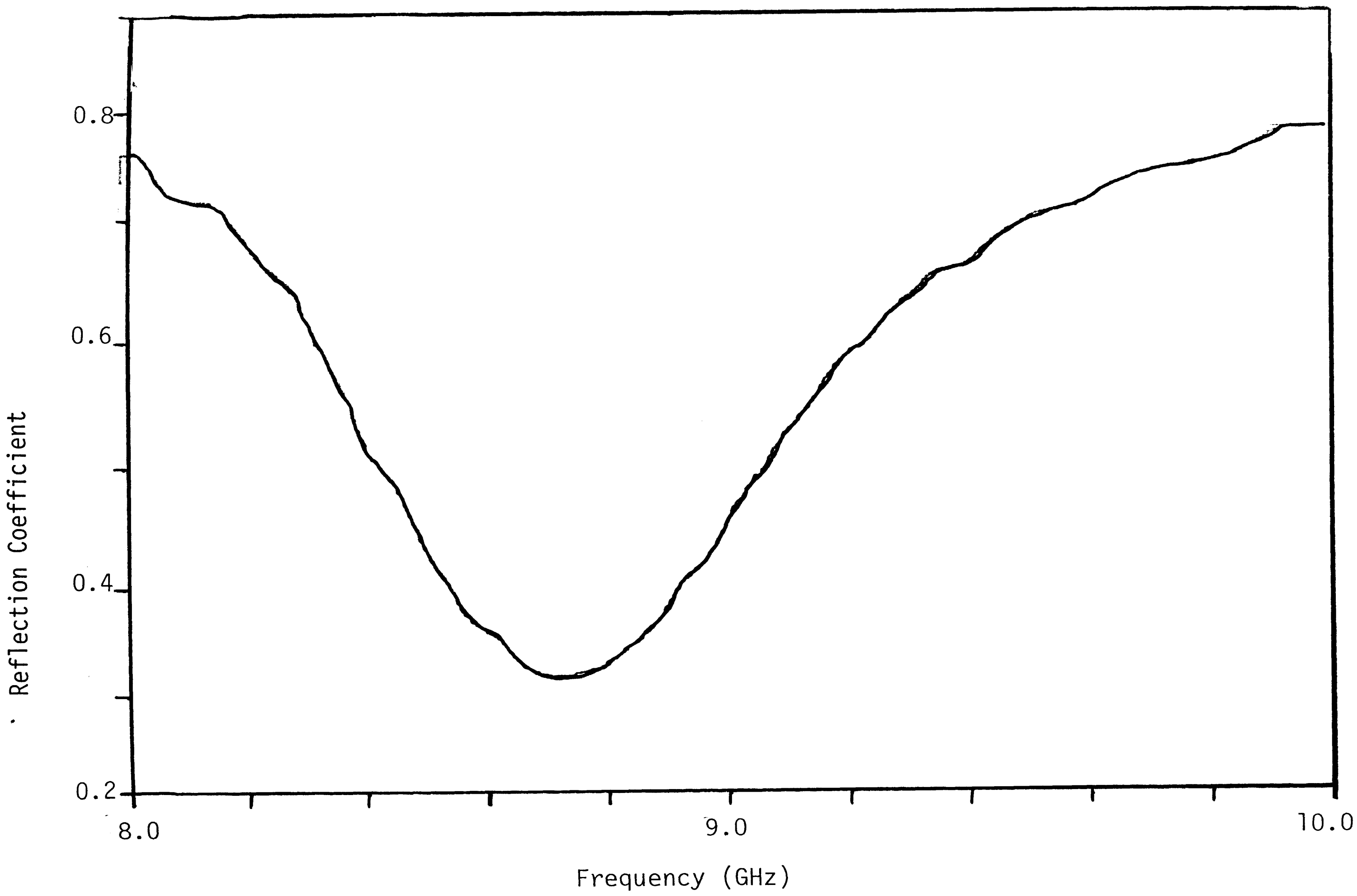


Fig. 2(b): Amplitude of the input reflection vs. frequency for the dual patch 1 with the patch terminated by a short circuit.

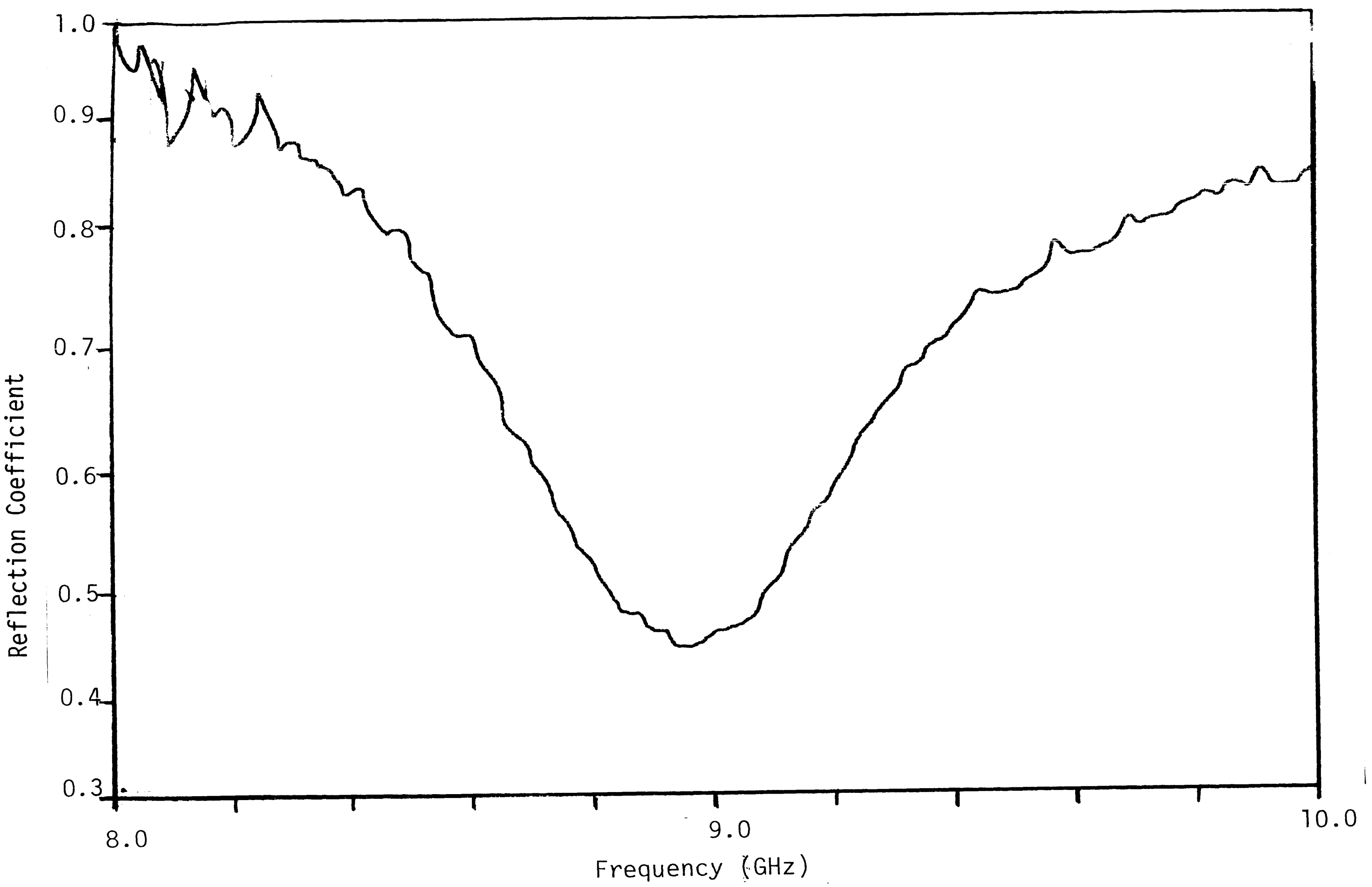


Fig. 3: Amplitude of the input reflection vs. frequency for the dual patch 2 with one patch terminated by 50 ohms.

resonant frequency is about 9.0 GHz. Similar measurements performed with the single patch showed its resonance frequency to be 8.8 GHz.

Scattering Characteristics

With each of the test configurations mounted with the patch plane in the vertical and the L-dimension (Fig. 1) in the horizontal plane, the complete (360 degree) horizontal plane backscattering patterns of the test models were measured in an anechoic chamber using standard techniques. Vertical polarization was used during all measurements.

Dual Patch 1

Portions of the forward region patterns for the dual patch 1 obtained at 8.7 GHz under the conditions of both patches open, shorted and terminated (in 50 Ω) are shown in Figs. 4(a), (b) and (c), respectively, where the returns from a 11.0 inch diameter conducting sphere are also included for calibration purposes. The results indicate that except for the side-lobe details, the scattering patterns are generally unaffected by the three conditions. In particular, the broad-side (i.e., in the zero degree direction) returns are the same in all three cases. It is argued that for the present case, the return from the large ground plane dominates the scattering which is not affected appreciably by that from the patches. Similar results were obtained at 8.5 GHz and 10.0 GHz chosen below and above the resonant frequency.

Single Patch

The returns from the single patch configuration being much smaller, it was difficult to obtain their complete scattering patterns

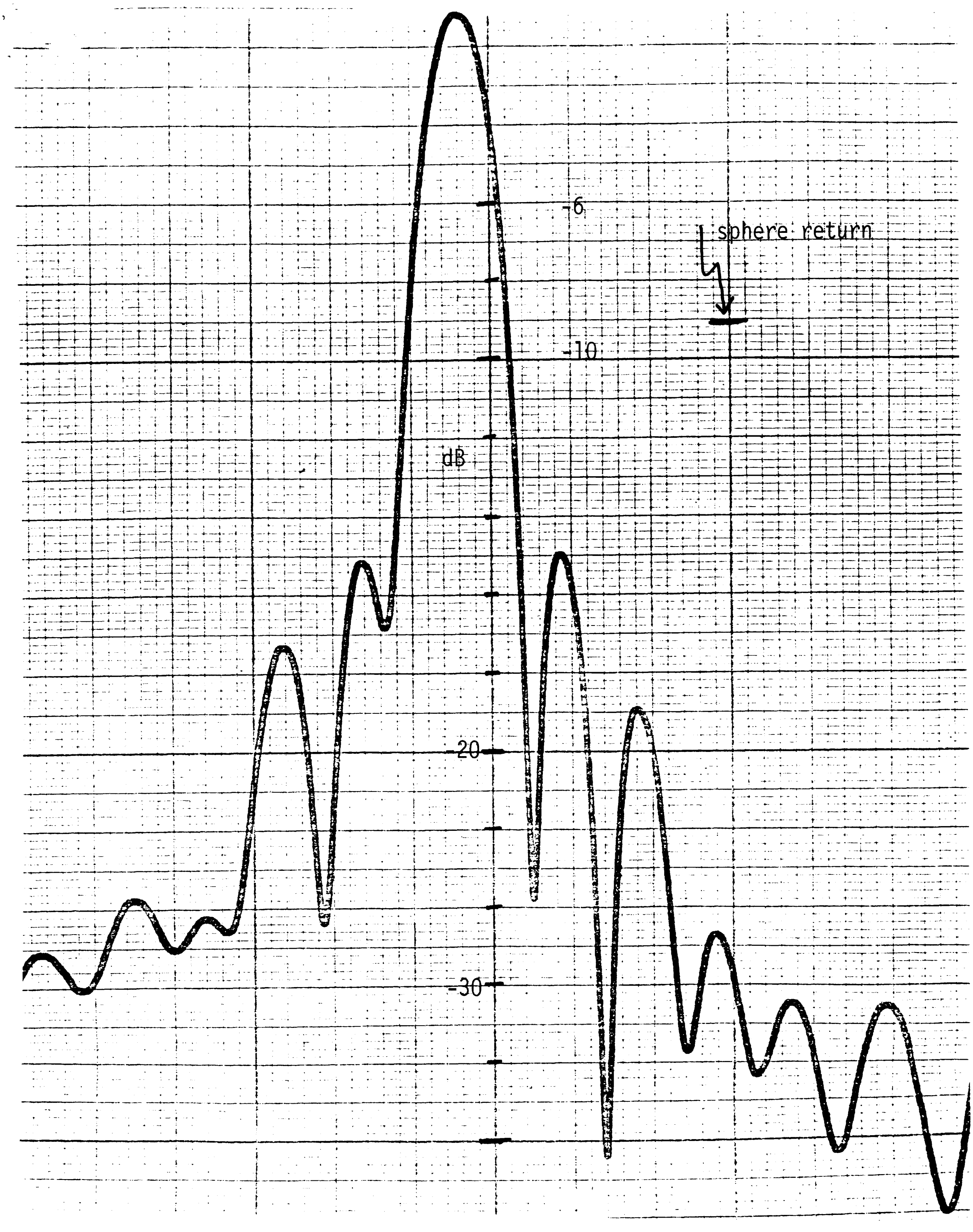


Fig. 4(a): Backscattering pattern of the dual patch 1 at 8.7 GHz.

Both patches terminated by an open circuit.

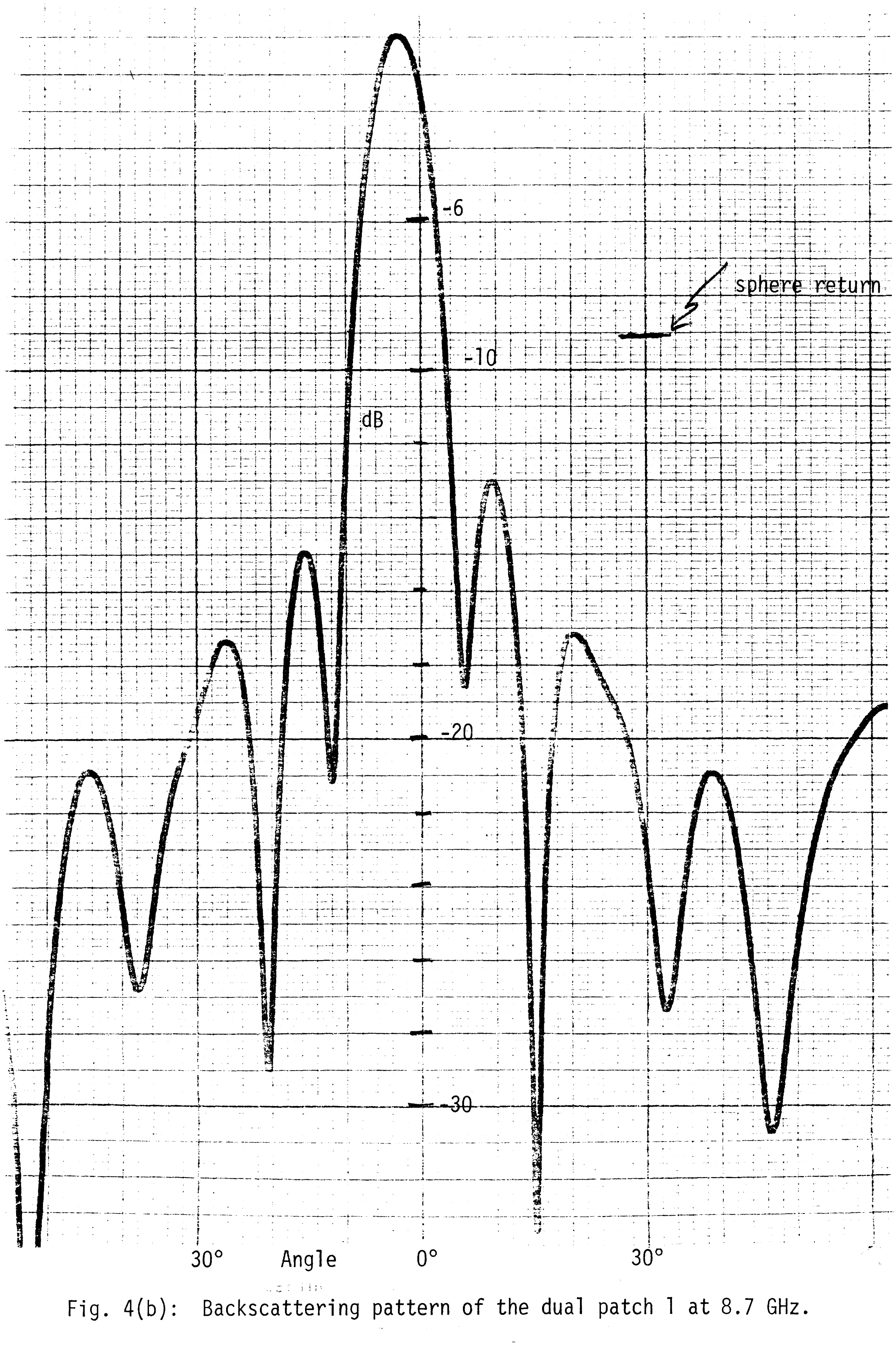


Fig. 4(b): Backscattering pattern of the dual patch 1 at 8.7 GHz.

Both patches terminated by a short circuit.

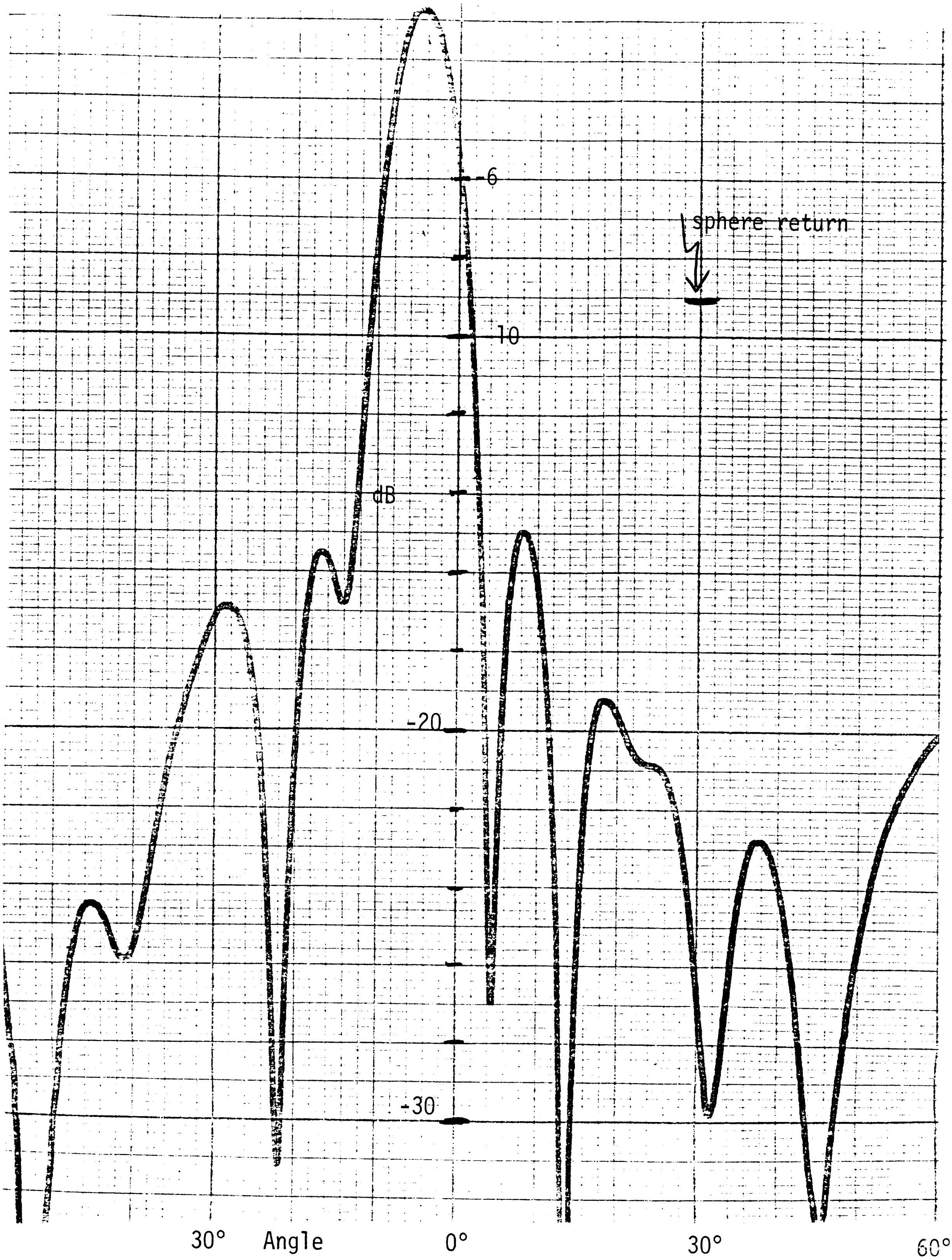


Fig. 4(c): Backscattering pattern of the dual patch 1 at 8.7 GHz. Both patches terminated by 50 ohms.

accurately. However, their broad-side returns relative to the 11.0 inch sphere were obtained at 8.5, 8.8 (resonant), and 10.0 GHz respectively. The results are given in Table 1. It is interesting to observe the differences in the returns obtained under the three conditions. More detailed and careful measurements should be carried out to ascertain the significance of these differences and to relate them to the antenna characteristics.

Dual Patch 2

Portions of the backscattering patterns of the dual patch 2 under the same three terminating conditions obtained at the resonant frequency of 9.0 GHz are shown in Figs. 5(a), (b) and (c), where it can be seen that the short circuit condition produces the maximum return. As expected, when the two patches are terminated by 50 ohms (Fig. 5(c)), the scattering pattern shows less severe side lobes. Corresponding results obtained at 8.5 and 9.9 GHz are shown in Figs. 6 and 7, respectively.

The broad-side back-scattering returns relative to the calibrating sphere obtained from Figs. 5 through 7 are shown in Table 2. The results indicate significant differences in the returns obtained under the three conditions. In particular, at the resonant frequency there is a 6 dB difference between the returns obtained under open and short conditions, the latter producing the larger return.

Table 1

Broadside Returns from the Single Patch

Condition	Return in dB Relative to the Sphere		
	8.5 GHz	8.7 GHz	10.0 GHz
Open	-24.1 dB	-25 dB	-31.5 dB
Short	-30.8 dB	-23.3 dB	-34.2 dB
Terminated	-28.7 dB	-33.5 dB	-34.0 dB

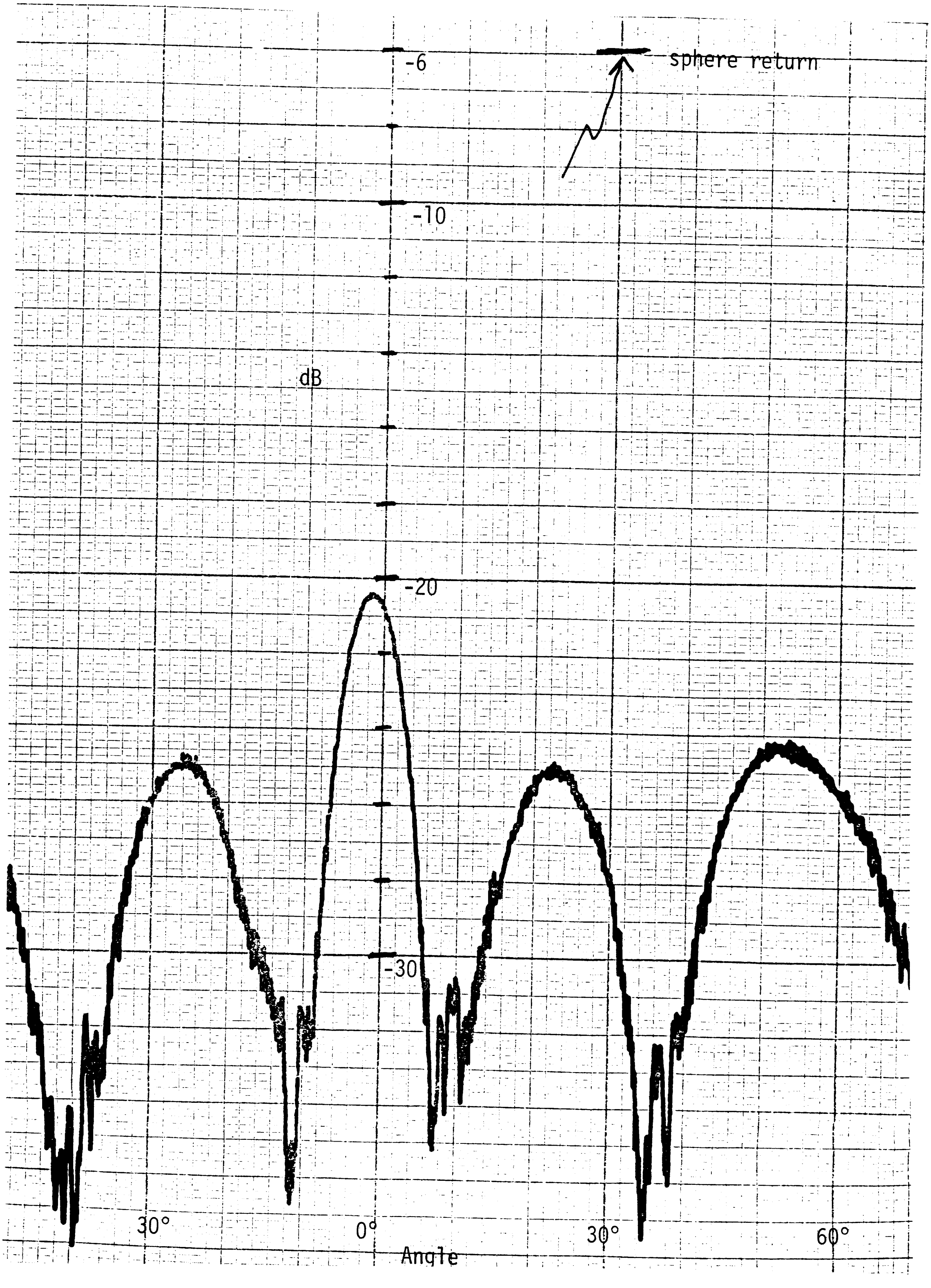


Fig. 5(a): Backscattering patterns of the dual patch at 9.0 GHz.

Both patches terminated by an open circuit.

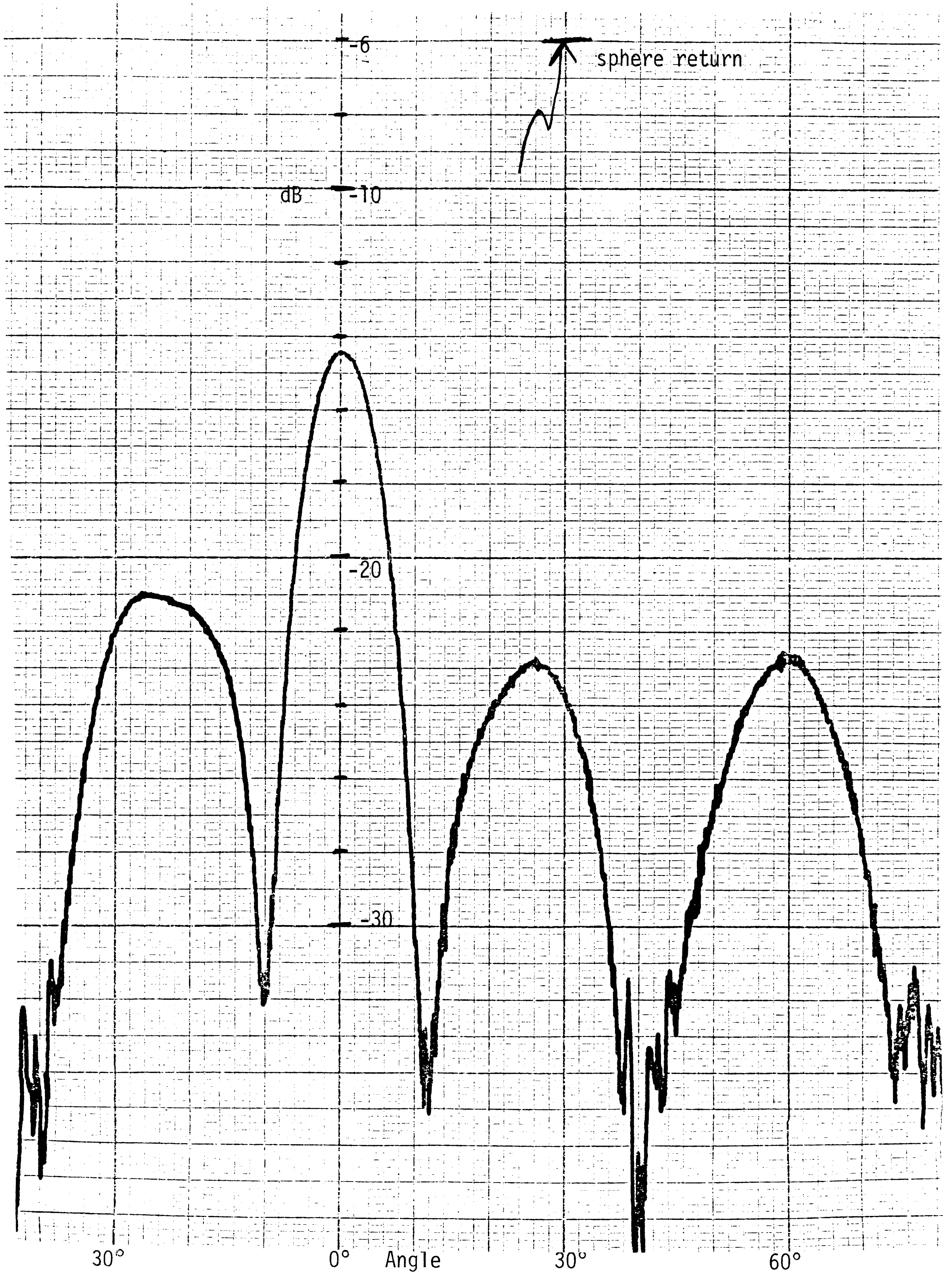


Fig. 5(b): Backscattering patterns of the dual patch at 9.0 GHz.

Both patches terminated by a short circuit.

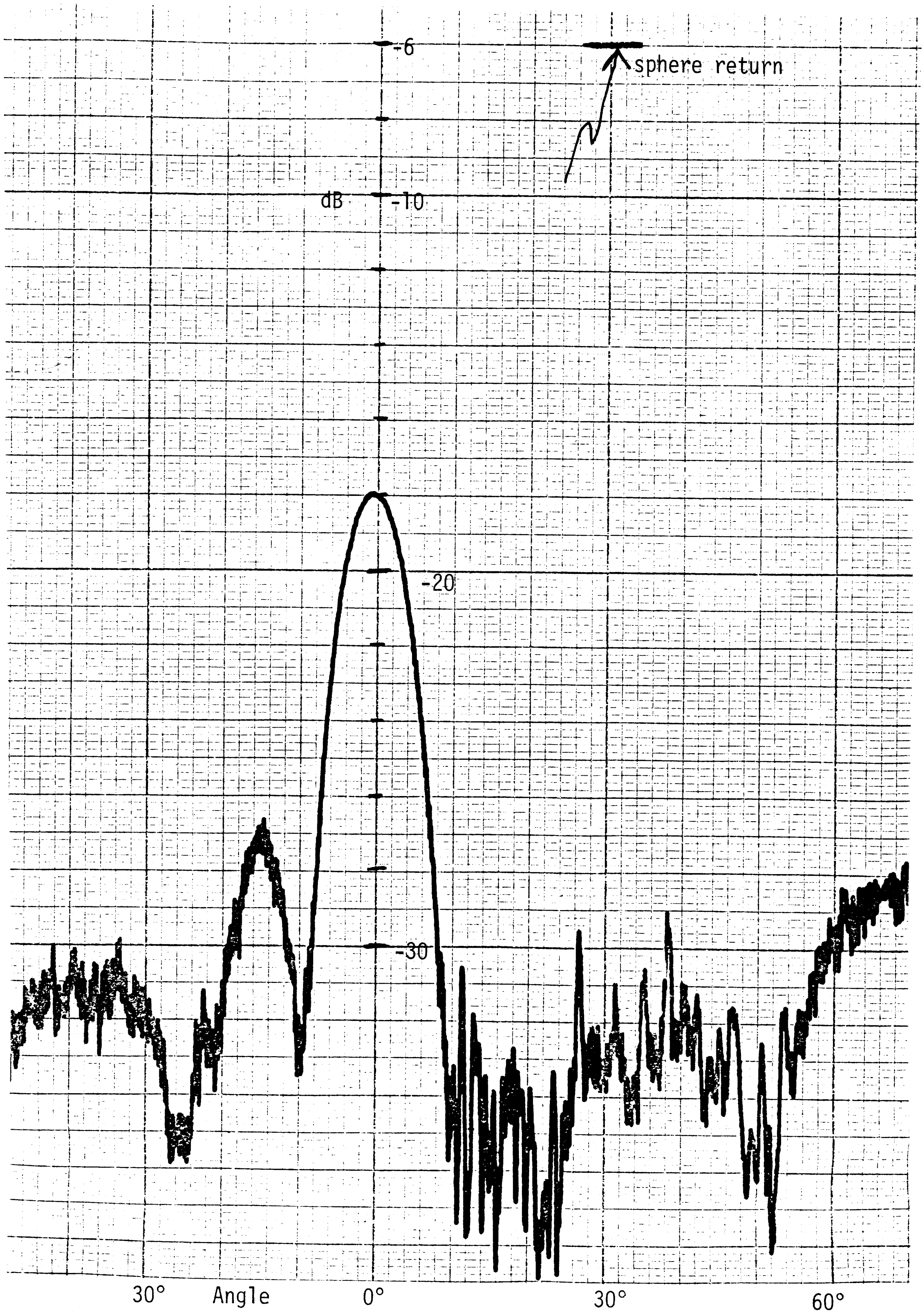


Fig. 5(c): Backscattering patterns of the dual patch at 9.0 GHz.

Both patches terminated by 50 ohms.

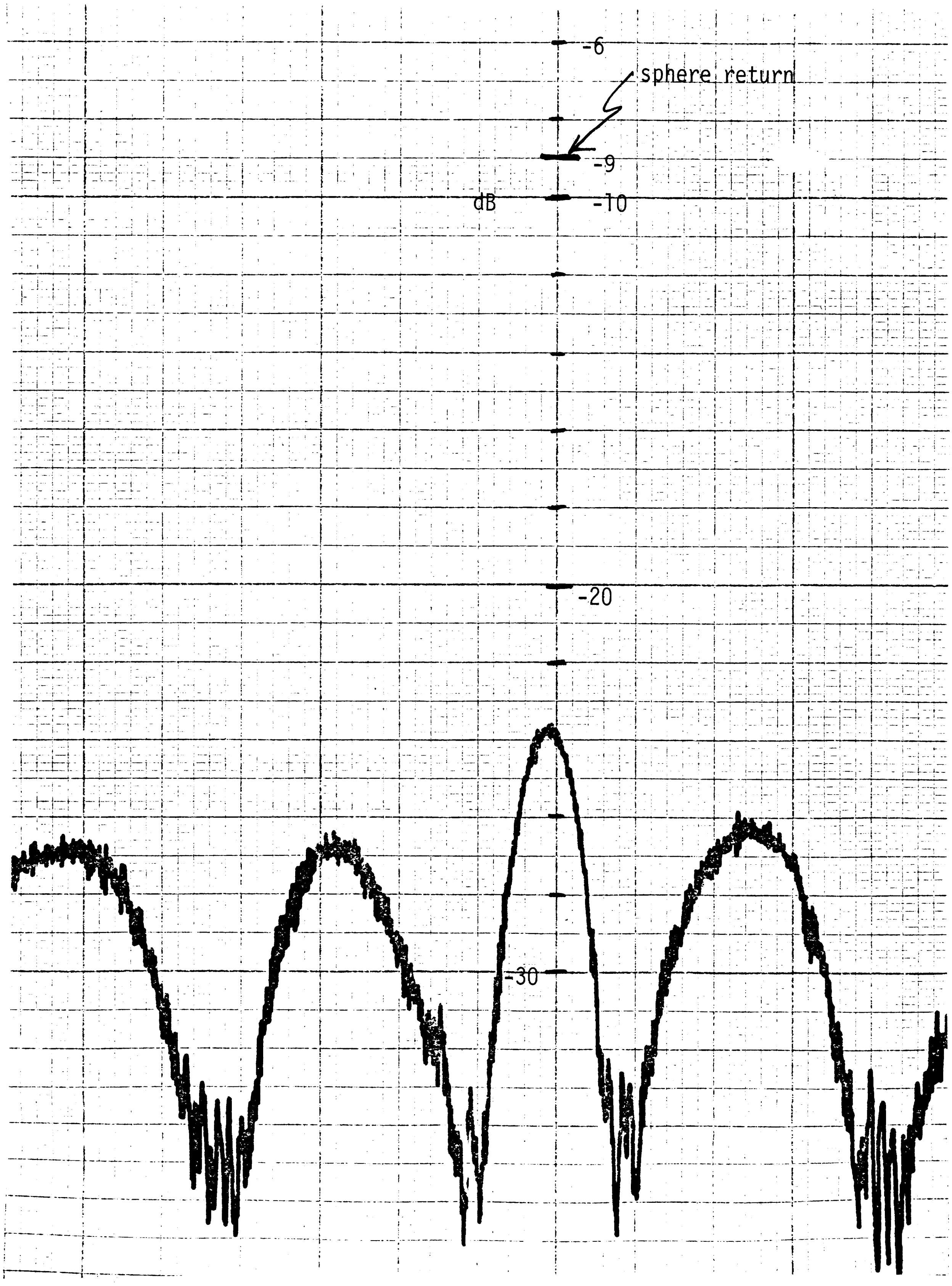


Fig. 6(a): Backscattering patterns of dual aptch 2 at 8.5 GHz.

Both patches terminated by an open circuit.

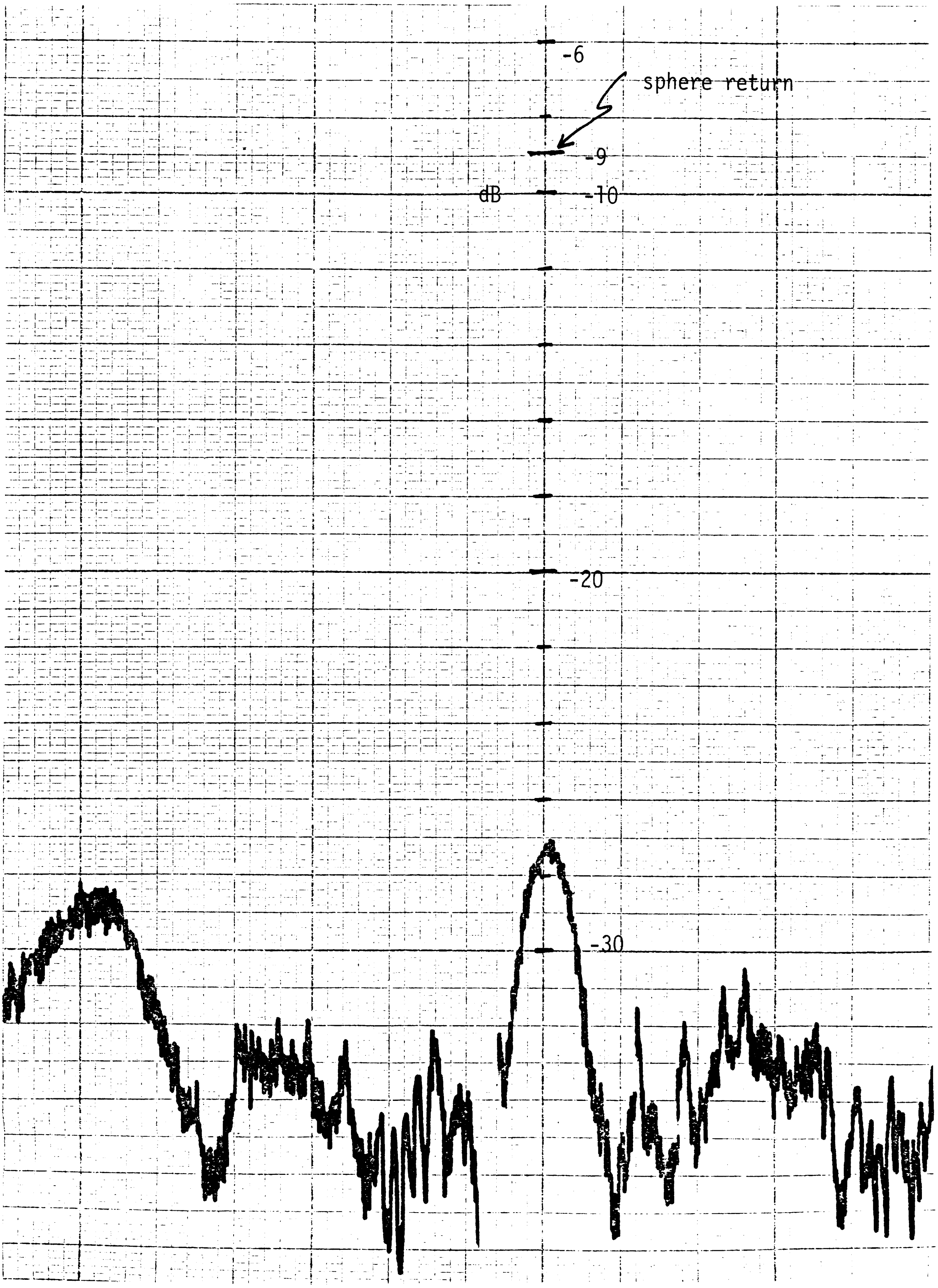


Fig. 6(b): Backscattering patterns of dual patch 2 at 8.5 GHz. Both patches terminated by a short circuit.

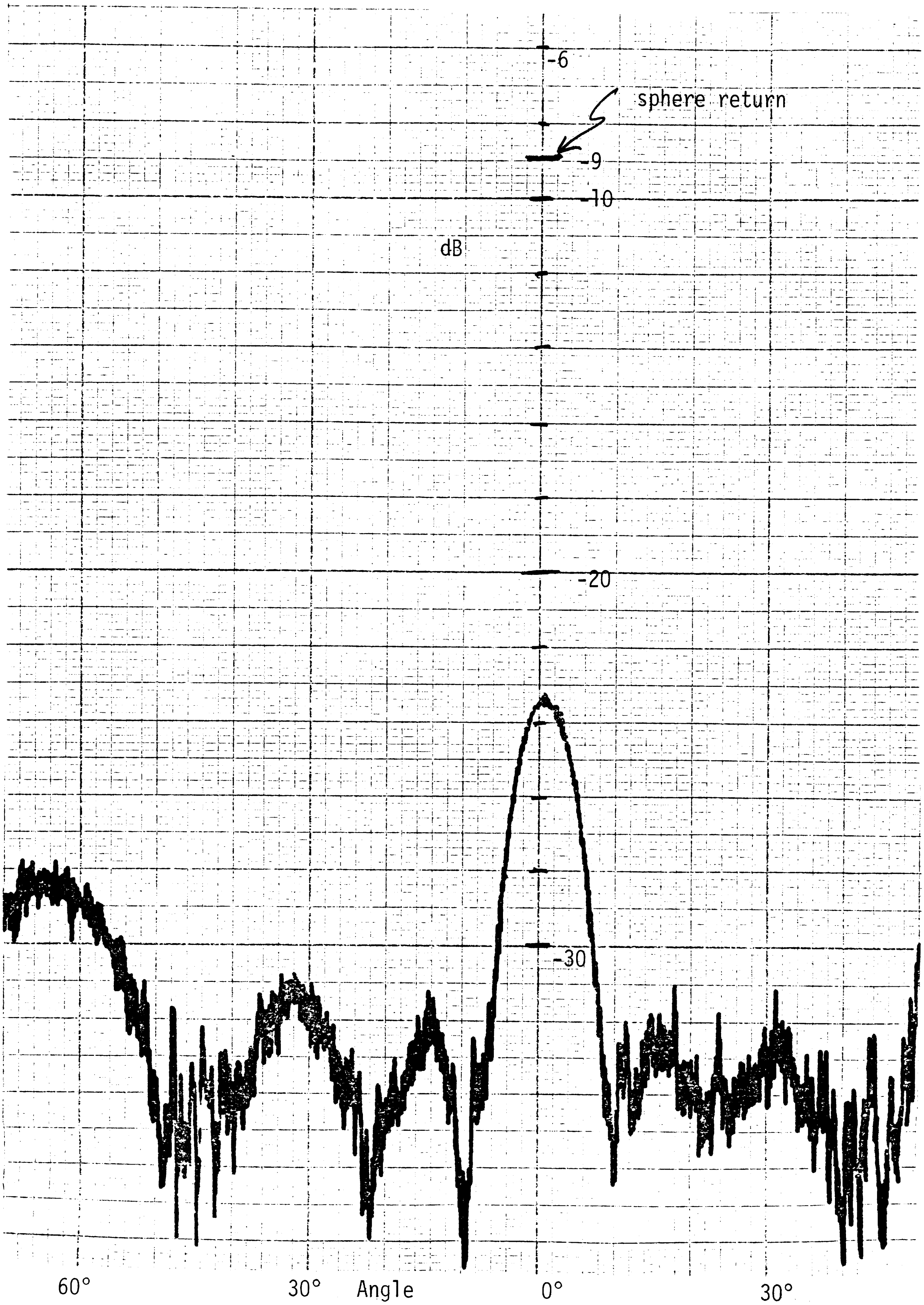


Fig. 6(c): Backscattering patterns of dual patch 2 at 8.5 GHz. Both patches terminated by 50 ohms.

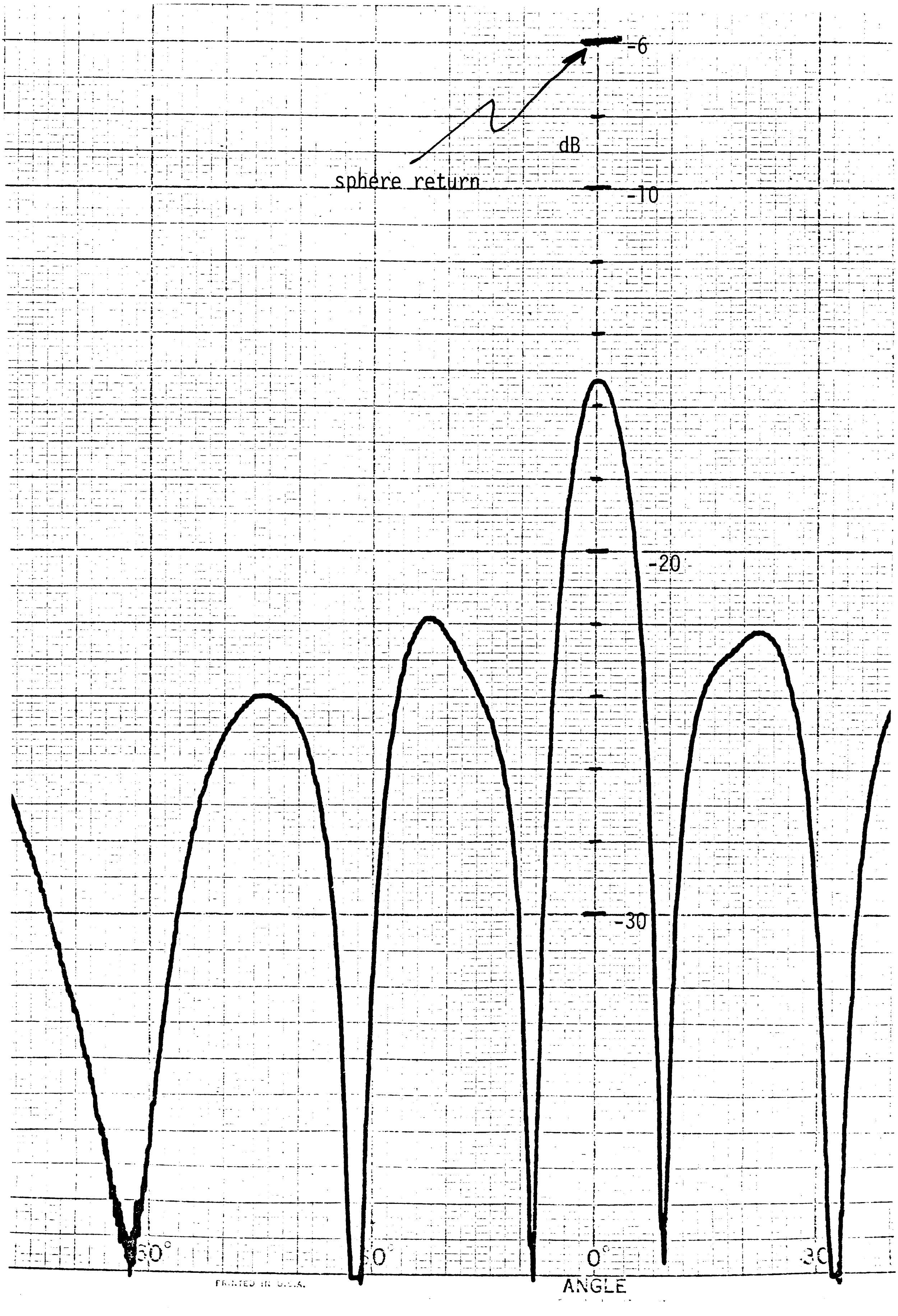


Fig. 7(a): Backscattering patterns of dual patch 2 at 9.9 GHz.

Both patches terminated by an open circuit.

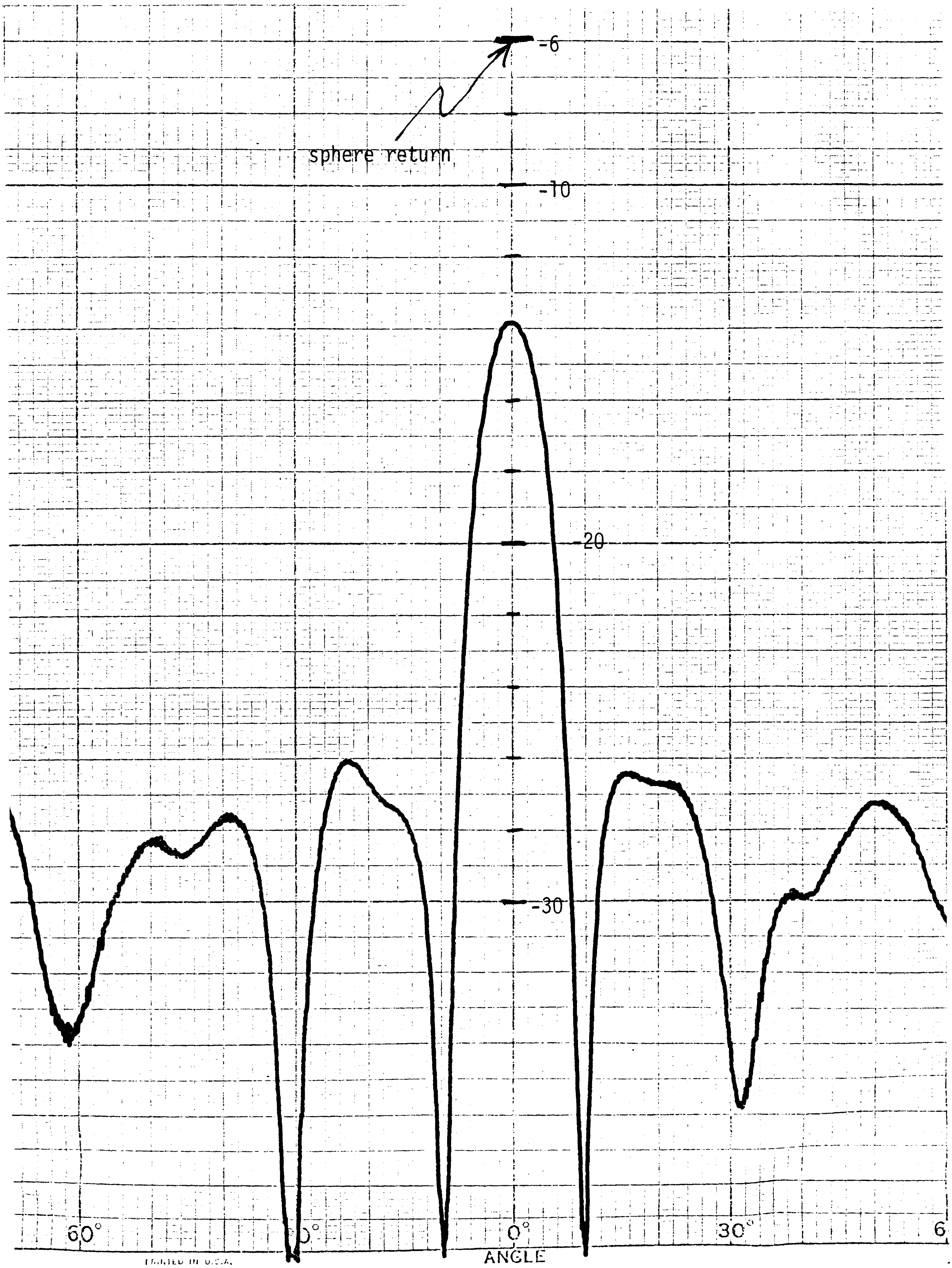


Fig. 7(b): Backscattering patterns of dual patch 2 at 9.9 GHz.

Both patches terminated by a short circuit.

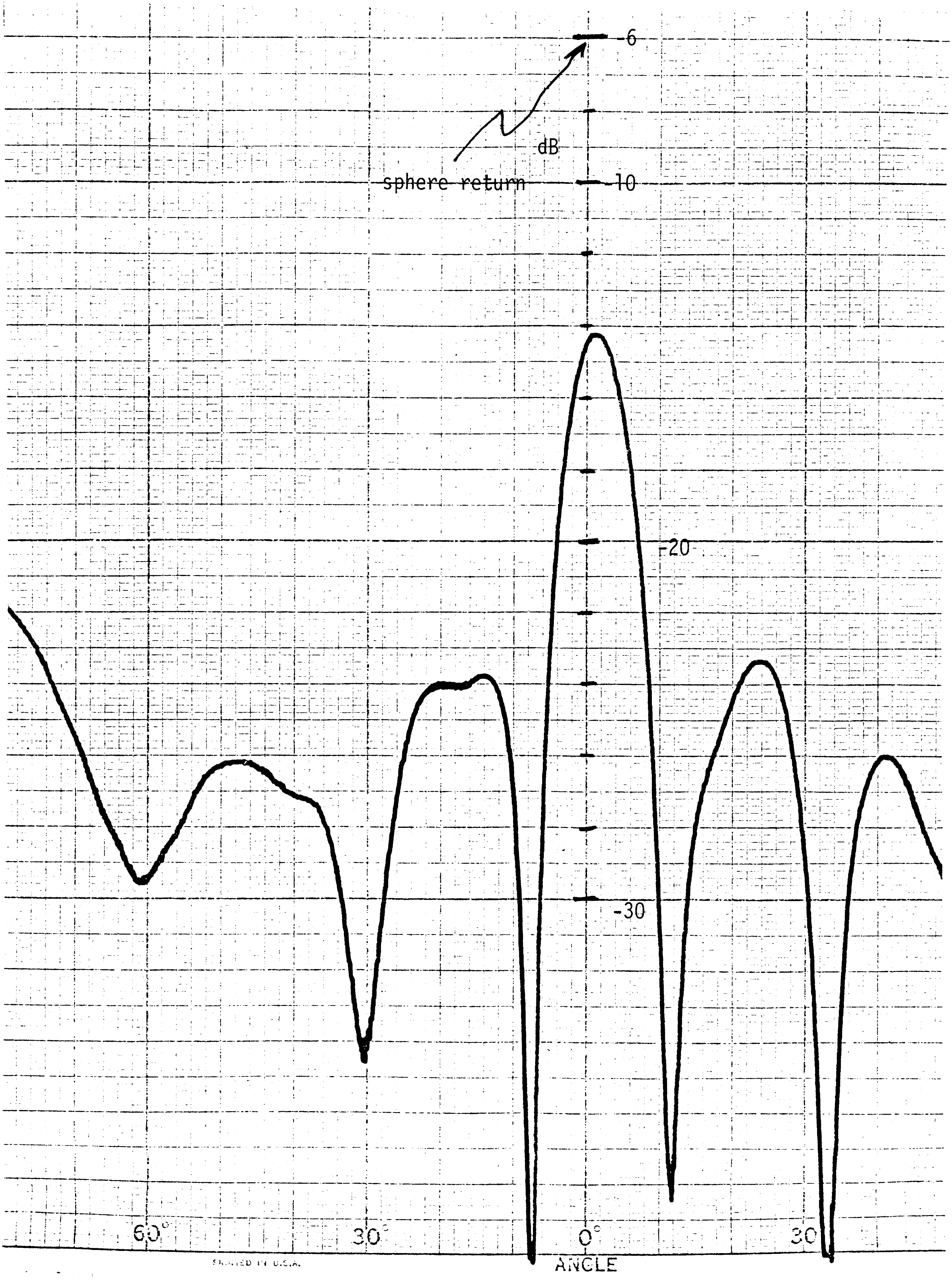


Fig. 7(c): Backscattering patterns of dual patch 2 at 9.9 GHz.
Both patches terminated by 50 ohms.

Table 2

Broadside Returns from the Double Patch 2

Condition	Return in dB Relative to the Sphere		
	8.5 GHz	9.0 GHz	9.9 GHz
Open	-14.8 dB	-14.4 dB	-9.2 dB
Short	-18.0 dB	-8.4 dB	-7.8 dB
Terminated	-14.0 dB	-12.0 dB	-8.2 dB

2.3 Discussion. The following general conclusions can be drawn from the backscattering characteristics of the patch antenna configurations discussed in the previous sections:

(i) At the resonant frequency the single patch antenna under short-circuit conditions produces a broadside return which is about 2.3 dB larger than that under the open-circuit condition.

(ii) The returns from the dual patch 1 are not appreciably affected by the terminating conditions of the patches; here, the scattering is mainly dominated by the large ground plane.

(iii) At the resonant frequency the dual patch 2 under short-circuit condition produces a broadside return which is about 6.0 dB larger than under open-circuit conditions; the broadside return under matched conditions is about 3.6 dB lower than the short-circuit case. Outside the resonant frequency, the scattering patterns tend to have larger returns in certain directions.

The most significant finding from the study is the 6.0 dB difference in the broadside returns under open and short circuit conditions obtained with the dual patch 2. Our limited study does not indicate whether larger difference in the returns may be obtained with similar configurations using more than two patches. However, the work does show that the reflecting properties of this type of structure can be controlled by varying the termination of the component patches. To bring out the full potentialities of the present array concept it is recommended that further experimental work be carried out to obtain the bistatic scattering characteristics of dual patch 2 type configurations using at least five patches. This would be of help for a theoretical analysis of the results described earlier and for the development of analytical models for similar surfaces containing a larger number of patches. It is appropriate to add that the suggested further work would also clarify certain aspects of the scattering behavior of antennas which are not presently well understood.

2.4 References

[1] D. L. Sengupta, "Resonant frequency of a tunable rectangular patch antenna," Elect. Letters, Vol. 20, No. 15, pp. 614-615, 19 July 1984.

[2] D. L. Sengupta, "Approximate expression for the resonant frequency of a rectangular patch antenna," Elect. Letters, Vol. 19, No. 20, pp. 834-835, 29 September 1983.

[3] I. J. Bahl and P. Bhartia, "Microstrip Antennas," Artech House, Dedham, MA, 1980.

3. The Application of Semiconductors

3.1 Literature Search. The objectives of the literature search were to determine what is known about electromagnetic reflection from semiconductor materials at microwave and millimeter wave frequencies, and to determine what configurations have been used to achieve some form of active control over the reflection properties of a surface. The task was performed by means of a computerized literature search, and a limited manual search. Included here are the results of the search to date, the strategies used, and suggestions for future work.

A computerized literature search was coordinated through the engineering library's Morita Holland, Shary Balius, and Margaret Bean. A description of this service, and some of the available data bases are included. In our search, we used the COMPENDEX, COMPREHENSIVE DISSERTATION INDEX, DROLS, INSPEC, and NASA/RECON data bases. Three separate search strategies were employed. These are:

1. (microwaves or millimeter waves) and (semiconductor or silicon or germanium or gallium arsenides).
2. (microwaves or millimeter waves) and (scattering) and (semiconductors).
3. (microwaves or millimeter waves) and (artificial dielectrics).

These are the basic forms of the strategies used. Minor modifications must be made to conform with the individual format of each data base. Of the three strategies, only the first was applied to all of the data bases. The other two were afterthoughts and were only used with the NASA/RECON data base, with only limited results, but it may be worthwhile to try these strategies on the other data bases.

It should be pointed out that computerized literature searches are far from foolproof, and are only as good as the strategies used. Since most searches look for keywords, even with very good strategies, some articles will be overlooked.

To supplement these computer efforts, recent issues of the IEEE Transactions on Microwave Theory and Techniques (June 1982 to October 1984) and Antennas and Propagation (January 1983 to September 1984) were scanned. This effort produced a number of interesting citations, and these have been presented along with the computer search results at the end of this memo.

The reference listings have been separated into three categories as follows:

A. literature considered most directly related to active control of reflection properties,

B. listings for other related references of a more general nature,

C. references related to the measurement of electrical properties of materials at microwave and millimeter wave frequencies.

The results of the search indicate that published work treating the active control of reflecting properties is very minimal. The first two citations in category A are the most directly applicable yet this work was performed about twenty years ago! On the other hand, several related articles have been located and the literature cited herein represents a good sampling of published work in technologies relevant to our subject.

The ideas presented in some articles may be easily extended to derive concepts for active control from a passive reflection problem. For example, reference A9 discusses a rectangular array of conducting pins embedded in a dielectric above a ground plane. A useful experiment may be to substitute pin diodes for the conductive pins, and add a means for biasing the diodes. A measurement of the reflecting properties of such a structure as the bias voltage is modulated may yield some interesting results.

As a final note, there has been significant work done in the determination of material parameters such as the complex refractive index of semiconductors at various frequencies. This information will be very important in making approximations of reflecting properties and the variations achievable from a given structure.

In summary, this search has revealed that work has been published on a variety of reflection problems, but only limited information seems to be available on reflection from semiconductors, and even less on active control ideas. On the other hand, this search was by no means exhaustive and further work is likely to be uncovered by additional computer and manual search efforts. Nonetheless, a substantial amount of related literature has been located and, at the least, establishes a firm base of information from which future research may be launched.

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WHAT A COMPUTER SEARCH CAN DO: The bibliographic search service may save time by:

- --retrieving citations which combine two or more concepts and manipulate search terms using Boolean operators.
- --searching for new words
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The search may provide a few relevant citations, an exhaustive bibliography or a periodic update of publications on specific topics.

WHO MAY USE THE SERVICE? UM faculty, students, and staff.

HOW LONG DOES IT TAKE? For quick reference searches requiring only a few citations, retrieval is immediate. Extended searches require a minimum of 24 hours preparation time after the search is submitted. If offline citation printouts are ordered an additional week is required to allow for printing, mailing (from California) and handling. Results will come to the library where they may be picked up and payment made.

HOW DO I APPLY? Information and search request forms are available at the Reference desks in the Engineering-Transportation and North Engineering Libraries. Submit completed forms to the Reference Librarian and a search time will be arranged. Searches are normally run while the patron is present.

COST: Most searches cost $10/database; usually 2 bases provide adequate coverage of a topic. Sample citations will be printed out at the time of the search. In addition, citations (title of the article, author's name, journal title, volume, data and page number, for example) printed offline are charged at approximately 10-15¢ each; citations with abstracts (summaries of the articles) cost approximately 20-30¢. PLEASE NOTE: complex searches requiring exceptional online time cost will be charged at the full cost (vendor charge, telecommunications and print costs.)

HOW DOES THE OUTPUT LOOK?

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File 8:COMPENDEX  - 70-82/Jan
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? S BUBBLE  (W) CAP?; S SIEVE (W) TRAY?; S DISTILLATION (W) COLUMN?
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               3    545 DISTILLATION (W) COLUMN?
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 MECHANICAL REQUIREMENTS FOR SIEVE AND VALUE TRAYS.  (ARTICLE TITLE)
 Kister, Henry Z.       (AUTHOR)
 ICI Aust. Ltd.   (AUTHOR AFFILIATION)
 Chem Eng. (New York)  v87 n23 Nov 17 1980 p283-285  CODEN: CHEEA3
 ISSN  0009-2460     (JOURNAL TITLE)
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SELECTED TECHNOLOGY DATA BASE PROFILES

(These are 18 of more than 200 available; ask about others)

ABI/INFORM (1971-) Covers all phases of business management and administration.

CA SEARCH (1967-) Corresponds to Chemical Abstracts.

CIS (1970-) Online version of the Congressional Information Service's Index to Publications of the United States Congress.

* COMPENDEX (1970-) Online version of Engineering Index. Coverage of 3500 journals, conference proceedings, and publications of engineering societies and organizations.

* COMPREHENSIVE DISSERTATION INDEX (1861-) A guide to all U.S. dissertations since 1861. Also includes many Canadian and foreign dissertations.

DOE/RECON Energy related information, water and environmental files primarily for reports from DOE contractors.

* DROLS Documents produced by defense contractors. Contains material back to the 1940's.

GRANTS (1977-) A source to more than 1500 grant programs available through government, commercial and private foundations.

ISMEC (1973-) Indexes articles in all aspects of mechanical engineering, production engineering and engineering management.

* INSPEC (1969-) Physics, electrotechnology, computers and control. Corresponds to Physics Abstracts, Electrical and Electronic Abstracts and Computer and Control Abstracts.

MANAGEMENT CONTENTS (1974-) Provides information in the areas of accounting, finance, decision sciences, operations research and marketing.

METADEX (1966-) Literature on the science and practice of metallurgy. Includes coverage from Alloys Index, Review of Metal Literature and Metals Abstracts.

MICROCOMPUTER INDEX (1980-) Articles, software, applications, reviews from 21 magazines such as InfoWorld, Byte and Dr. Dobb's.

* NASA/RECON For report literature from NASA contractors.

NIH-EPA CIS Information on toxic substances, properties, nomenclature, emergency spills and chemical structures.

NTIS (1964-) Government sponsored research & development relating to the hard and soft sciences.

PTS F&S INDEXES (1872-) Domestic and international company, product and industry information including sales forcasts, new products and market shares.

QL (QUICK LAW) CANADA Canadian legislative information and several water files of interest.

SIE CURRENT RESEARCH (last 2 years) Reports of government and privately funded scientific research projects either currently in progress or completed within the past 2 years.

REFERENCE LISTINGS

CATEGORY A: LITERATURE MOST RELAVENT TO STUDY

[A1] H. Jacobs, E. Horn, R. Hofar and G. Morris, "Angular Effects in a Millimeter Wave Semiconductor Interferometer," U.S. Army Electronics Command Rep. ECOM-2816 (AD-653646), Mar. 1967.
Comments: Investigated electromagnetic energy incident upon a layered system composed of air, semiconductor, air and metal reflectors. The reflection coefficient of the system was varied by modulating the conductivity of the semiconductor.

[A2] H. Jacobs and F. A. Brand, "The Interaction of Electromagnetic Radiation and Semiconductors," U. S. Army Research Office, (AD-286638), Dec. 1962.
Comments: Formulates equations for the interaction of electromagnetic radiation and semiconductors. Measured results for the fundamental properties of semiconductors using microwave techniques.

[A3] T-C. Chen, T-P. Ma, R. C. Barker, "Infrared Transparent and Electrically Conductive Thin Film of In/Sub 2/O/Sub 3/", *Appl. Phys. Lett.*, Vol. 43, No. 10, 901-3, 15 Nov. 1983.
Comments: Reference to Antireflection Coatings, Multiple Reflectors, and Electronic Conduction in Crystalline Semiconductor Thin Films.

[A4] "Investigation of Microwave Artificial Dielectrics with Controllable Index of Refraction," General Electric Co. Rep. R62ELC6 (AD-273066), Jan. 1962.
Comments: Discusses feasibility of photocontrolling an artifical dielectric consisting of semiconductor capacitive junctions.

[A5] R. W. Lothrop, "Microwave Properties of Germanium and Silicon Windows", Naval Weapons Lab, Rep. NWL-TR-2815 (AD-753466), Sep. 1972.

Comments: Theoretical analysis and on-the-bench tests related to determining the required doping levels for germanium and silicon to produce infrared windows with large attenuations to microwave energy.

[A6] J. H. Wang, "Characteristics of a New Class of Diode-switched Antenna Phase Shifter," *IEEE Trans. Antennas Propagat.*, Vol. AP-31, No. 1, pp. 156-159, Jan. 1983.

Comments: Some mention of application as a reflecting element. Switching the terminating impedance of a multiarm spiral leads to scattering pattern variations; however, the effectiveness of antenna for this application is not broadband.

[A7] R. J. King, D. V. Thiel and K. S. Park, "The Synthesis of Surface Reactance Using and Artificial Dielectric," *IEEE Trans. Antennas, Propagat.*, Vol. AP-31, No. 3, pp. 471-475, May 1983.

Comments: Theoretical and experimental treatment of a rectangular array of conducting pins embedded in a thin dielectric layer above a ground plane. Surface reactance may be synthesized to be independent of the angle of incidence for plane waves.

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3.2 Conceptual Design of Experiments Employing PIN Diodes. This section describes a series of six experiments designed to make use of commercially available PIN diodes in demonstrating that semiconductor junctions may be used to achieve active control over the backscattering of a body. The objective here was to investigate the extent to which the backscattering of a sectioned conducting structure can be altered by forward biasing PIN diodes used to connect the sections. The structures which are suggested range from a simple thin wire in air to a planar arrangement of rectangular conducting strips.

It should be noted that PIN diodes were selected because of their desirable switching properties and their wide availability. Ultimately it may be desirable to develop a customized device, or wafer specifically suited for use as a controllable scattering element.

It is recommended that the experiments that follow be considered for further analysis and that some or all of the ideas presented here be implemented in an actual experiment to be carried out in the laboratory. Practical considerations and other details of the experiments will be examined later.

Description of Experiments

The following discussion concerns six different scattering structures. Methods for making cw backscattering measurements are well understood. As suggested by Fig. 8, a styrofoam pedestal will be used to support the body under test. Single frequency measurements of the backscatter from the body will be made as the body is rotated, resulting in a plot of the backscattered amplitude versus angle of incidence.

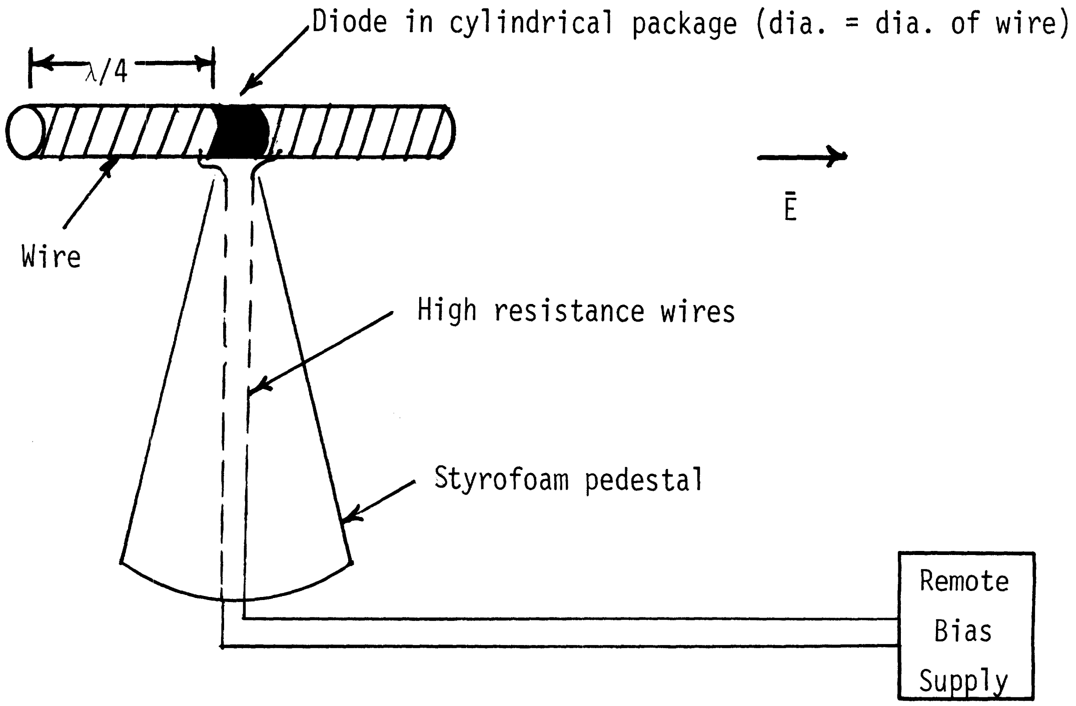

Fig. 8: Active control of scattering from a thin wire.

In the first experiment (Fig. 8), a thin half-wavelength wire is divided in two by a diode. When the diode is forward biased (or "on"), the surface current will resonate in the presence of an incident field. This should yield a relatively large amplitude backscatter over a wide range of angles. Reverse biasing the diodes, will interrupt this resonance condition, causing a significant reduction in the backscattering amplitude, particularly at frequencies for which the entire structure is close to resonance.

The next experiment (Fig. 9) represents the first step in evolving towards a planar structure. The same principle of experiment A is now applied to a rectangular conducting strip mounted on a piece of dielectric, cut to the dimensions of the strip. The dielectric backing is needed for mechanical rigidity, and to facilitate the mounting of the diode. It is desired that the backing material have as low a dielectric constant as possible, to prevent the scattering from the board from masking the desired results.

The third experiment (Fig. 10) is designed to investigate the effect on the scattering of the rectangular dielectric board used in the above two experiments. A comparison of the results from experiments B and C should indicate the magnitude of this effect.

The fourth experiment (Fig. 11) should demonstrate that by effecting a change over a larger area, the difference in the backscattering amplitude achieved with the two diode states can be increased.

The next experiment (Fig.12) represents the limiting case of the array of conducting strips shown in Fig. 11, as the number of strips

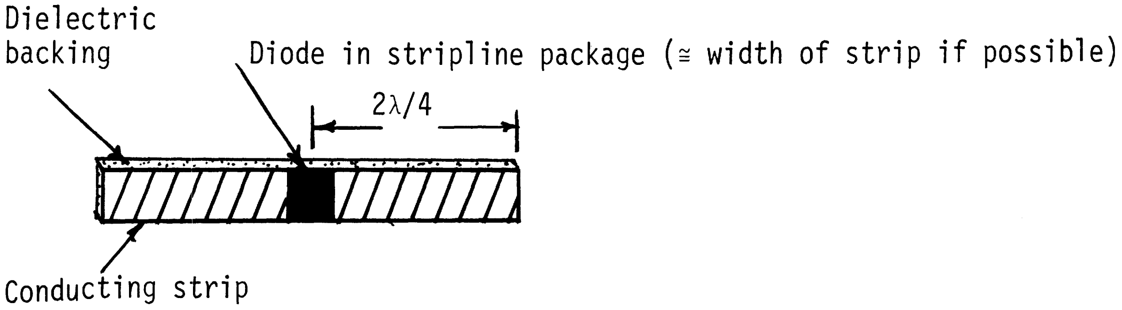

Fig. 9: Active control of scattering from a thin rectangular strip.

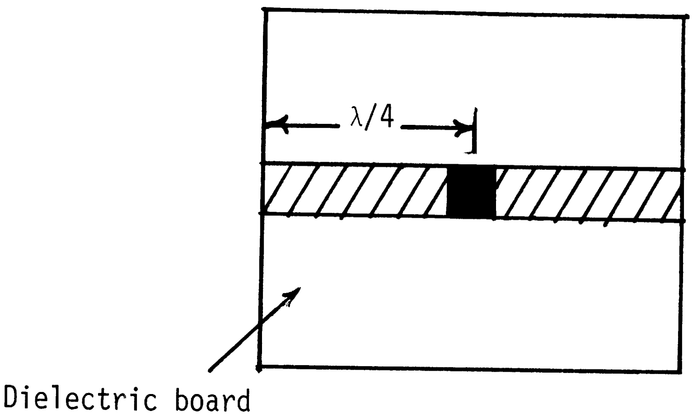

Fig. 10: Active control of scattering from thin strip on rectangular dielectric board.

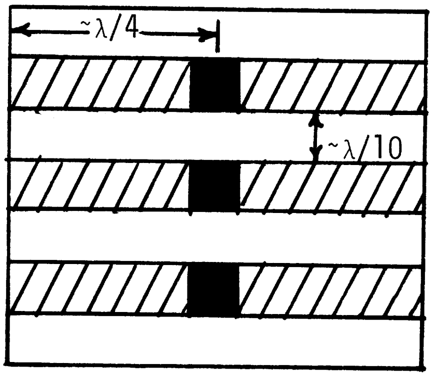

Fig. 11: Active control of scattering from periodic array of strips.

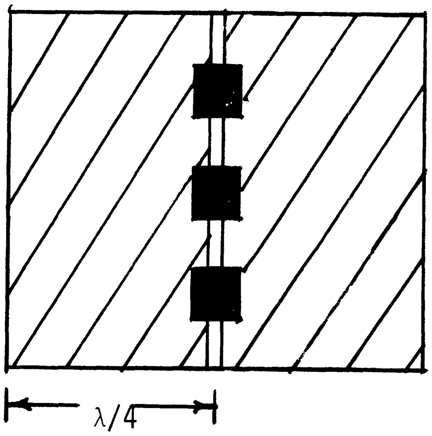

Fig. 12: Active control of scattering from a conducting sheet.

increases and their spacing decreases. The number of diodes should not be too important as long as their spacing is small compared to a wavelength. One problem with this structure is the appreciable capacitance expected across the small gap needed to accommodate the diodes. Depending on the measurement frequency, this could shunt out the effect of the diodes.

The last experiment (Fig. 13) is presented merely to suggest a simple extension of the previous experiments that represents a step towards an array of controllable scattering elements. In concept, if a biasing scheme were used that allowed for each diode to be biased independently, the backscattering pattern could be altered to take on several different characteristics depending on the bias states of the various diodes.

Another extension of the above experiments is to increase the measurement frequency, and perform the same measurements. As indicated in the sketches each of the structures discussed is intended to be about one half wavelength in length at the measurement frequency (with the diodes "on"). It may be worthwhile to make backscattering measurements of the scattering characteristics at higher frequencies also, where the structures are now a few wavelengths in length. In this case, the change incurred (between the diode states) for near glancing angles should be most interesting. It is expected that the position of the lobes in the backscattering pattern will then change significantly. In contrast, for larger wavelengths, the main lobe is so wide that the amplitude change of the lobe should dominate.

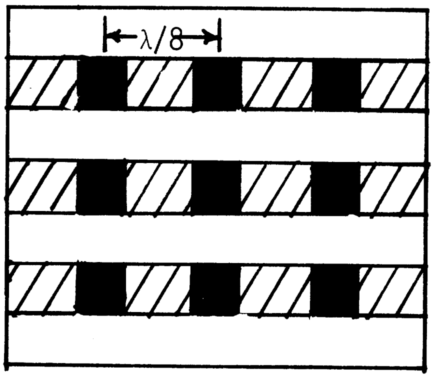

Fig. 13: Active control of scattering from periodic array of strips with multiple diode arrangements.

4. Effect on Impedance Discontinuities on Traveling Waves

Traveling waves are one of the most important contributors to the scattering from long slender bodies, and in the case of structures such as the fuselage of an aircraft it is possible to produce a reasonably complete description of the backscattering by taking into account the traveling waves and, where appropriate, the specular contributions and the side lobes thereof. When the incident magnetic vector is perpendicular to the plane formed by the direction of incidence and the axis of the body, the fan-shaped pattern characteristic of a traveling wave is a key feature of the overall scattering, and the first lobe is often the major contributor to the scattering at angles close to end-on incidence.

The scattering pattern of a thin plate or ribbon also displays a similar lobe structure at angles close to edge-on incidence when the magnetic vector is parallel to the surface, and it is customary to attribute at least the first lobe to a traveling wave. In effect, we are thinking of each narrow slice of the plate or ribbon as a strip or wire supporting a traveling wave and as shown by Senior (1984), this argument can be justified. In studying traveling waves it is therefore sufficient to consider the single two-dimensional problem of an H-polarized plane wave incident on a strip or ribbon, and this is often used as a model of an aircraft wing.

For an infinitesimally thin perfectly conducting strip illuminated at edge-on incidence in a plane perpendicular to the generators of the strip, the backscattered field with H-polarization is zero, but as the angle of incidence increases, a traveling wave lobe appears. The angle at which the maximum of the lobe occurs is

$$\theta = 49.4\sqrt{\frac{\lambda}{w}} \quad \text{(degrees)}$$

where λ is the wavelength and w is the width of the strip, and corresponds to the reflection of the (surface) traveling wave at the rear edge of the strip. If we could cause this reflection to occur at some position short of the rear edge, the traveling wave lobe would be shifted in angle, and this might from the basis for some method of cross section control. As an example, if $w = 5\lambda$ the maximum of the lobe occurs at $\theta = 22$ degrees, whereas if $w = 2.5\ \lambda$ the maximum is at $\theta = 31$ degrees. Thus, by cutting a strip in two by means of a central slot whose impedance could be controlled, we might hope to displace the lobe by as much as 9 degrees. One method for achieving the control could be with PIN diodes as discussed in Section 2.2, and since the extreme impedances correspond to the short-circuit and open-circuit conditions, we limited our attention to these.

To test the method we used the computer program REST-H which computes the bistatic and backscattered far field as well as the currents for an H-polarized plane wave incident on a strip. We first tried the case of a perfectly conducting strip 3λ in width with and without a 0.1λ gap that breaks up the strip into 2λ and 0.9λ sections. To our surprise the backscattering patterns showed no detectable shift in the traveling wave lobe, and the only differences produced by the gap were changes of about 2 dB in the amplitude of the lobe and the adjacent returns. At angles near normal incidence in the strip, there were virtually no changes at all in the pattern, as expected.

From an examination of the currents induced on the strip it appears that if the two sections into which the strip is broken are roughly integer multiples of $\lambda/2$ the gap has relatively little effect on the overall current distribution, and, in particular, the phase (on which the lobe position primarily depends) is almost unaffected. We therefore chose a strip 3.25λ in width and repeated the experiment using a gap 0.1λ wide dividing the strip into 2.0λ and 1.15λ sections. The results are shown in Fig. 14, and we observe that with the gap present, i.e., open-circuited, the lobe maximum is shifted from 27 to 34 degrees. For a range of incidence angles out to (about) 17 degrees from edge-on, the shift decreases the return by about 10 dB; at $\theta \cong 28$ degrees the returns are almost the same, and for the next 30 degrees or so the gap has led to a somewhat larger return.

From these (and other) examples that have been studied, it appears that under the right conditions, a "cutting" of the strip can shift the position of the traveling wave lobe and thereby control the scattering, but the process is frequency sensitive. If the portion cut off is almost anti-resonant (i.e., 0.75λ, 1.25λ,...) in width, the shift in the traveling wave lobe occurs as predicted, but when it is of resonant width, there is little or no shift. A more pronounced and frequency independent effect is observed if the original strip is loaded so as to suppress the traveling wave lobe. This could be done by means of a resistive or impedance taper close to the rear edge, starting at zero a wavelength or so ahead of the rear edge and rising to (say) 1000 ohms at the edge itself. Such a load reduces by 20 dB or more the traveling wave lobe which would otherwise occur,

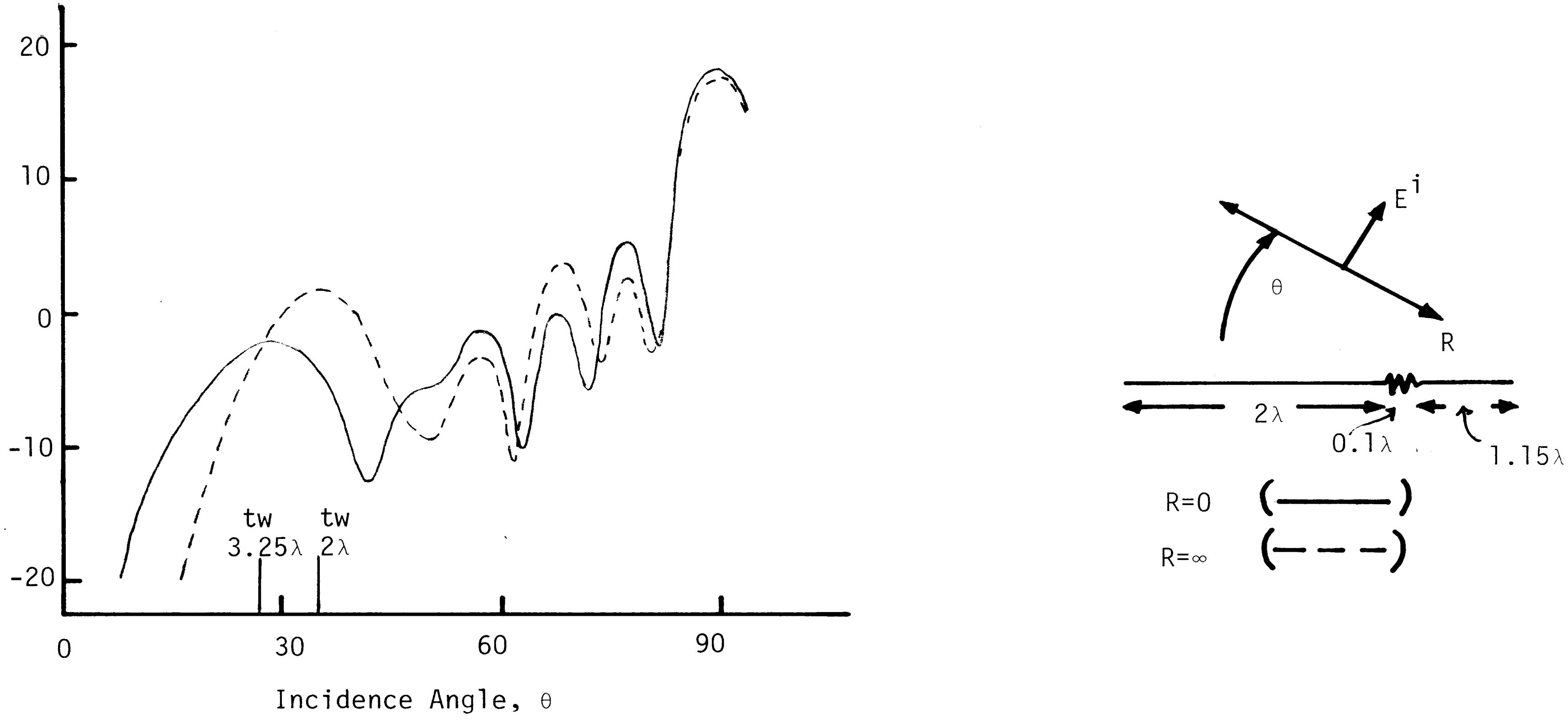

Fig. 14: Backscattering from solid and gapped strips.

and if a gap were now introduced just in front of the load, the resulting reflection should nullify the effect of the taper. Although this has not been examined in detail, it would be possible to do so using the computer codes which are available.

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