

REVISION NO.

DATE 10/4/82

~~XSCN004~~Lab ECSL/EED

Research Communications (2)
Project File
Other _____
Other _____

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEETDate November 4, 1983Project No. A-3370 ~~School~~ Lab ECSL/EED

Includes Subproject No.(s) _____

Project Director(s) Dr. James A. Fuller GTRI / ~~GTRI~~Sponsor CND IncorporatedTitle Development of Dual IR/MM-Wave Aperture AntennaEffective Completion Date: 7/29/83 (Performance) 7/29/83 (Reports)

Grant/Contract Closeout Actions Remaining:

- ☐ None
- ☒ Final Invoice ~~and Final Project Report~~
- ☐ Closing Documents
- ☐ Final Report of Inventions
- ☐ Govt. Property Inventory & Related Certificate
- ☐ Classified Material Certificate
- ☐ Other _____

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A-3370



ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
A Unit of the University System of Georgia
Atlanta, Georgia 30332

22 November 1982

CVD, Incorporated
35 Industrial Parkway
Woburn, Massachusetts 01801

Attention: Dr. Raymond L. Taylor
Vice President, Research and Engineering

Reference: CVD Subcontract No. 0203
"Development of Dual IR/MM-Wave Aperture Antenna"
Georgia Tech Project A-3370

Subject: Monthly Progress Report No. 1
October 1982

Gentlemen:

Introduction. This first Monthly Progress Report covers the period from contract initiation, 30 September, through 31 October. CVD, Inc., awarded this antenna development project to the Georgia Tech Engineering Experiment Station (EES) as a subcontract under Prime Contract No. P. O. CH6411, Ch.1, with the Boeing Aerospace Company. The work is being performed in the Electromagnetic Effectiveness Division (EMED) of the Electronics and Computer Systems Laboratory (ECSL), which is one of eight laboratories that form the EES. Mr. Fred L. Cain is Director of ECSL, and Dr. Charles E. Ryan, Jr., is Chief of EMED. The Project Director, Dr. James A. Fuller, has primary responsibility for performance under this contract. Dr. Fuller will be directly assisted in technical efforts by Mr. Thomas S. Taylor. Telephone numbers for these individuals are provided below:

Fred Cain	(404) 894-3542
Chuck Ryan	(404) 894-3597
Jim Fuller	(404) 894-3322
Tom Taylor	(404) 894-3271

Status. Dr. Ray Taylor visited Georgia Tech on 1 October to discuss initiation of the contract. It was agreed that the initial effort at Georgia Tech should be concentrated (1) on development of a waveguide-to-microstrip (WG/MS) transmission-line transition and (2) on the measurement of dielectric properties of CVD ZnSe.

Dimensions for dielectric samples to fit in U-band (WR-19) waveguide and a piece of waveguide (a U-band horn) were provided to Dr. Taylor for use in sample preparation. (Through our error, outside, rather than inside, dimensions of the waveguide were provided, so the first samples obtained were too large.) The samples will be tested in a resonant cavity formed by a shorted section of U-band waveguide.

The WG/MS transition is being developed at X-band (8-12 GHz), using a section of single-ridged waveguide with a tapered ridge as an intermediate stage. To make this transition, an axial slot is milled in the center of the broad wall (H-plane) of the rectangular waveguide. The ridge is formed by a metallic vane that is inserted through the slot in such a way as to taper from the H-plane wall of the waveguide to the exposed microstrip line on the dielectric substrate. Parameters that affect the reflection are the length and taper in the transition region, the width of the ridge, and the extension of the ridge beyond the end of the waveguide. For the preliminary work, a 50 Ohm microstrip line has been formed on a teflon-fiberglass substrate. The final design must be developed on a CVD ZnSe substrate, which will be provided by CVD, Inc. In the meantime, CVD, Inc., is developing the process for metallizing substrates.

Problems. No unusual problems were encountered during this reporting period.

Plans. During November, development of the WG/MS will continue. Recently procured U-band instrumentation will be assembled and checked; and dielectric measurements will be started, when samples are available.

Respectfully submitted,

James A. Fuller
Project Director

Approved:

Charles E. Ryan, Jr.
Chief,
EM Effectiveness Division

ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
A Unit of the University System of Georgia
Atlanta, Georgia 30332

13 December 1982

CVD, Incorporated
35 Industrial Parkway
Woburn, Massachusetts 01801

Attention: Dr. Raymond L. Taylor
Vice President, Research and Engineering

Reference: CVD Subcontract No. 0203
"Development of Dual IR/MM-Wave Aperture Antenna"
Georgia Tech Project A-3370

Subject: Monthly Progress Report No. 2
November 1982

Gentlemen:

Status. During November, the following tasks were addressed:

- * Development of a waveguide-to-microstrip (WG/MS) transition.
- * Measurement of dielectric properties of ZuSe.
- * Participation in a program review at CVD, Inc.

Development of the WG/MS transition began with some experiments that were conducted using X-band (8 to 12 GHz) waveguide (WR-90) and a microstrip transmission line formed on a "Polyguide" substrate. The waveguide has interior dimensions $A = 0.900$ in. and $B = 0.400$ in. The microstrip substrate has a dielectric constant of $K = 2.32$ and a thickness $T = 0.062$ in. The WG/MS transition is made by inserting a ridge, or vane, through the top wall (H-plane wall) of the waveguide, as shown in Figure 1. As the insertion depth of the ridge increases, the cutoff frequency and the impedance of the waveguide decrease; also, the electric field in the ridge-loaded waveguide is concentrated under the ridge. Therefore, a tapered ridge provides a gradual transition from high impedance waveguide to low impedance microstrip line, where reflection and radiation can be minimized. Figure 2 shows the return loss (i.e., magnitude of the reflection coefficient), measured as a function of frequency, for one preliminary experimental configuration. In this case, the ridge width is $W_R = 0.125$ in., and the microstrip line width is $W = 0.085$ in. The

impedance of this microstrip line is about 80 Ohms. The ridge taper was a smooth "S-shaped" curve that was ground by hand on a sander. (The contour shown in Figure 1 is a tracing of the ridge.) This design provides a 15 dB return loss over a band near 10 GHz, but we want to achieve a 20 dB return loss ($VSWR = 1.22$) for the transition to be used on this program.

To optimize the design, the experimental work is being supplemented by calculations that describe the reflection coefficients of non-uniform (tapered) transmission lines. The theory for such lines is well-known (e.g., R. C. Johnson, "Design of Linear Double Tapers in Rectangular Waveguides," IEEE Trans. Microwave Th. and Tech., Vol. 7, July 1959, pp. 374-378), and the Project Director has previously developed computer codes to perform these calculations for non-uniform ridged waveguide. The object of the calculations is to determine the width, length, and shape of the ridge to minimize reflections at the microstrip junction.

We had an opportunity to obtain dielectric measurements on a piece of ZnSe of unknown origin. The measurements were made at 93.860 GHz in a Fabry-Perot interferometer, by personnel in the Electromagnetics Laboratory at the Georgia Tech EES. The result was a dielectric constant $K = 9.10$, and a loss tangent $\tan \delta = 0.001$. It is possible that this loss tangent represents the noise level of the system. We have recently received from CVD, Inc., six slabs of CVD ZnSe, and we plan to obtain the same type of data on the new material. We will also measure dielectric properties at 45 GHz in a waveguide cavity, when the machined samples are available.

Problems. During assembly of recently procured U-band instrumentation, we concluded that the multiplier was damaged, and we returned it to the vendor. We do not yet require a U-band source, but a long turn-around time on this item could delay this program. At this time, we do not expect this to be a problem.

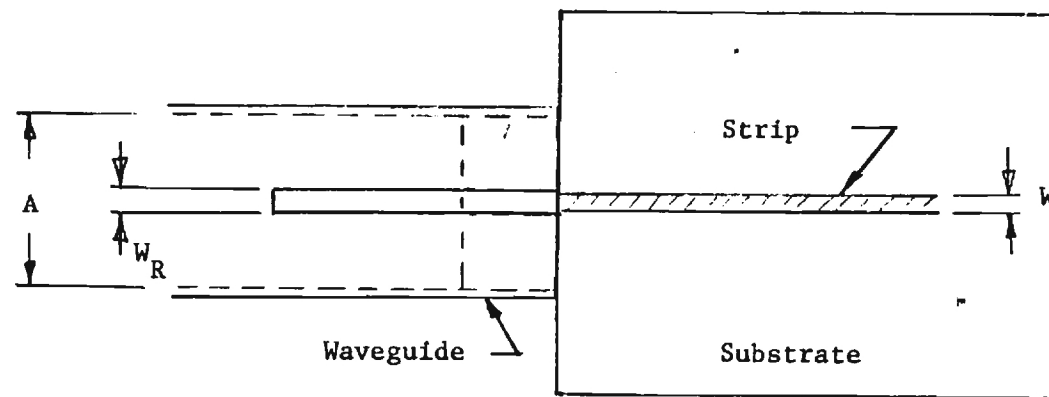
Plans. During December, development of the WG/MS transition will continue.

Respectfully submitted,

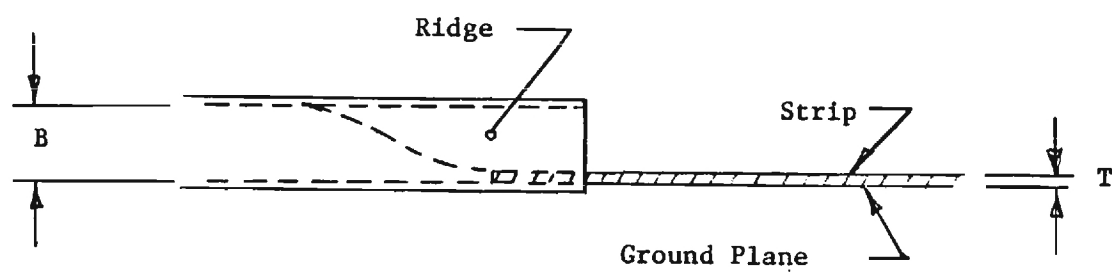
James A. Fuller
Project Director

Approved:

Charles E. Ryan, Jr. /
Chief,
EM Effectiveness Division



(a) Top View



(b) Side View

Figure 1. Sketch of waveguide-to-microstrip transition.

WAVEGUIDE TRANSITION TO MICROSTRIP

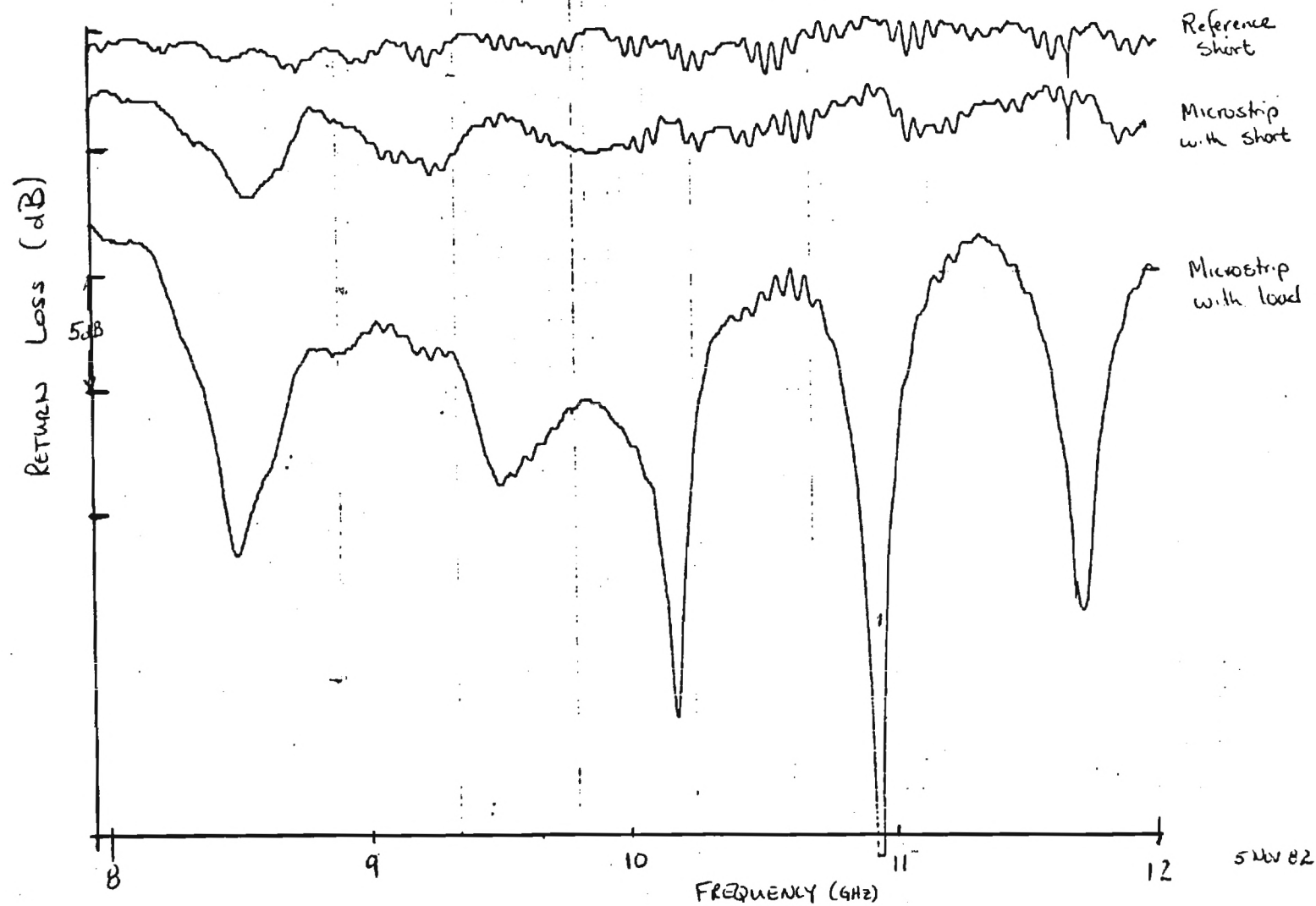


Figure 2. Return loss for a preliminary waveguide-to-microstrip transition.



Georgia Institute of Technology

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

15 January 1983

CVD, Incorporated
35 Industrial Parkway
Woburn, Massachusetts 01801

Attention: Dr. Raymond L. Taylor
Vice President, Research and Engineering

Reference: CVD Subcontract No. 0203
"Development of Dual IR/MM-Wave Aperture Antenna"
Georgia Tech Project A-3370

Subject: Monthly Progress Report No. 3
December 1982

Gentlemen:

Status. During December, the following tasks were addressed:

- * Development of a waveguide-to-microstrip (WG/MS) transition.
- * Check-out of the millimeter-wave network analyzer for dielectric measurements.

To guide the WG/MS transition development, an analytical model is being used to calculate the reflection coefficient for a non-uniform ridged waveguide section, where a tapered ridge is used as an impedance transformer between rectangular waveguide and a microstrip transmission line. The first calculations completed were for linear and for exponential variations in the height of the ridge, because the computer code was originally developed for those types of transitions. The code was then modified to allow for a sinusoidal ridge profile. This provides a transition without discontinuities in the slope of the ridge profile, which can improve the impedance transformation and, in some cases, inhibit the excitation of higher-order waveguide modes. The calculated results indicate that the reflection coefficient for the transition can be reduced below -20 dB over at least half of the waveguide band.

A millimeter-wave automatic network analyzer is being configured to support this and other programs at Georgia Tech. In December, the system became operational in some waveguide bands, and as a check-out exercise, we took measurements to determine the dielectric constant (K) of a plastic

Monthly Progress Report No. 3
CVD Subcontract No. 0203
15 January 1983
Page 2

material (Rexolite 1422) at Ka-band. The result, $K = 2.51$, is consistent with the value, $K = 2.53$, which is published as the dielectric constant at X-band. Six samples of zinc selenide, cut to fit U-band waveguide, were received from CVD, Inc., in December. However, the U-band source for the analyzer system is being repaired. We expect it to become available in January, and we will proceed with the dielectric measurements.

Problems. No unusual problems were encountered during this reporting period.

Plans. During January, we plan to fabricate an X-band (i.e., frequency-scaled) version of the WG/MS transition, with a microstrip substrate that has a suitably high dielectric constant (either 3M Epsilam-10 or CVD-ZnSe). We also plan to complete dielectric measurements with the ZnSe samples.

Respectfully submitted,

James A. Fuller
Project Director

Approved:

Charles E. Ryan, Jr.
Chief,
EM Effectiveness Division

ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
A Unit of the University System of Georgia
Atlanta, Georgia 30332



15 February 1983

CVD, Incorporated
35 Industrial Parkway
Woburn, Massachusetts 01801

Attention: Dr. Raymond L. Taylor
Vice President, Research and Engineering

Reference: CVD Subcontract No. 0203
"Development of Dual IR/MM-Wave Aperture Antenna"
Georgia Tech Project A-3370

Subject: Monthly Progress Report No. 4
January 1983

Gentlemen:

Status. During January,, the following tasks were addressed:

- * Dielectric measurements for CVD ZnSe.
- * Development of a (WG/MS) transition.
- * Development of a resonant column array at X-band.

Six ZnSe samples were supplied by CVD, Inc. These were supplied in pairs with three different lengths and with cross-sections ground to fit tightly inside U-band waveguide. Because air-gaps between the sample and waveguide are inevitable and are a potential source of measurement error, Georgia Tech gold-plated five sides of one set of (three) samples. (This procedure was recommended by Dr. R. Heeren of Boeing.) Dielectric properties are calculated from the measured reflection coefficient of a sample placed in a short-circuited waveguide. Preliminary results for six measurements of the plated samples indicate a dielectric constant of $K = 8.0$ or $K = 10.9$. We believe that the $K = 10.9$ value is probably correct, and the $K = 8.0$ value occurs when there is a gap between the plated side of the sample and the side of the waveguide. We plan to make additional measurements with samples cut to fit in circular waveguide. The circular samples can be fit more accurately; also, we are equipped to utilize a resonant cavity approach for such samples, and the resonance method will yield a better measurement of the loss properties of the low-loss ZnSe. A sketch of the desired samples is attached.

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CVD Subcontract No. 0203
15 Febraury 1983
Page 2

A very successful waveguide-to-microstrip (WG/MS) transition was demonstrated at X-band. The transition is based on a three-inch long ridge that has a cosine-shaped taper in ridge height. This design provides a -20 dB reflection over a 25 percent bandwidth, which is entirely adequate.

By experimental trial and error, a resonant column of five microstrip elements was developed sufficiently to demonstrate that the concept of interest can be expected to work. The design was implemented with plastic substrates (i.e., 3M K-6098 teflon/glass and polycarbonate), which have dielectric constants of about $K = 2.3$.

The U-band multiplier that was previously reported deffective has been repaired. In addition, its operation has been substantially improved by the replacement of the original silicon diode with a Georgia Tech gallium arsenide diode.

Problems. No unusual problems were encountered during this reporting period.

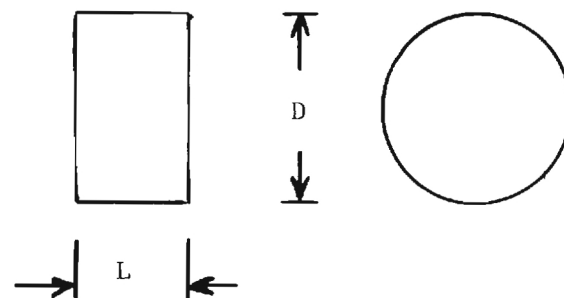
Plans. During February, work on the X-band resonant column will continue. A microwave network analyzer must be used to characterize the resonant conductance of the individual radiating element as a function of element size and offset from the transmission feedline. A more precisely fabricated version of the WG/MS transition will be made in the machine shop, and it will be mated with a microstrip transmission line to be formed by gold-plating a 0.050-inch thick slab of CVD-ZnSe. A program review at Georgia Tech was scheduled for 7 February.

Respectfully submitted,

James A. Fuller
Project Director

Approved:

Charles E. Ryan, Jr.
Chief,
EM Effectiveness Division



ZnSe Sample Dimensions
For
Dielectric Measurements

<u>Band</u>	<u>Material</u>	<u>D(in.)</u>	<u>L(in.)</u>
Ka	ZnSe	.2840 $\begin{smallmatrix} +.0000 \\ -.0005 \end{smallmatrix}$	.109 $\begin{smallmatrix} + \\ -.001 \end{smallmatrix}$
Ka	ZnSe	.2840 $\begin{smallmatrix} +.0000 \\ -.0005 \end{smallmatrix}$	.182 $\begin{smallmatrix} + \\ -.001 \end{smallmatrix}$
U	ZnSe	.1890 $\begin{smallmatrix} +.0000 \\ -.0005 \end{smallmatrix}$	.065 $\begin{smallmatrix} + \\ -.001 \end{smallmatrix}$
U	ZnSe	.1890 $\begin{smallmatrix} +.0000 \\ -.0005 \end{smallmatrix}$	.108 $\begin{smallmatrix} + \\ -.001 \end{smallmatrix}$



ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
A Unit of the University System of Georgia
Atlanta, Georgia 30332

14 March 1983

CVD, Incorporated
35 Industrial Parkway
Woburn, Massachusetts 01801

Attention: Dr. Raymond L. Taylor
Vice President, Research and Engineering

Reference: CVD Subcontract No. 0203
"Development of Dual IR/MM-Wave Aperture Antenna"
Georgia Tech Project A-3370

Subject: Monthly Progress Report No. 5
February 1983

Gentlemen:

Status. During February, the following tasks were addressed:

- * Dielectric measurements for CVD ZnSe.
- * Development of a waveguide-to-microstrip (WG/MS) transition.

Dr. Ron Bohlander and an assistant asked for an opportunity to re-measure the CVD ZnSe slabs in their 94 GHz Fabry-Perot interferometer, because they were not satisfied with a previous attempt. Their final results are presented in an attached memo.

Shop drawings were prepared, and an X-band version of a WG/MS transition was fabricated in the machine shop. This unit is designed to interface with a microstrip line deposited on a slab of CVD ZnSe. The line deposition is in progress, and the configuration should be ready for tests in the near future. Several radiating elements are being deposited on a second slab of ZnSe, and the combination will be used to measure the shunt admittance of the isolated element. With that information, a small array can be designed; and if the configuration is satisfactory, the design can be directly scaled for 45 GHz operation.

On 7 February, a program review was held at Georgia Tech. Attendees included Fred Burkette and Bob Heeren from the Boeing Co., Ray Taylor and Ellery Snyder from CVD, Inc., and Jim Fuller, Tom Taylor, and Bruce Warren from Georgia Tech. Other contacts at Georgia Tech during the 7-8 February visit included the following:

Jim Wiltse	- Assoc. Dir., EES
Dave Schmieder	- Chief, EO Div.
Walter Cox	- Chief, Phy. Sci. Div.
Charlie Rucker	
Jerry Hill	
Charlie Brown	- Chief, Development Div.
Carl Cash	
Pete Britt	

Problems. No unusual problems were encountered during this reporting period.

Plans. During March, we plan to assemble the components needed to demonstrate X-band operation of microstrip radiators fabricated on ZnSe substrates. As a step toward developing the process for a second CVD material deposition, we would like to have CVD, Inc., fabricate a microstrip transmission line with a cutout for transition attachment, as shown in the attached figure.

Respectfully submitted,

James A. Fuller
Project Director

Approved:

Charles E. Ryan, Jr.
Chief,
EM Effectiveness Division



ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
A Unit of the University System of Georgia
Atlanta, Georgia 30332

ELECTROMAGNETICS LABORATORY
MILLIMETER WAVE TECHNOLOGY DIVISION

March 4, 1983

Memorandum

TO: Jim Fuller, ECSL/EMED
FROM: Ron Bohlander and George Kirkman, EML/MMD
SUBJ: Optical Constants of ZnSe

This is to bring you up to date on measurements we have made of the ZnSe samples you provided on your project A-3370. One of us (G.F.K.) has made measurements of the refractive index n (or dielectric constant ϵ_r) and of the loss tangent $\tan \delta$ of the samples in a semi-confocal Fabry-Perot cavity, using the method described by K. H. Breeden and J. B. Langley in the Rev. Sci. Instrum. 40, 1162-3 (1969).

Recently in our investigation, inconsistent results were obtained when we attempted to repeat our first measurements. For example, results for n varied between 3 and 3.5 and for $\tan \delta$ between 0.001 and 0.020, and the size of random effects like instrumental noise could not explain this variation. In addition, we obtained results for stacks of ZnSe plates and again there were considerable variations depending on the thickness of the stack. This was not expected since the plates were flat enough to stack well and to appear to be like a homogeneous sample to a sufficient approximation.

We have, however, more recently identified and removed the cause of this confusion; namely, higher-order modes. With no material in the cavity, higher-order modes are suppressed by virtue of the size of the flat mirror in the semi-confocal arrangement. This mirror is small enough that higher-order modes leak around the mirror and are not contained by

the cavity. The problems arose because the ZnSe samples are much wider than this mirror and are able themselves to reflect the higher-order modes with relatively high efficiency due to the high dielectric constant of the material. This was confirmed by scanning the moving mirror of the cavity and finding spurious resonances. Bogus results can be explained then as being a measurement of the wrong resonance when the ZnSe was in the cavity.

This problem was eliminated by adding further higher-order mode suppression in the form of an absorbing collar around the radiation beam within the cavity. As an additional precaution, the E-H tuner that is used to match signals into the cavity was always adjusted to about the same level of null reflection with the sample in the cavity to try to eliminate possible effects of the material on the coupling part of the cavity factor. The results given on the attached table were obtained with this arrangement, and much better agreement between the samples and the various stacks is shown. The uncertainties indicated in the Table are those due to random effects only. One may note that there is some residual inconsistency between results which is larger than the random errors and which may be due to any of the following causes: (1) the individual samples may in fact have slightly different optical properties, (2) the results from the stacks of samples may be affected in a minor way by the thin air-gap interfaces between samples, and (3) there may be some additional residual perturbation on the cavity or on the cavity coupling due to the high dielectric constants of the samples. There is not sufficient information at present with which to establish the relative importance, if any, of these suggested mechanisms.

One further problem has been noted. In the case of sample #4, the Q of the cavity increased slightly with the sample in the cavity. In terms of a loss tangent, this would imply a non-physical, slightly negative value ($\tan \delta \sim - .001$). We can only speculate that the most likely explanation is that the sample may be perturbing the coupling in and out of the cavity in a way that the E-H tuner does not fully compensate.

Nevertheless, from previous experience we feel that it is safe to conclude that the loss tangent of the ZnSe samples ($\tan \delta \leq .003$) and that a value of the index of refraction in the range 3.00 to 3.08 can be inferred. The average value observed was 3.03_4 .

xc: John Cotton
Joe Newton
Vernon Brady

Table of Fabry-Perot Cavity Measurements of ZnSe Plates
Frequency: 94 GHz

Individual Samples

Sample	Thickness (in.)	Refractive Index n	Dielectric Constant ϵ_r	Loss Tangent Tan δ
1	.054	3.021 $\pm$.005	9.13 $\pm$.03	.0017 $\pm$.0005
2	.053	3.034 $\pm$.005	9.21 $\pm$.03	.0019 $\pm$.0005
3	.047	3.062 $\pm$.005	9.38 $\pm$.03	.0029 $\pm$.0005
4	.059	3.019 $\pm$.005	9.11 $\pm$.03	*

Stacks of Samples

Samples in Stack	Refractive Index n	Dielectric Constant ϵ_r	Loss Tangent Tan δ
1,2	3.004 $\pm$.005	9.02 $\pm$.03	.0019 $\pm$.0005
1,2,3	3.036 $\pm$.005	9.22 $\pm$.03	.0025 $\pm$.0005
1,2,3,4	3.022 $\pm$.005	9.13 $\pm$.03	.0027 $\pm$.0005

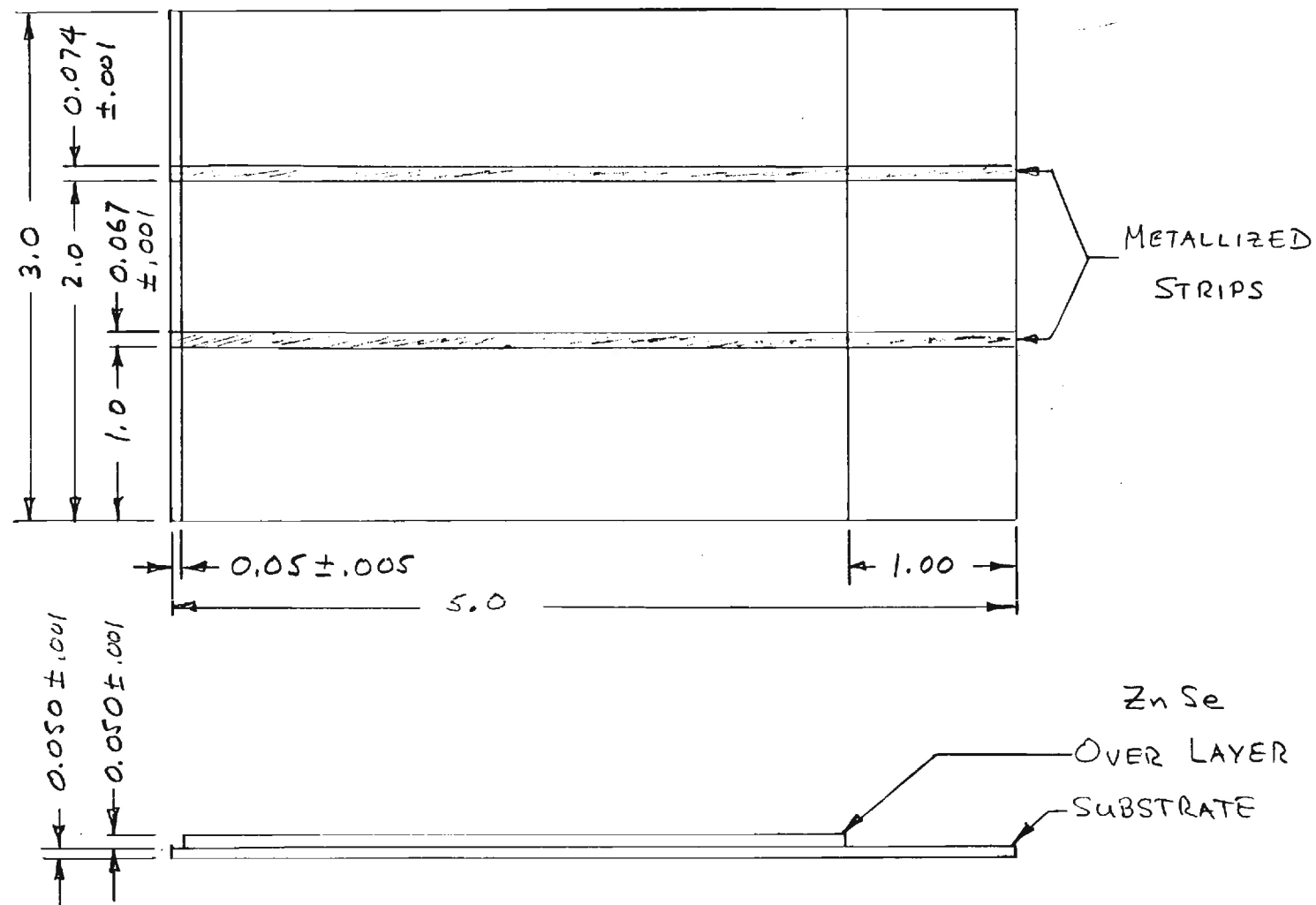


Figure. Sketch for a ZnSe test piece to evaluate microstrip transmission lines and fabrication processes.



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13 April 1983

CVD, Incorporated
35 Industrial Parkway
Woburn, Massachusetts 01801

Attention: Dr. Raymond L. Taylor
Vice President, Research and Engineering

Reference: CVD Subcontract No. 0203
"Development of Dual IR/MM-Wave Aperture Antenna"
Georgia Tech Project A-3370

Subject: Monthly Progress Report No. 6
March 1983

Gentlemen:

Status. During March, the following tasks were addressed:

- * Deposition of a microstrip (MS) feedline on ZnSe.
- * Test and tuning of a new waveguide-to-microstrip (WG/MS) transition with a MS transmission line on ZnSe.

A microstrip transmission line was formed on a ZnSe substrate by sputtering gold through a photo-etched mask on the substrate. The thickness of the substrate was 0.058 inches, the width of the line was 0.081 inches, and the thickness of the line was 2.3 micrometers. This line behaved qualitatively much the same as a line formed with copper tape, which indicates that the thin metallization is effective.

With no special tuning, the WG/MS transition matched into the ZnSe MS transmission line with a return loss of about 10 dB over the range of X-band waveguide. Through use of a tuning post under the ridge, the match could be improved to the desired 20 dB over a smaller frequency range. The transition is basically satisfactory, although it is more difficult to match into a narrow line on ZnSe than it is for a wider line on a teflon substrate. A tuning screw will be needed to finalize the design.

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CVD Subcontract No. 0203
13 April 1983
Page 2

Problems. No unusual problems were encountered during this reporting period.

Plans. Admittance measurements for a radiating microstrip element will be undertaken in April. Also, a meeting with Boeing and CVD, Inc., is planned for 26-27 April at the Air Force Wright Aeronautical Laboratories.

Respectfully submitted,

James A. Fuller
Project Director

Approved:

Charles E. Ryan, Jr.
Chief,
EM Effectiveness Division



ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
A Unit of the University System of Georgia
Atlanta, Georgia 30332

19 May 1983

CVD, Incorporated
35 Industrial Parkway
Woburn, Massachusetts 01801

Attention: Dr. Raymond L. Taylor
Vice President, Research and Engineering

Reference: CVD Subcontract No. 0203
"Development of Dual IR/MM-Wave Aperture Antenna"
Georgia Tech Project A-3370

Subject: Monthly Progress Report No. 7
April 1983

Gentlemen:

Status. During April, the following tasks were addressed:

- * Admittance measurements for five-element arrays of copper taped elements on ZnSe substrates, performed at X-band frequencies.
- * Dielectric measurements of five circular samples of ZnSe at Ka-band frequencies.
- * Fabrication of a microstrip termination, using sputtered titanium.
- * Deposition of three different five-element arrays of gold-sputtered elements on a ZnSe substrate.
- * Participation in a briefing at AFWAL/AADM.

Georgia Tech has used a gold sputtering capability to fabricate preliminary test pieces that will provide the basis for experimental design of an X-band array. There is clearly not time in the remaining contract period to allow iterations between tests at Georgia Tech and fabrication at CVD, Inc. We will need to base the design of a U-band (45 GHz) array on whatever experiments can be completed at Georgia Tech in the next week or two. Figure 1 shows a photocopy of the sputtered microstrip line and the group of three arrays that have been completed. These arrays have not been tested, but they are based on experiments with similar copper-taped arrays. CVD, Inc., is currently fabricating a microstrip line with a ZnSe over-layer, also for X-band tests. We may be able to specify an array of

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CVD Subcontract No. 0203
19 May 1983
Page 2

elements to be deposited on the CVD-fabricated piece, by the time the current processing is completed.

The dielectric constants of the circular samples of CVD-ZnSe provided by CVD, Inc., have been measured in a shorted circular waveguide at Ka-band frequencies. This method indicates that the dielectric constant is about 8.85, and the loss tangent is less than 0.01. An example of the result is shown in Figure 2. Data has also been obtained using a resonant cavity technique, which is appropriate for low-loss materials, but the measured admittance data has not yet been reduced to obtain dielectric properties.

On 27 April, a briefing was presented by Boeing, CVD, MIT, and Georgia Tech at the Air Force Wright Avionics Laboratories. A list of attendees is attached.

Problems. There has been some difficulty in handling the fragile ZnSe substrates at Georgia Tech. Two were broken during testing, and two more were broken during attempts at metallization; so only two whole pieces remain. This will be adequate, if we do not break any more. Even with the extended contract period, it is clear there will be difficulty in completing the desired amount of fabrication, testing, and iteration.

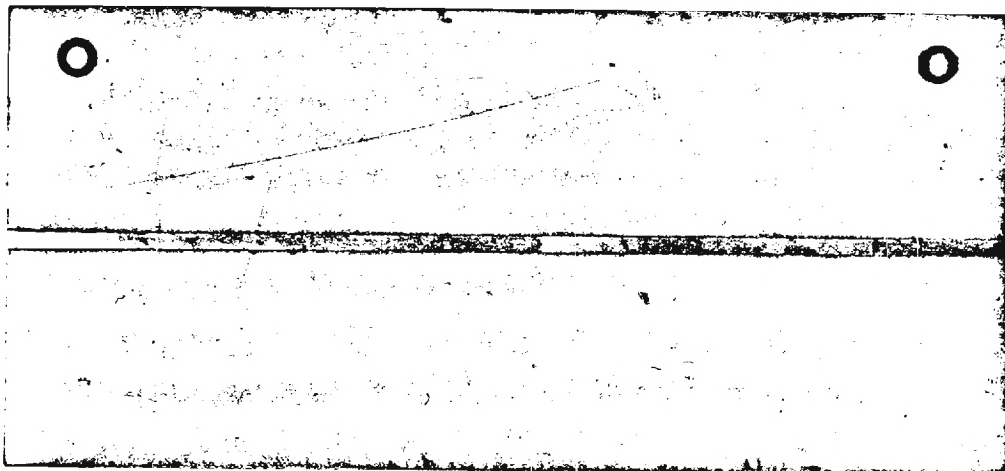
Plans. During May, the X-band array design should be finalized and the dimensions for a U-band unit provided to CVD, Inc., for fabrication. On 21 May, Boeing has arranged a briefing at DARPA, in which Georgia Tech and CVD will participate

Respectfully submitted,

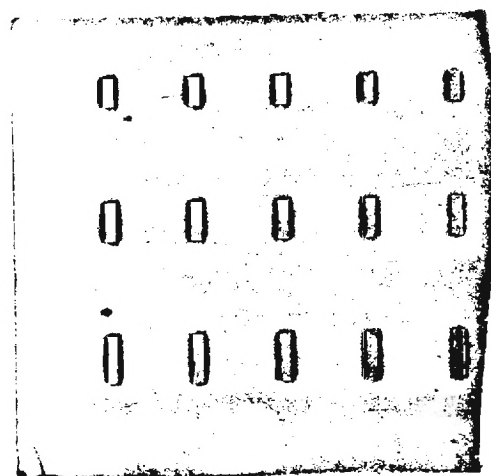
James A. Fuller
Project Director

Approved:

(
Charles E. Ryan, Jr.
Chief,
EM Effectiveness Division



(a) Microstrip line



Array No. 1

Array No. 2

Array No. 3

(b) Radiating elements

Figure 1. Sputtered gold microstrip line and radiating elements for X-band tests.

April 27, 1983

RON DE	Boeing Engr. Tech.	(206)
R24 Taylor	CVD Inc.	(617)
Robert F Don	CVD Inc.	(617) 93
JAMES A. FULL	GEORGIA TECH EES	(404) 89.
FRED BURA	BOEING	(206) 71
BOB HEER	BOEING	(206) 71
KENNETH	MASS. INST. TECH	(617) 21
Robert T.	AFWAL/AADM	(513) -
Ed Ste	AFWAL/AADM	
Robert M.	AFWAL/AADM-2	513-25
Mark C	AFWAL/AADM-2	(513) 2
DEAN EPH	AFWAL/AADM-2	(513) 2
SAH SCHU	CVD, INC	253-71
Terry De	AFWAL/AADM-2	25
Raymond R	AFWAL/AARI-5	25
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A-3370

ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
A Unit of the University System of Georgia
Atlanta, Georgia 30332

20 June 1983

CVD, Incorporated
35 Industrial Parkway
Woburn, Massachusetts 01801

Attention: Dr. Raymond L. Taylor
Vice President, Research and Engineering

Reference: CVD Subcontract No. 0203
"Development of Dual IR/MM-Wave Aperture Antenna"
Georgia Tech Project A-3370

Subject: Monthly Progress Report No. 8
May 1983

Gentlemen:

Status. During May, the following tasks were addressed:

- * Impedance measurements of three different five-element arrays fabricated at Georgia Tech with gold elements.
- * Participation in a briefing at DARPA on 21 May.

The three arrays of gold elements were fabricated by sputtering a thin deposition of gold through a photo-etched mask and then plating additional gold to build the thickness to about 2.5 microns. This same process has been used previously to make microstrip feed lines for this program. The three arrays were sized to compare three lengths of elements, while holding the element width and spacing constant. The three lengths were $L = 0.15$, 0.20 , and 0.25 inches. The widths were 0.05 inches, and the spacings were 0.45 inches. This selection of length was based on results of other tests with elements made from copper tape, which indicated that $L = 0.20$ inch was a good size. The tests with the new elements also indicate that of the three lengths, $L = 0.20$ is the best. All three lengths could be made to couple and radiate, by trial-and-error adjustment of the offset between the elements and the microstrip feedline; but the direction of radiation was skewed undesirably for the short and long elements.

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Page 2

Adjustment of the offset is quite critical, and the slight air gap between our layers of ZnSe is a factor in this adjustment. Therefore, the arrays that we can fabricate at Georgia Tech will not be entirely adequate to determine dimensions for multilayer ZnSe arrays that are grown into single monolithic units with no air gaps. To continue the experimental development, we will need to rely on the monolithic arrays that can only be fabricated by CVD, Inc. To finalize the element/feedline offset, it will be desirable to fabricate several structures with different offsets that bracket an estimate based on our current tests. These structures could be incorporated on a single substrate, to minimize the number of operations. Such an undertaking is probably not possible within the current contractual time period.

If there are no further program extensions, we will be able to do no more than test the feedlines that are currently being fabricated by CVD, Inc. We could test those feedlines with elements that have been gold-plated on a separate substrate at Georgia Tech. If there are further program extensions, we will also need to have CVD, Inc., fabricate scaled-down feedlines that can be tested at U-band (45 Ghz) frequencies.

Problems. No unusual problems were encountered during this reporting period.

Plans. We have received notice that the contract will be extended through July and that the requirement for U-band fabrication and testing is changed to X-band. When we receive the feedlines from CVD, Inc., we will test them for loss characteristics and for excitation of radiating elements.

As a result of our briefing to Ltc. James Acklin at DARPA, there is a possibility that Boeing may extend the program with DARPA funding. In that event, we will be able to undertake fabrication and testing of millimeter-wave components, but some additional planning will be needed.

Respectfully submitted,

James A. Fuller
Project Director

Approved:

Charles E. Ryan, Jr.
Chief,
EM Effectiveness Division

FINAL REPORT

PROJECT A-3370

DEVELOPMENT OF A DUAL-APERTURE INFRARED/MILLIMETER-WAVE ANTENNA

By

**J. A. Fuller
T. S. Taylor
G. N. Hill**

Prepared for

**CVD, INCORPORATED
35 INDUSTRIAL PARKWAY
WOBURN, MASSACHUSETTS 01801**

Under

**Subcontract No. 0203
BOEING AEROSPACE COMPANY
Purchase Order CH6411-01**

Report Period from September 3, 1982 through July 29, 1983

GEORGIA INSTITUTE OF TECHNOLOGY

**A Unit of the University System of Georgia
Engineering Experiment Station
Atlanta, Georgia 30332**



GEORGIA INSTITUTE OF TECHNOLOGY
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FINAL REPORT
20 October 1983

Prepared under

Boeing Aerospace P. O. CH6411-Ch.01
Subcontract No. 0203
Georgia Tech Project No. A-3370

for

CVD, Inc.
35 Industrial Parkway
Woburn, Massachusetts 01801

PREFACE

This Final Report documents antenna development research conducted by the Engineering Experiment Station (EES) at the Georgia Institute of Technology for CVD, Inc., and the Boeing Aerospace Co. The EES work was conducted under Subcontract No. 0203 with CVD, Inc., and CVD, Inc., operated as a contractor to the Boeing Aerospace Co. under Purchase Order CH6411, Ch.01. Technical direction was provided by Dr. R. L. Taylor of CVD, Inc., and Mr. F. Burkett of Boeing Aerospace. The EES Project Director was Dr. J. A. Fuller. This report covers work accomplished during the period 30 September 1982 through 29 July 1983.

Design and testing activities were conducted by J. A. Fuller, T. S. Taylor, and P. G. Friederich, in the Electromagnetic Effectiveness Division (EMED) of the EES Electronics and Computer Systems Laboratory (ECSL). Metallization activities, including gold plating on zinc selenide, were conducted by G. H. Hill, in the Physical Sciences Division of the Electromagnetics Laboratory (EML).

The authors would like to acknowledge the encouragement and technical advice provided by Dr. R. G. Heeren, during the period he was with Boeing Aerospace. The authors also express their appreciation for support and assistance provided by Mr. F. L. Cain, Director, ECSL, Dr. C. E. Ryan, Jr., Chief, EMED, and Ms. B. E. Gonzalez, who prepared briefing materials and reports.

Respectfully submitted,

James A. Fuller
Project Director

Approved:

Charles E. Ryan, Jr.
Chief,
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SECTION I

INTRODUCTION

There is considerable current interest in the development of dual-mode sensors for missile seeker applications[1], and one of the most attractive is a combination of infrared (IR) and millimeter-wave (mmW) systems. CVD, Inc., has established a very practical fabrication process (chemical vapor deposition) for the production of zinc selenide (ZnSe) and zinc sulfide (ZnS) windows for IR sensors. With the goal of developing a mmW radar antenna that can be integrated into an IR window, the Boeing Aerospace Company established a research contract (Purchase Order CH6411) with CVD, Inc., with a subcontract to the Georgia Tech Engineering Experiment Station (EES). This contract was designed to resolve the major feasibility issues associated with an antenna concept that was proposed by Georgia Tech.

In discussions with representatives of CVD, Inc., the following guidelines were established for a mmW antenna development program:

1. The mmW antenna should be incorporated into the ZnSe window for an IR sensor.
2. The mmW antenna should cause the minimum possible blockage of the IR sensor.
3. The mmW antenna fabrication process should be compatible with the CVD window fabrication process.
4. The mmW antenna should have clear potential to function as a radar antenna.
5. Some form of electronic beam-scanning should be possible.
6. Millimeter-wave frequencies of 45 and 94 GHz are of interest.

The initial planning effort for this work was directed toward development of a 94 GHz, frequency-scanned array antenna. In a proposal to CVD, Inc., Georgia Tech described a concept and outlined a program to fabricate and test an antenna [2]. However, it made clear that an attempt to fabricate a complete array antenna entailed significant risk, because new design and fabrication processes had to be developed. There was very little information available on the electrical properties of the ZnSe material at microwave or mmW frequencies, and there was no way to predict whether usable mmW microstrip transmission lines could be sandwiched into

multilayer ZnSe structures. After further negotiations with Boeing and CVD, Inc., Georgia Tech proposed a smaller program to concentrate on the most critical feasibility issues.

This Final Report documents antenna development work done by Georgia Tech, under a subcontract from CVD, Inc., during the period 30 September 1982 through 29 July 1983. The antenna investigated is a linear array of microstrip dipole radiators, which are electromagnetically coupled to a microstrip transmission line. Although related concepts for microstrip antennas have been investigated previously [3-6], this version seems to be new, and certainly the integral fabrication in a ZnSe substrate is new. The main technical accomplishments of the work by Georgia Tech and CVD, Inc., are the following:

- * The dielectric properties of CVD-ZnSe have been measured at mmW frequencies and at temperatures to 550°C, and the material has been shown to have good properties for use as a substrate for microstrip structures.
- * The antenna concept has been demonstrated to have potential as a radar array antenna.
 - The microstrip dipole element radiates with characteristics similar to other resonant elements, such as a thin-wire dipole or a slot.
 - Excitation of the element can be accurately controlled by a simple adjustment of the electromagnetic coupling to the microstrip transmission line.
 - Excitation and radiation has been demonstrated for a linear array (i.e., a series-fed column) of elements at X-band frequencies.
- * A waveguide-to-microstrip (WG/MS) transition and a microstrip matched termination have been developed, as necessary components for experimental development and testing of the antenna.
- * CVD, Inc., has demonstrated the capability to fabricate a monolithic, multilayer structure, in which metallic (platinum) circuits are incorporated into the ZnSe substrate.

* Georgia Tech and CVD, Inc., participated with Boeing in briefing four Government organizations on this dual-mode antenna concept. Included were the following:

- Air Force Wright Aeronautical Laboratories
- Defense Advanced Research Projects Agency
- Air Force Armament Laboratory
- Army Missile Command

The program has demonstrated the viability of a new antenna concept and fabrication process that have significant potential for mmW radar and dual-mode seeker applications. To fully develop the concept, more work is needed in several areas. One remaining issue, which should be addressed as soon as possible, is the determination of the loss in mmW microstrip transmission lines that are made by the CVD process. Beyond that issue, if it is satisfactorily resolved, an almost unlimited effort could go into the development of many types of antennas, including the development of theoretical and experimental design procedures. Also, there is a possibility that the same ideas and processes could be applied to incorporate antennas into more rugged radome materials such as silicon nitride.

SECTION II

SUMMARY OF ACTIVITIES

The scope of this research program was confined to address the critical, high-risk associated with a new antenna concept and fabrication process. The objective was to advance the technology to a point that it would interest Government agencies concerned with dual-mode (mmW/IR) missile seeker applications. This section summarizes the technical activities undertaken and the program reviews that were presented to develop Government interest. Technical results are discussed in the following section (Section III).

A. Technical Activities

The technical tasks that were planned for this program involved joint efforts by Georgia Tech and CVD, Inc., where Georgia Tech addressed mmW design and testing, and CVD, Inc., addressed fabrication processes and provided the fabricated components needed for testing. The program was primarily experimental, and the following tasks were undertaken by Georgia Tech:

1. Develop a waveguide-to-microstrip (WG/MS) transition to enable testing of components with conventional waveguide instrumentation.
2. Develop a monolithic microstrip (MS) transmission line that is embedded in a ZnSe substrate.
3. Design and develop electromagnetically (EM) coupled radiating elements and demonstrate a series-fed column (linear array) of elements formed as a monolithic antenna structure in a ZnSe substrate.
4. Develop a matched termination for the microstrip transmission line.
5. Measure radiation patterns for the series-fed column antenna.
6. Develop analytical models to support the design of the WG/MS transition, the MS transmission line, and the column antenna.

To save time and to allow more iterations, Georgia Tech relied as much as possible on test structures that could be fabricated at Georgia Tech. CVD, Inc., aided this approach by supplying blank slabs of ZnSe material, which Georgia Tech used as substrates for transmission lines and antenna

elements. This approach proved necessary, because the development of processes for fabrication of multilayer, monolithic ZnSe circuit structures was, itself, a difficult and time consuming task for CVD, Inc. Georgia Tech and CVD, Inc., both had problems with breakage of the rather fragile substrates during metallizing and re-deposition operations. These problems prevented the fabrication (and testing) of the monolithic structures identified in Tasks 2, 3, and 5. However, Georgia Tech was able to complete some limited development and testing of multilayer structures, by stacking separate slabs of ZnSe, on which metallized circuits had been applied. This approach was adequate to demonstrate operating principles and to show that useful antenna operation was achievable. However, further development and tests with monolithic multilayer structures will be necessary to establish antenna design procedures and performance capabilities.

Georgia Tech began the program with plans to develop first X-band (8 to 12 GHz) versions of the required components and then to scale the designs for operation at a U-band (40 to 60 GHz) frequency of 45 GHz. The X-band designs were more suitable for fabrication at Georgia Tech, because the large dimensions allowed relaxed tolerances. Also, more X-band test equipment was available, and it was easier to use. The requirement for U-band development was dropped late in the program, when it became evident that there was not adequate time for the required iterations of fabrication and testing operations.

Early in the program, before ZnSe substrates became available, the experimental work was conducted using various common plastic substrates, such as teflon/fiberglass (3M "K-6098"), polyolefin (Custom Materials "Polyguide"), and polycarbonate (GE "Lexan"). With these materials, microstrip transmission lines were fabricated, the X-band waveguide-to-microstrip transition was designed, and EM-coupled radiating elements were demonstrated.

In the third month of the program, CVD, Inc., supplied six slabs of ZnSe with dimensions of 2.5 x 5.0 x 0.05 inches. These provided the basis for essentially all of the experimental antenna development.

Initially, the metallic circuit elements were formed using copper tape. This allowed changes to be made easily; but the lack of precision in cutting tape and the air gaps between stacked layers, caused by the thick tape, rather quickly limited advances made using tape.

After approximate circuit dimensions were established with taped structures, more precise experiments were conducted using gold circuits applied through photo-etched masks. To conserve gold, the structures were formed by first sputtering thin layers (less than 1,000 Angstroms) through masks on the ZnSe substrates and then plating to build the thin layers to a thickness of about 25,000 Angstroms. This thickness of about three skin depths at 10 GHz was adequate to form a low-loss transmission line.

The difficulty of maintaining precision alignment of stacked, multilayer structures and air gaps between layers limited the degree of development that could be accomplished using Georgia Tech fabricated circuits. Because the antenna is a resonant structure, the EM-coupled layers must be aligned to within a few thousandths of an inch, even at X-band, and air gaps between layers must be eliminated to achieve reasonable repeatability. Therefore, further development of the antenna will require that test pieces be fabricated as monolithic structures, using CVD, Inc., processes. The major milestone yet to be achieved in this regard is the demonstration that microwave and mmW losses in the monolithic structures are sufficiently low to provide good transmission lines and radiation efficiency.

An incidental activity during the contract period was the measurement of dielectric properties of CVD ZnSe. CVD, Inc., supplied samples for several waveguide bands, and Georgia Tech made measurements using several different methods, including a Fabry-Perot interferometer, a shorted rectangular waveguide, and a circular waveguide cavity. For some samples, dielectric properties were measured at temperatures from ambient to 550 C. The dielectric properties are definitely suitable for microwave and mmW substrate applications.

B. Program Reviews and Briefings

A number of meetings were held during this program to review technical progress with Boeing representatives and to present briefings to Government agencies with potential interest in dual-mode seeker concepts.

Technical program reviews for Boeing were held at CVD, Inc., on 9 November 1982 and at Georgia Tech on 7-8 February 1983. In addition, technical discussions with CVD, Inc. took place at Georgia Tech on 1 October 1982 and 19 April 1983.

To assess and develop Government interest in the dual-mode mmW antenna concept, Boeing arranged for CVD, Inc., and Georgia Tech to present briefings for the following organizations:

- * Air Force Wright Aeronautical Laboratories (AFWAL)
Date: 27 March 1983
- * Defense Advanced Research Projects Agency (DARPA)
Date: 21 May 1983
- * Air Force Armament Laboratory (AFATL)
Date: 30 June 1983
- * Army Missile Command (MICOM)
Date: 27 July 1983

The briefing charts used by Georgia Tech for these presentations are included in Appendix A. In all cases, the briefings were favorably received, and there is a definite possibility that DARPA and MICOM may support further work.

SECTION III

ANTENNA DEVELOPMENT

The technical tasks undertaken in this program were designed to accomplish a series of developments that would lead to the demonstration of a linear array antenna, fabricated as a monolithic microstrip structure in a CVD ZnSe substrate. The linear array was to be a series-fed, resonant array that would represent one column of a planar array. The required tasks were accomplished adequately to demonstrate feasibility of the antenna concept. The demonstration of a monolithic array antenna was necessarily deferred until multilayer ZnSe fabrication processes were further advanced. This section discusses the technical tasks that have been accomplished during the program.

A. Dielectric Property Measurements

The dielectric constant and loss tangent of CVD ZnSe were measured in three mmW frequency bands, using several different methods that were available at Georgia Tech. The results indicate that at room temperature the dielectric constant is about 9.0, and the loss tangent is below 0.001. As the temperature increases to 550 C, the dielectric constant increases linearly to about 10.0, and the loss tangent increases to about 0.01. Compared with ceramics such as aluminum oxide or silicon nitride, which have similar dielectric constants, ZnSe is significantly more sensitive to temperature; but here only room temperature properties are of present concern, and these are certainly suitable for mmW microstrip circuit structures.

The first dielectric measurements were performed by inserting the 0.05-inch thick slabs of CVD ZnSe into a Fabry-Perot cavity resonator. This instrument, which is maintained by the EES Electromagnetics Laboratory, is a quasi-optical resonator that is particularly suited for samples that are available as slabs of uniform thickness. The instrument was adjusted to resonate near 94 GHz, and the results are given in Table 3-1. Further discussions of this measurement are provided in Appendix B.

The next series of dielectric measurements was performed on samples machined to fit inside U-band (WR-19) rectangular waveguide. Measurements were made with the samples placed in short-circuited waveguide to obtain dielectric properties at 44 GHz. The results, which are shown in Table 3-2, were considered questionable. For this measurement to be valid, the

TABLE 3-1

FABRY-PEROT CAVITY MEASUREMENTS OF CVD ZnSe DIELECTRIC
PROPERTIES AT 94 GHz

(a) Individual Samples				
Sample	Thickness (in.)	Refractive Index n	Dielectric Constant K	Loss Tangent Tan δ
1	.054	$3.021 \pm .005$	$9.13 \pm .03$	$.0017 \pm .0005$
2	.053	$3.034 \pm .005$	$9.21 \pm .03$	$.0019 \pm .0005$
3	.047	$3.062 \pm .005$	$9.38 \pm .03$	$.0029 \pm .0005$
4	.059	$3.019 \pm .005$	$9.11 \pm .03$	
(b) Stacks of Samples				
Samples in Stack		Refractive Index n	Dielectric Constant K	Loss Tangent Tan δ
1,2		$3.004 \pm .005$	$9.02 \pm .03$	$.0019 \pm .0005$
1,2,3		$3.036 \pm .005$	$9.22 \pm .03$	$.0025 \pm .0005$
1,2,3,4		$3.022 \pm .005$	$9.13 \pm .03$	$.0027 \pm .0005$

TABLE 3-2

SHORTED RECTANGULAR WAVEGUIDE MEASUREMENTS
OF CVD ZnSe DIELECTRIC PROPERTIES AT 44.3 GHz

<u>Sample</u>	<u>Length (in.)</u>	<u>Dielectric Constant K</u>	<u>Loss Tangent Tan δ</u>	
1	0.1857	12.0		} Gold-Plated Sides
2	0.1446	10.9	< 0.05	
3	0.1037	12.5		
4	0.1858	11.1		
5	0.1442	10.0	< 0.05	
6	0.1038	10.6		

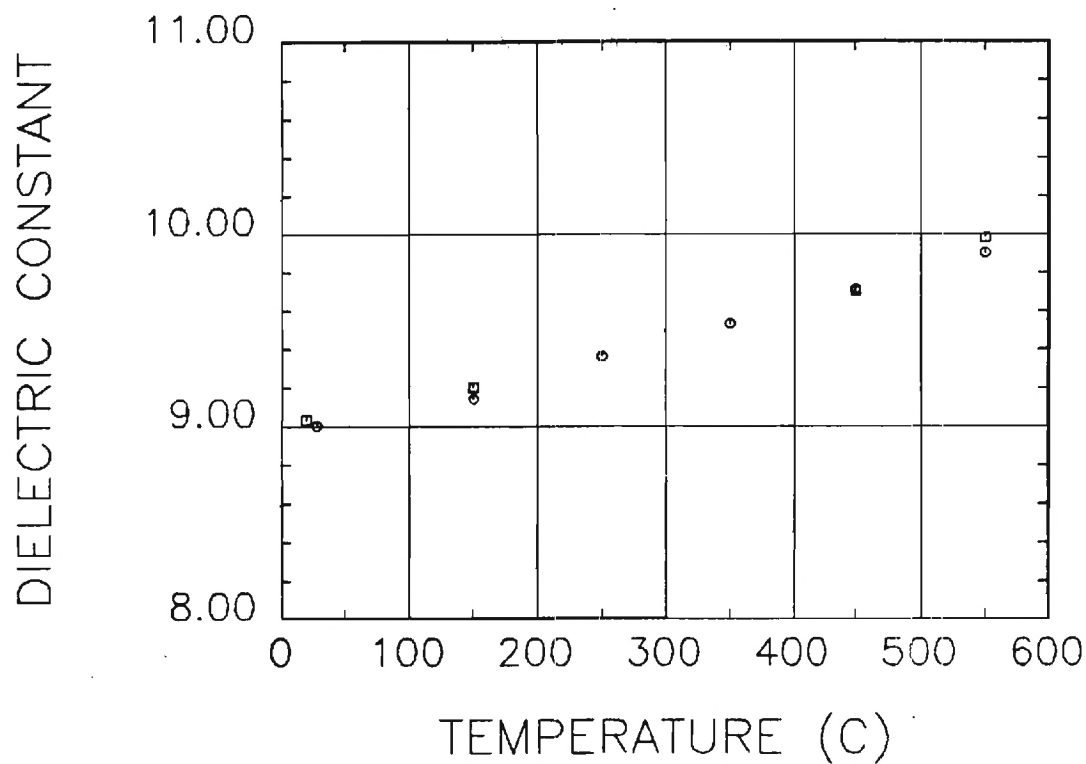
Note: These data are believed to reflect errors associated with the imperfect fit of samples in waveguide (i.e., air gaps).

sample must fit tightly in the waveguide, and such a fit could not be achieved with the imperfect extruded tubing used in commercial waveguide sections. Two approaches were followed to compensate for the imperfect sample fit. For Samples 1, 2, and 3 in Table 3-2, the sides adjacent to the waveguide walls were gold-plated. The gold did not fill the air gap; instead, it bifurcated (split) the waveguide and introduced an edge discontinuity, with the result that the measurement was probably made worse. For Samples 4, 5, and 6 in Table 3-2, a theoretical correction was applied, based on the known width of the air gap. This approach was probably better, and it was limited mainly by the irregularity of the gap. In general, the shorted waveguide method is not very sensitive to small loss tangents, and the loss tangent of ZnSe appeared to be lower than the sensitivity of this instrumentation.

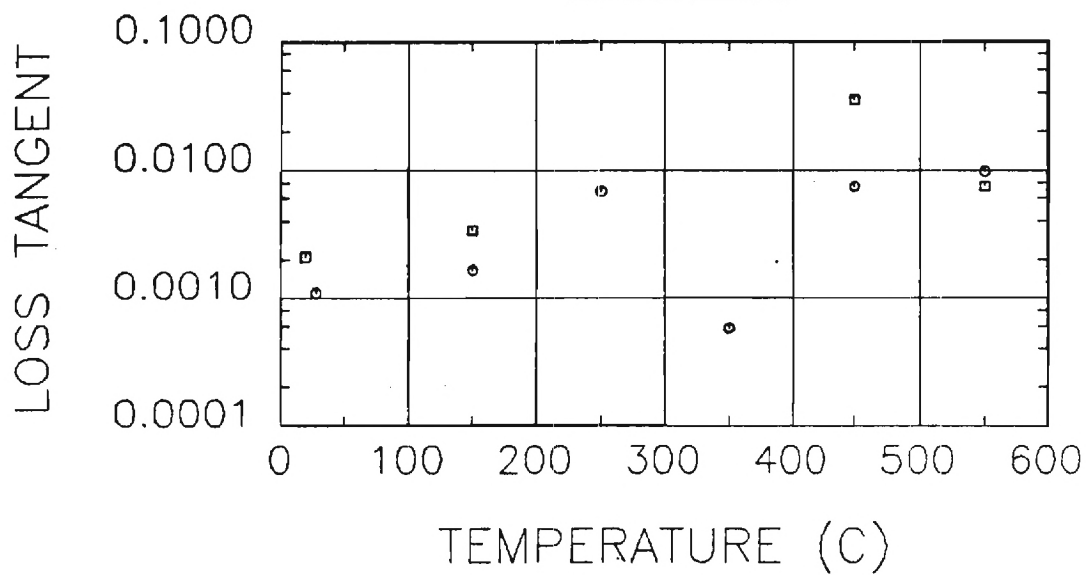
An additional series of dielectric measurements was performed on samples machined to fit in circular waveguide cavities. A very tight sample fit can be obtained in circular waveguide, and resonant cavity measurements are sensitive to small loss tangents. These measurements were performed at Ka- and U-band frequencies and at temperatures from ambient to 550 C, using instrumentation and techniques that have been developed under Contract No. F33615-82-C-1718 with the Air Force Wright Aeronautical Laboratories, Avionics Laboratory (AADM-1). Typical results are shown in Figures 3-1, 3-2, and 3-3, at frequencies of 29.2, 36.1, and 42.4 GHz, respectively. Additional data for other frequencies and other samples are included in Appendix C. This new measurement system is unique in providing a multi-band, high-temperature capability, and there is a need to develop further the processes for system calibration and error-correction. The frequency-dependent variations in dielectric constant are repeatable, but they seem to be due to the instrumentation, rather than the ZnSe. The scatter in the loss tangent data is due to random errors in the measurement of very small quantities. The variation in properties, increasing with temperature, are believed to be accurately indicated by Figures 3-1, 3-2, and 3-3.

B. Microstrip Transmission Line

A conventional microstrip (MS) transmission line is formed by a flat, narrow strip conductor that is supported over a conducting ground plane by an electrically thin dielectric layer (substrate). The strip width W , its height H above the ground plane, and the dielectric constant K of the

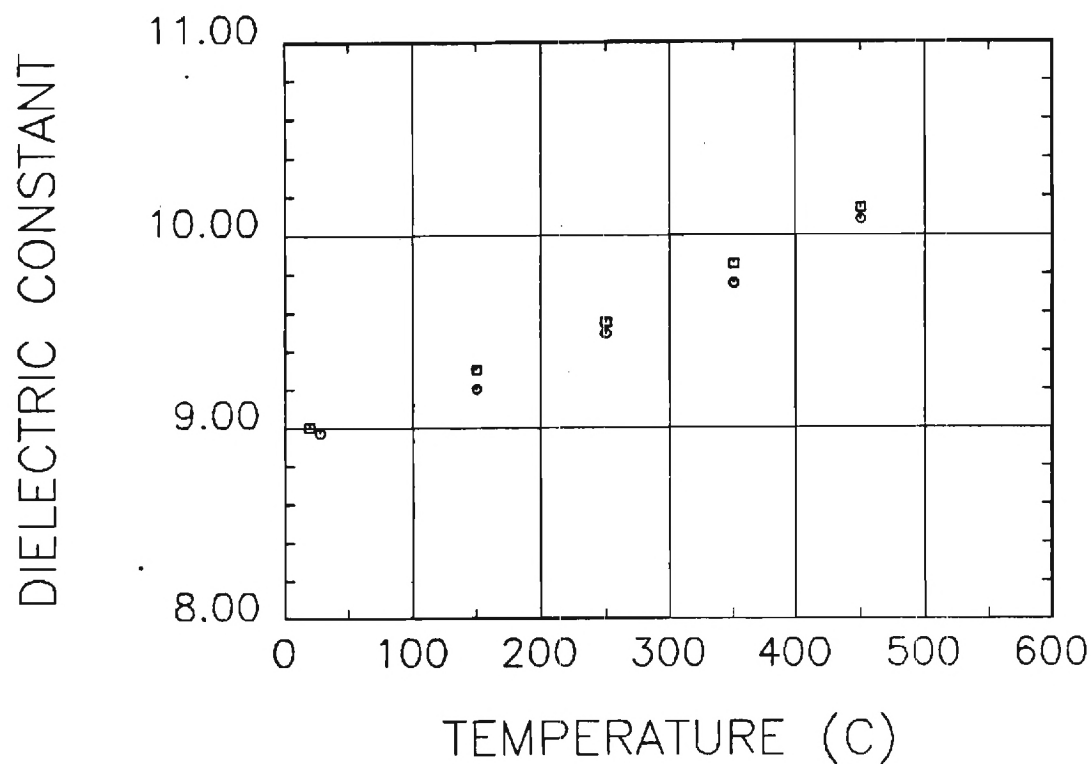


29.2 GHZ

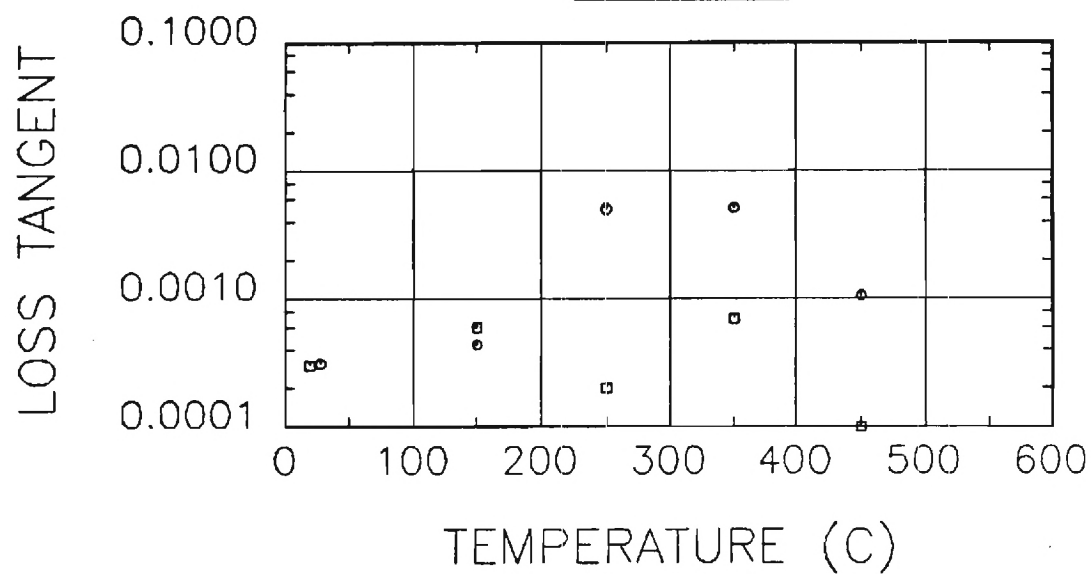


SAMPLE ID. ■ ZSC1A
○ ZSD1A

Figure 3-1 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 29.2 GHz.

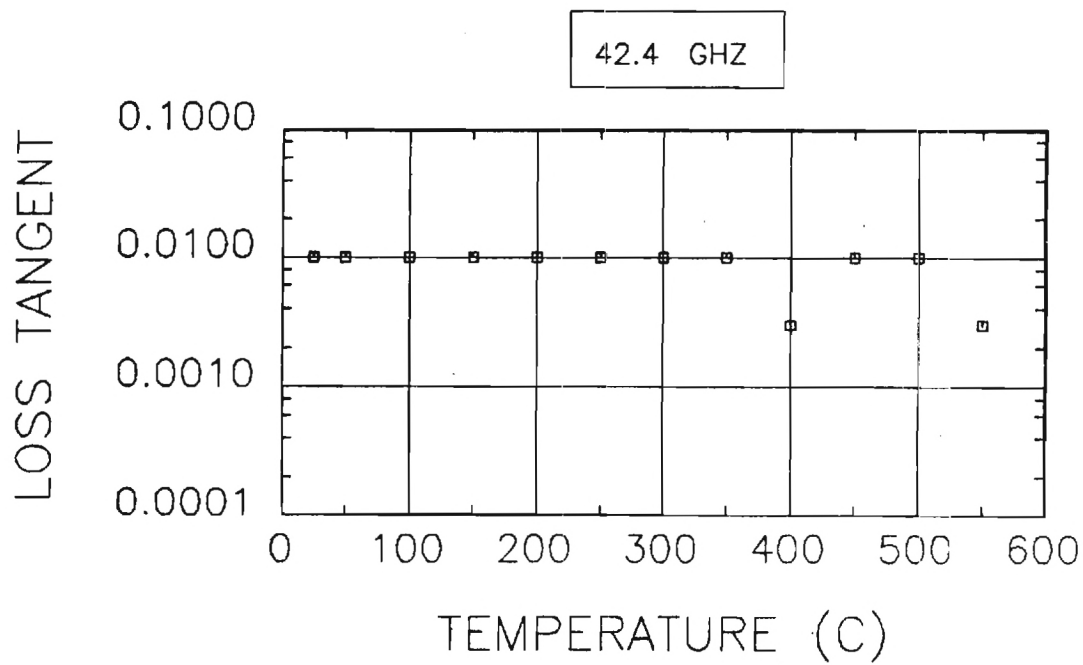
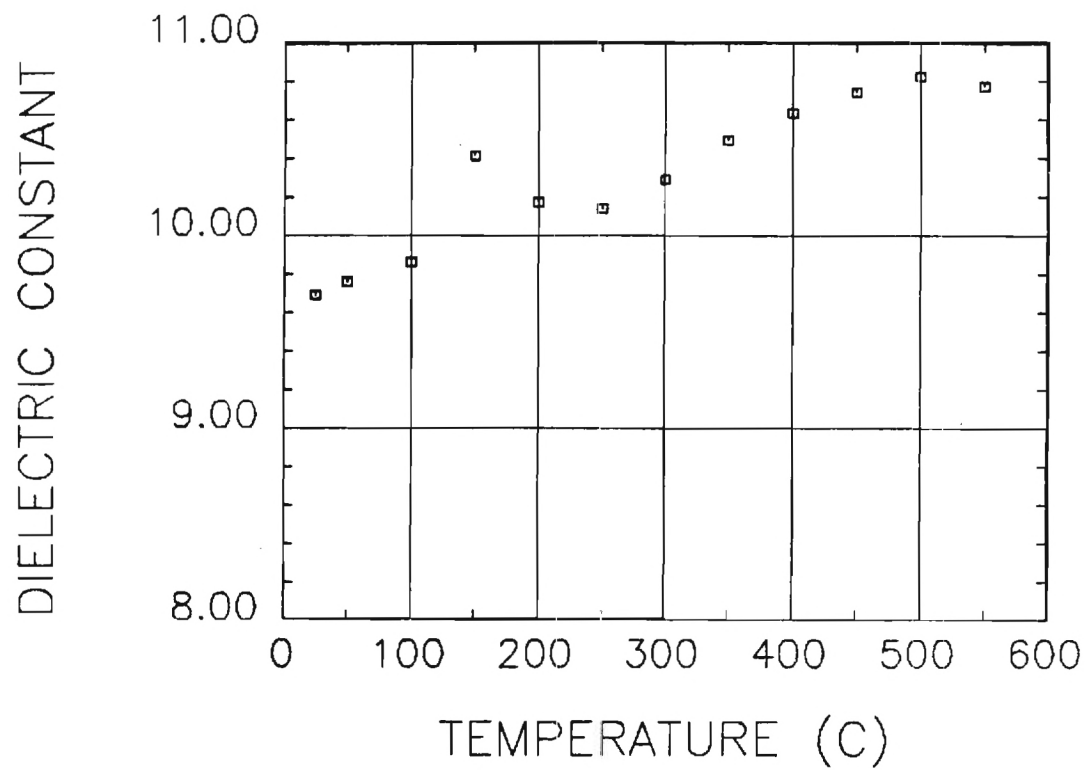


36.1 GHZ



SAMPLE ID. □ ZSC1A
○ ZSD1A

Figure 3-2 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 36.1 GHz.



SAMPLE ID. □ ZS1U

Figure 3-3 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 42.4 GHz.

substrate determine the characteristic impedance Z_0 of the transmission line. There is no exact, closed form solution for electromagnetic (EM) propagation on MS line, but there are a number of good approximate solutions [7]. For $W \geq H$, the impedance is given by

$$Z_0 = \frac{120\pi}{\sqrt{K_e}} \left[\frac{W}{H} + 1.393 + 0.667 \ln \left(\frac{W}{H} + 1.444 \right) \right]^{-1}, \quad (3-1)$$

where K_e is an "effective" dielectric constant,

$$K_e = \frac{K+1}{2} + \frac{K-1}{2} \left[1 + 12 \frac{H}{W} \right]^{-\frac{1}{2}}. \quad (3-2)$$

The effective dielectric constant is smaller than the actual value for the substrate, because the electric field is not entirely contained within the substrate. Instead, fringes of the field extend into the air above the substrate and lower the apparent dielectric constant of the transmission line medium. When the actual dielectric constant of the substrate is known, a conventional microstrip transmission line can be designed for any desired impedance, using Equations (3-1) and (3-2).

Constraints on the characteristic impedance of a transmission line usually arise from requirements to interface with standard transmission lines, such as 50 Ohm coaxial line or rectangular waveguide. For this antenna work, an interface with waveguide is required, but the special transition is not available commercially. For reasons of convention, $Z_0=50$ Ohms was taken as a starting point for the MS line. Experimental work to develop waveguide-to-microstrip (WG/MS) transition indicated that satisfactory results (i.e., impedance match) could be achieved with microstrip impedances in the neighborhood of 50 Ohms. Also, the resulting physical dimensions were reasonable from a fabrication viewpoint.

As an example, if $W/H = 1$ and $K = 9$, the impedance given by Equation (3-1) is $Z_0 = 51$ Ohms. To achieve the desired quasi-TEM mode of propagation on the line, W and H must be much less than the electrical wavelength λ_m in the medium. Therefore, at a frequency $f = 10$ GHz in ZnSe with $K = 9$,

$$W, H \ll \lambda_m = \frac{11.803}{f\sqrt{K}} \text{ inches} \quad . . . f \text{ in GHz} \quad (3-3)$$

$$= 0.393 \text{ inches}$$

The ZnSe plates supplied by CVD, Inc., had thicknesses of approximately 0.05 inches and provided a substrate thickness H that adequately satisfied the requirement of Equation (3-3).

The microstrip configuration required in this antenna differs from the conventional form associated with Equation (3-1). For the antenna, the strip conductor is embedded within the dielectric layer, while for the conventional transmission line, the strip lies on the surface of the layer. Fringing of the electric field is different for these two cases, and the "effective" dielectric constant given by Equation (3-2) is less appropriate for the antenna configuration. Where for $W/H = 1$ and $K = 9$, Equation (3-2) indicated $K_e = 6.1$, experimental measurement of the wavelength along the embedded MS line indicated K_e in the range of 6.8 to 7.2.

The experimental development was conducted first using a readily available plastic substrate (3M K-6098) with a thickness $H = 0.062$ inches and later using CVD ZnSe plates with thicknesses of approximately 0.050 inches. This work was done at X-band frequencies near 10 GHz. The original plan to conduct a final development at 45 GHz was not executed, but that work would have been a straightforward scaling of dimensions by the frequency ratio 10:45. Table 3-3 shows the baseline microstrip parameters that were selected for the stages of this task. Originally, it was assumed that the dielectric constant of ZnSe would be near $K = 10$. Impedances were calculated using a slightly more complicated model than Equation (3-1), which included a correction for the dispersive (non-TEM) nature of microstrip propagation [7] .

Experimental development of the WG/MS transition indicated that a well matched, non-radiating transition was more difficult to achieve, as the strip width W was reduced. Therefore, because there were no other serious constraints on the microstrip impedance, an increase in width was allowed. To evaluate and finalize the design for a monolithic microstrip transmission line, the fabrication of a test piece with the dimensions shown in Figure 3-4 was undertaken by CVD, Inc. This piece contains two MS lines. The upper layer of ZnSe is masked away to expose ends of the lines

TABLE 3-3

DESIGN STAGES FOR MICROSTRIP LINES

<u>Stage</u>	<u>Frequency GHz</u>	<u>Substrate</u>	<u>Dielectric Constant K</u>	<u>Substrate Thickness (in.)</u>	<u>Line Width (in.)</u>	<u>Z(Ohm)</u>
1	10	3M K-6098	2.45	.062	.229	50
2	10	CVD ZnSe	10	.050	.067	50
3	45	CVD ZnSe	10	.011	.015	50

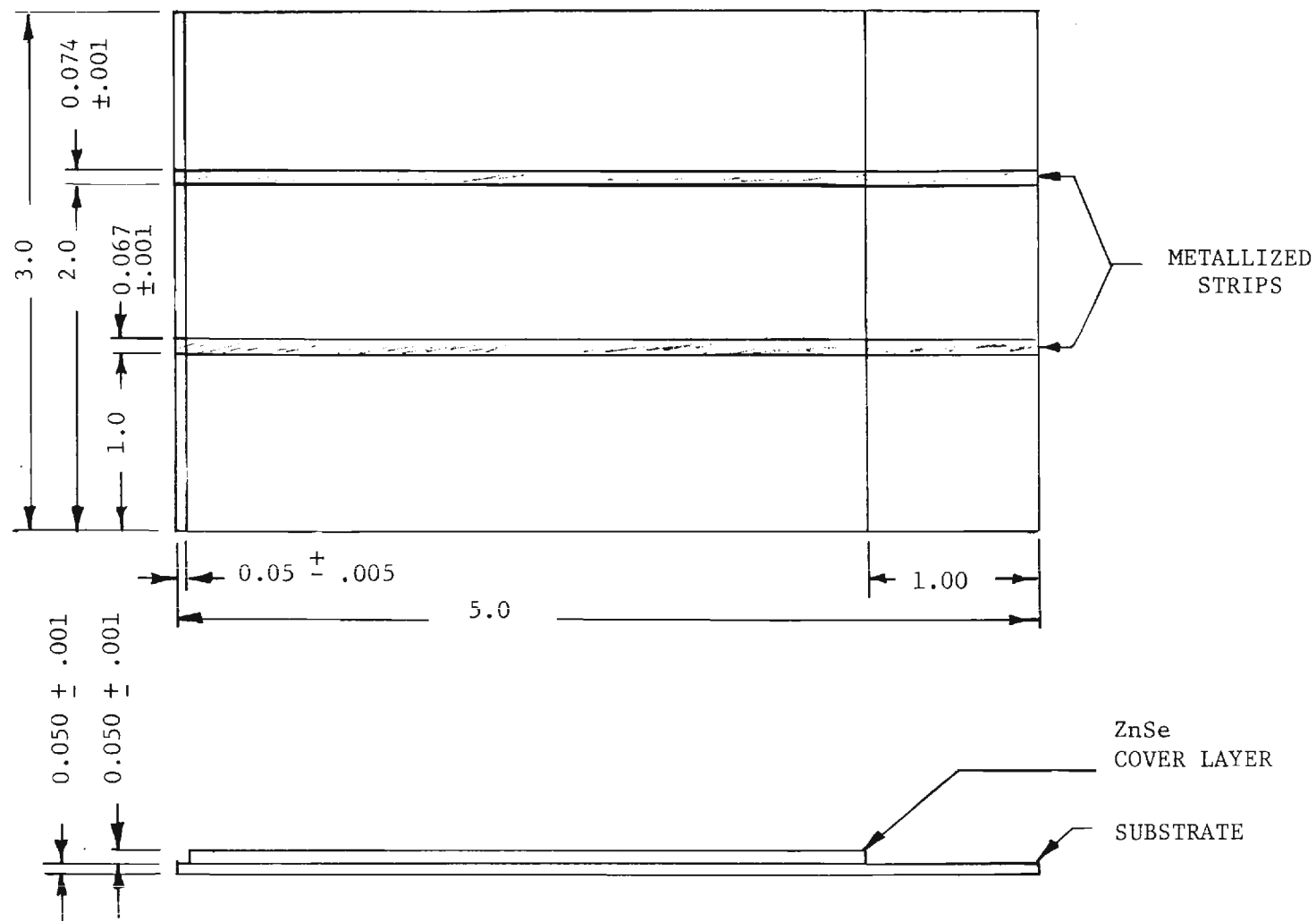


Figure 3-4. Sketch of a CVD ZnSe test piece to be fabricated for evaluation of microstrip transmission lines and fabrication processes.

for attachment of the WG/MS transition at one end and a matched termination at the other end. Based on Equation (3-1) and measurements indicating $K_e = 7$, the narrower MS line has an impedance $Z_0 = 42$ Ohms, and the broader one has $Z_0 = 40$ Ohms. We expect the transition will be more effective with the broader line. However, tests have not been possible, because CVD, Inc., experienced unexpected problems in fabrication of the test piece, and it could not be completed during the program.

A monolithic test piece with MS lines is needed to finalize the MS design, but it is needed even more to evaluate the microwave and mmW attenuation associated with the structure and fabrication process. For preliminary tests, Georgia Tech EES applied gold metallization patterns to ZnSe substrates. Sputtering and plating were combined to obtain a metal thickness of 23,000 Angstroms, which is three skin-depths at 10 GHz, and the attenuation was small enough to be not easily measured. CVD, Inc. has found that good electrical conductors, such as gold, silver, and copper, do not survive multiple CVD operations. After considerable experimentation, platinum has been selected for the metallized circuits. The skin-depth in platinum at 10 GHz is 15,800 Angstroms, and at 45 GHz, it is 7,450 Angstroms. Therefore, thicknesses of at least 20,000 to 30,000 Angstroms are required, and the metal conductivity must not be degraded by multiple (high-temperature) CVD operations. The required thicknesses are achievable, but it remains to be established that the conductivity of the metallized circuits is preserved at a level comparable to the conductivity of bulk metal. It is expected that the required tests may still be conducted in the near future.

C. Waveguide Transition

Because all mmW test instrumentation is implemented in waveguide, the development of a waveguide-to-microstrip (WG/MS) transition was necessary. Requirements for this transition were the following:

1. Construction that permits interchanging microstrip circuits with good repeatability of electrical performance.
2. Impedance transformation between waveguide and microstrip structures without reflection or radiation.

3. Operational bandwidth adequate to allow for unanticipated variations in the resonant frequency of the antenna.

The transition was designed as a two-stage device, where the first stage transforms rectangular waveguide to single-ridged waveguide, and the second stage transforms ridged waveguide to microstrip line. Figure 3-5 shows a drawing of the transition. This device was fabricated for tests of X-band components, using X-band (WR-90) waveguide. The ridged transition was formed by introducing a tapered metallic vane through the center of the broad wall of the X-band waveguide. The width of the vane is 0.090 inch, and the insertion depth of the vane is described by a cosine contour over an axial length of 3.0 inches. At the open end of the waveguide, the gap between the bottom of the vane and the bottom of the waveguide can be adjusted to match the thickness of the microstrip substrate. The adjustment permits the vane to be contacted and clamped on the strip conductor of the MS line.

The choice of a cosine taper was based on previous experience with ridged waveguide transitions. The width and length of the vane were determined using a fairly well known calculation of the reflection from a transmission line with a non-uniform characteristic impedance and propagation constant [8]. If the impedance is $Z(x)$ and the propagation constant is $\gamma(x)$ at any distance x along the line, the reflection coefficient R at $x = 0$ is given by

$$R = \int_0^L \frac{Z'(x)}{Z(x)} \exp \left[-2 \int_0^x \gamma(s) ds \right] dx \quad (3-4)$$

This model assumes the impedance variation occurs between $x = 0$ and $x = L$, and it assumes that the fields are accurately described by a single mode. The model is not accurate at the microstrip junction, but it is reasonably accurate in the ridged waveguide section. Results of a numerical integration are shown in Figure 3-6, which presents the amplitude of the reflection coefficient as a function of frequency. The calculated result indicates that, excluding the microstrip junction, the transition should cause very little reflection.

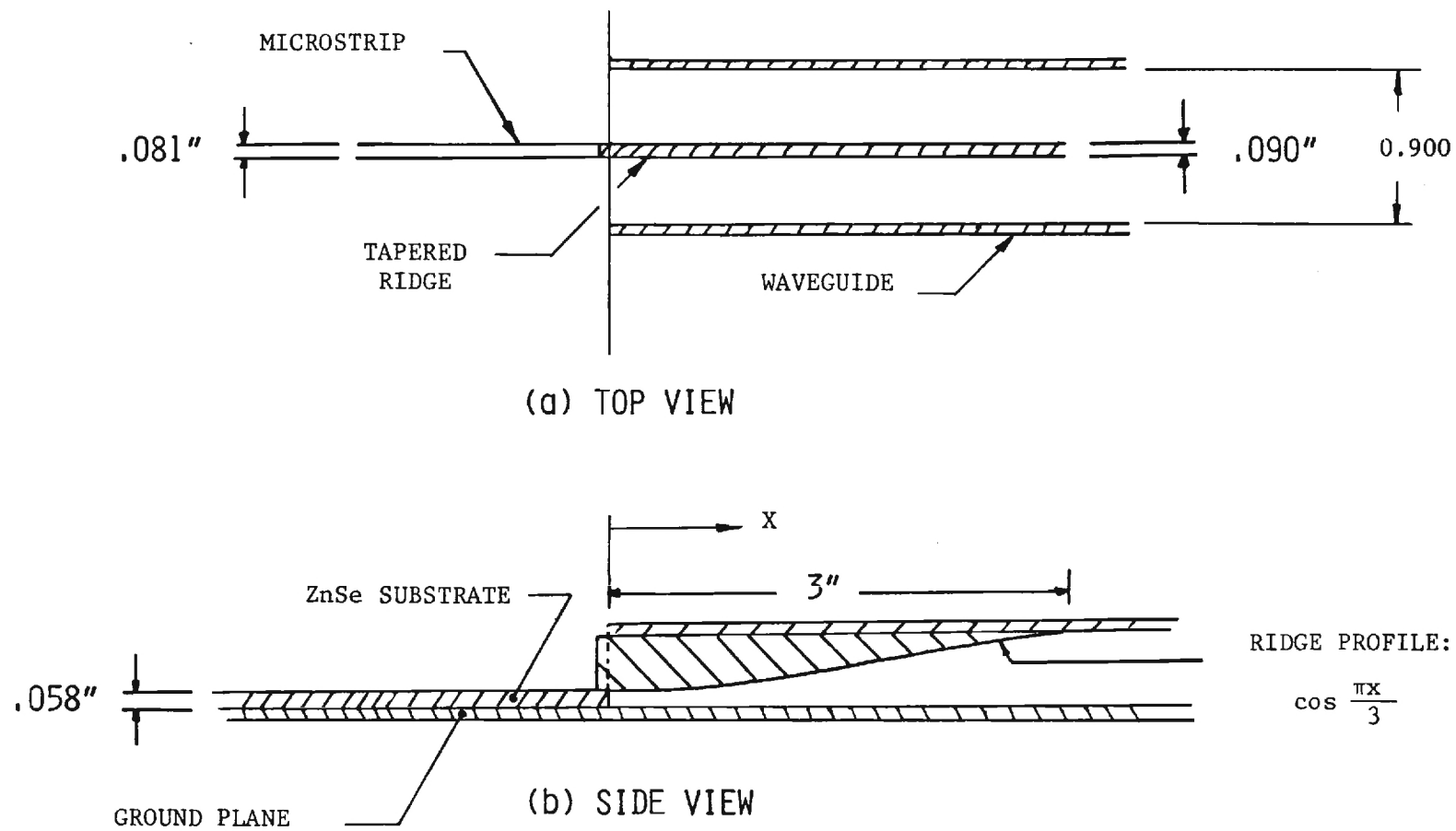


Figure 3-5. Ridged waveguide transition from X-band waveguide to microstrip.

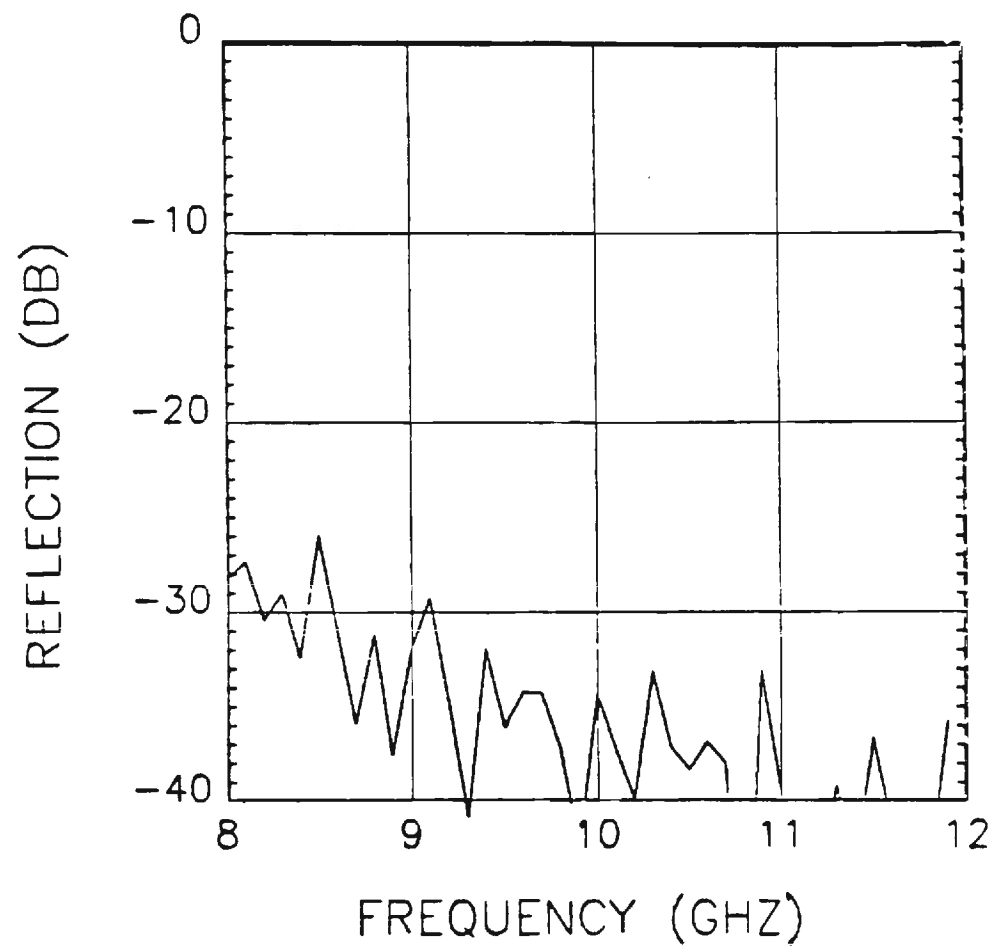


Figure 3-6. Calculated reflection for the waveguide transition.

The vane, or ridge, provides a low reflection impedance transformation within the waveguide, but equally important for this application, it concentrates the field in the small region between the vane and the lower waveguide wall. This concentration makes possible a non-radiating junction with the MS line. It was determined experimentally that, if the width of the vane was reduced much less than 0.090 inch, the field was not contained under the vane, and the MS junction caused radiation losses.

This construction provided a very satisfactory WG/MS transition. It worked well with MS lines on low-K plastic substrates. It also worked well with the high-K ZnSe substrates, but then it was necessary to insert a tuning screw beneath the vane, near the open end of the waveguide. A 6-32 screw was inserted through the bottom (broad) wall of the waveguide, at a distance of 0.09 inches from the open end of the waveguide.

Measurements of reflections from the transition, under several loading conditions, are shown in Figures 3-7(a), (b) and 3-8(a), (b). In each case, the "Reference Short" trace is provided to establish the reflection level from a waveguide short placed at the end of the rectangular waveguide. In Figures 3-7, the MS line is formed on a low-K plastic substrate (3M K-6098), and in Figures 3-8, the line is on ZnSe.

In Figures 3-7(a) and 3-8(a), the MS line is 5-inches long and is terminated in an open circuit. The measurement shows that a 2 to 3 dB loss is incurred in a round-trip path through the transition and MS line. Because open circuits, short circuits, and other discontinuities on MS line radiate energy, it cannot be determined from these results how much of the loss is due to dissipation and how much is due to radiation at the end of the line. However, it was determined by probing that radiation from the end of the line was significant (i.e., detectable), while radiation near the transition was not. Therefore, most of the loss is attributed to radiation from the open end of the MS line. It is significant that approximately the same losses were observed with gold-plated lines, copper-taped lines, plastic substrates, and ZnSe substrates. These observations suggest that conductor and dielectric dissipation do not contribute substantially to the loss.

In Figures 3-7(b) and 3-8(b), the MS lines are terminated in absorbing loads. The measured reflection is a coherent sum of a small reflection from the transition and a small reflection from the load. The occurrence

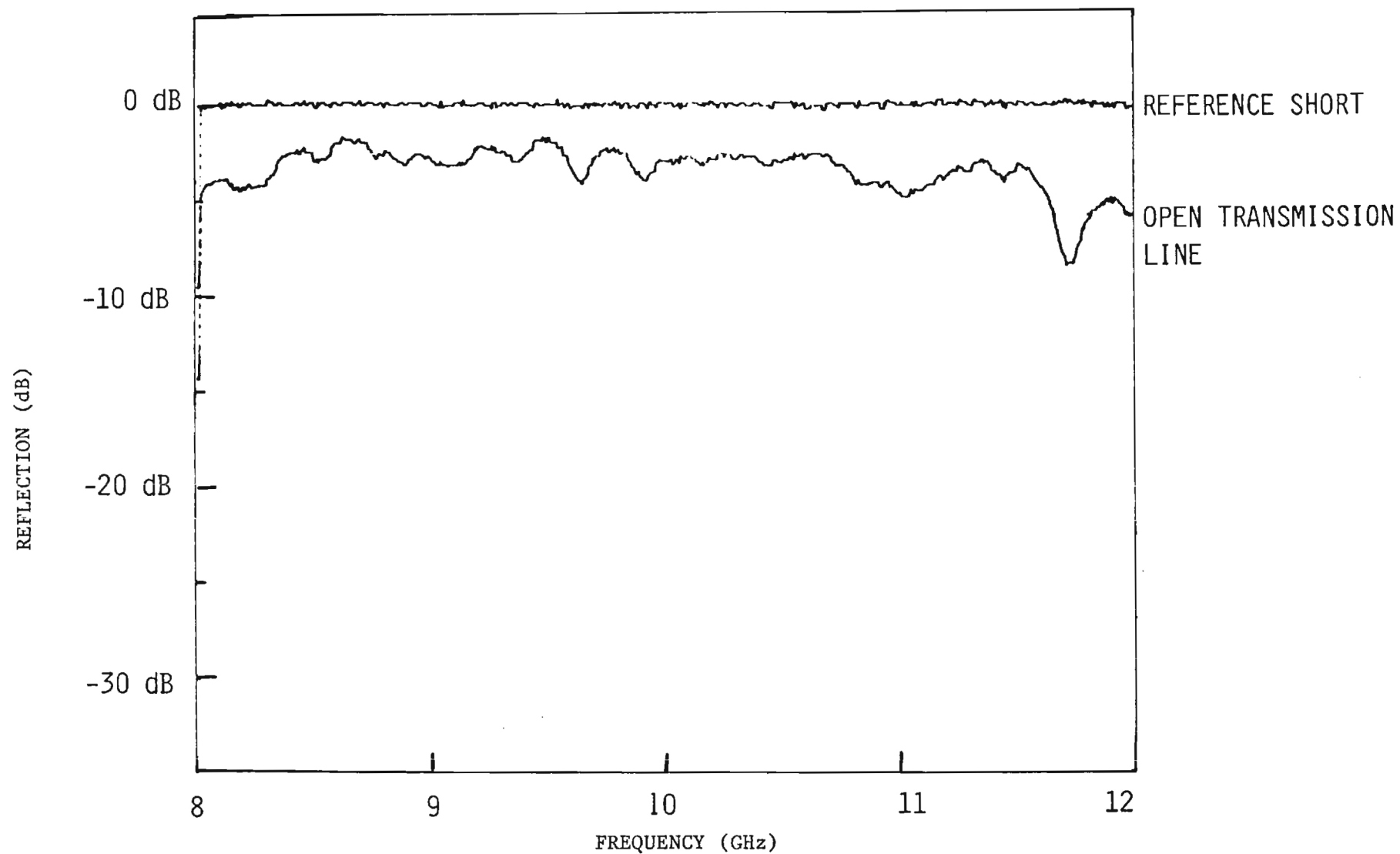


Figure 3-7(a). Reflection from a five-inch open-circuited MS transmission line on a plastic substrate (3M K-6098), measured through the WG/MS transition.

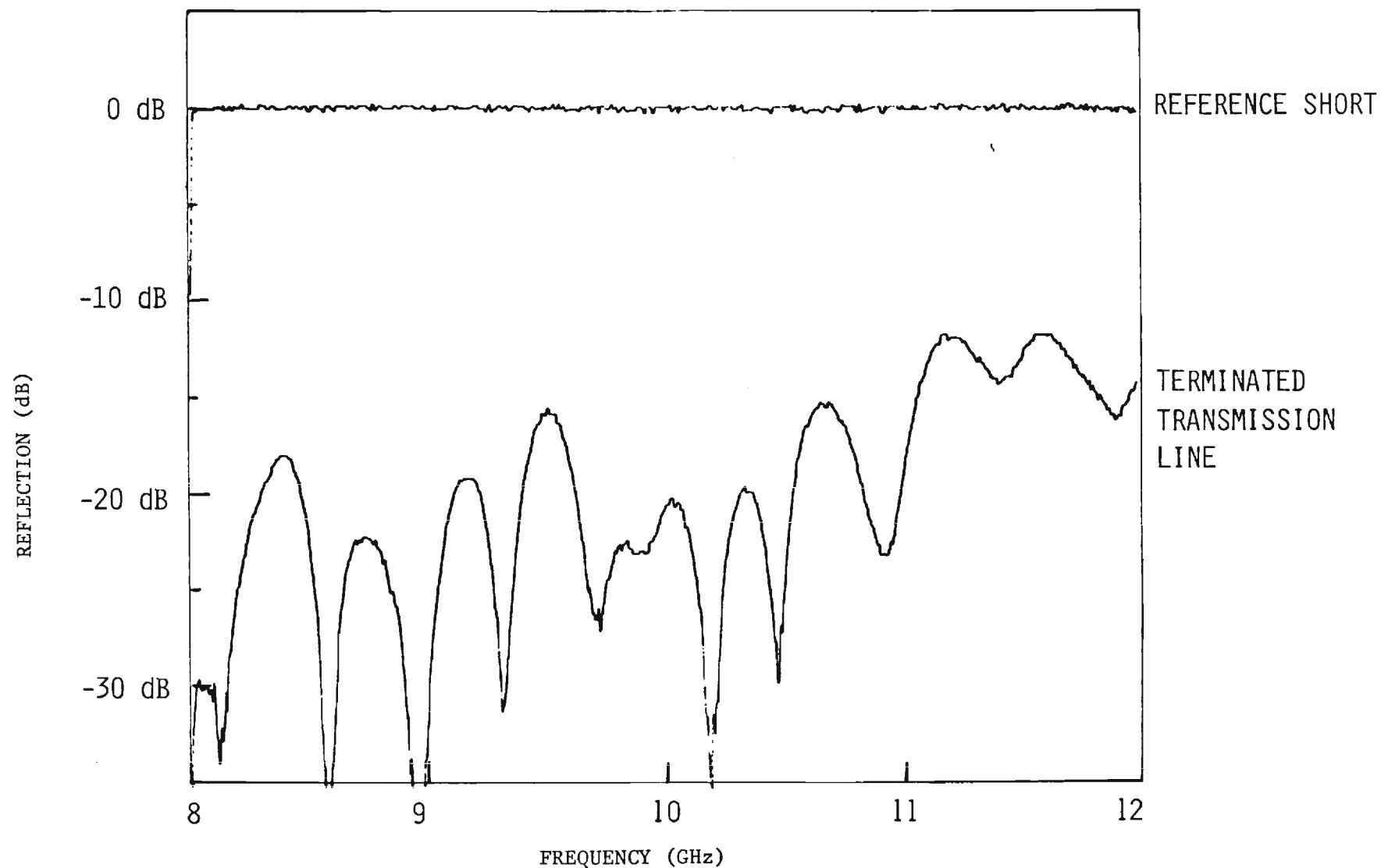


Figure 3-7(b). Reflection from a five-inch match-terminated MS transmission line on a plastic substrate (3M K-6098), measured through the WG/MS transition.

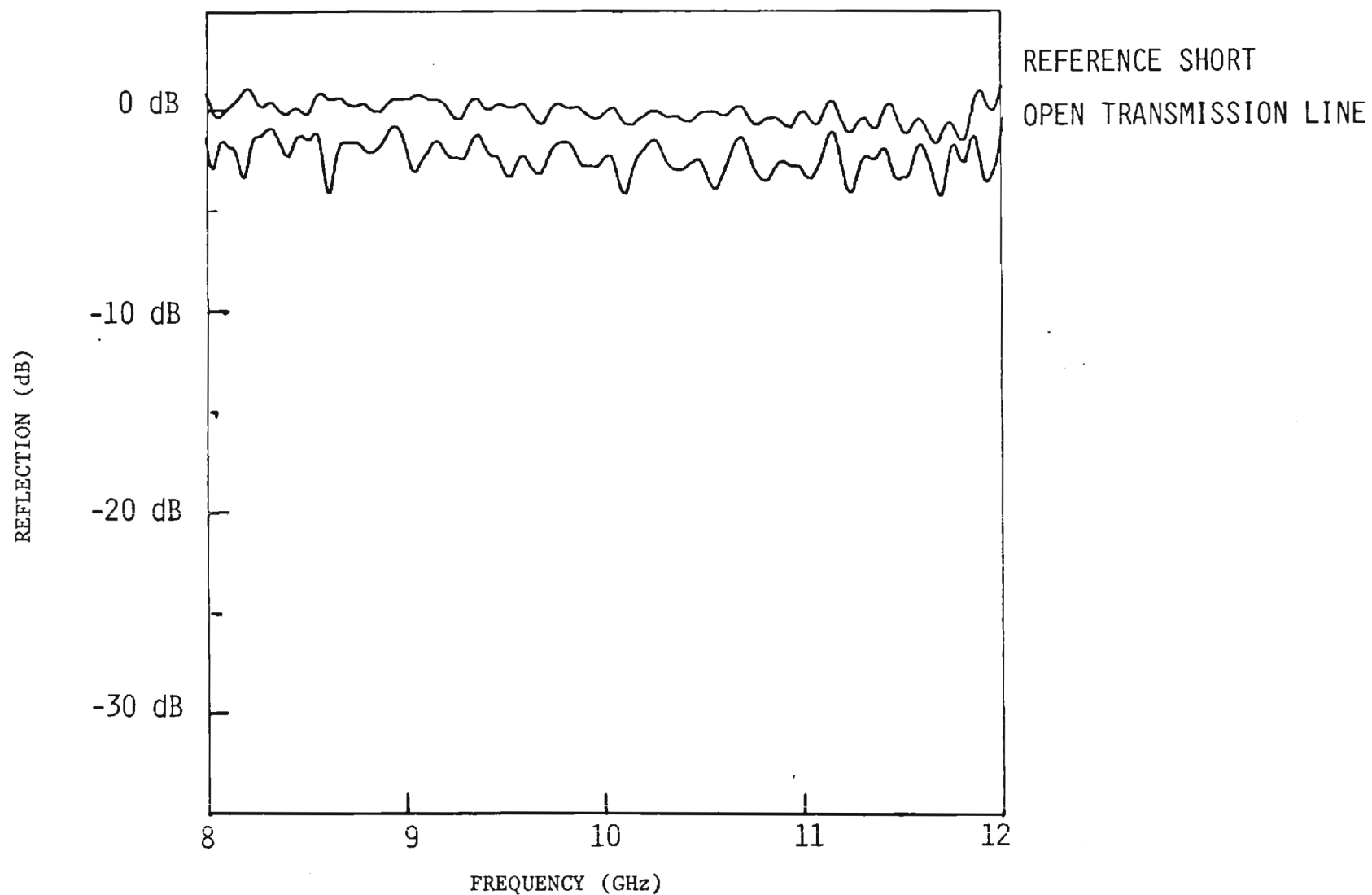


Figure 3-8(a). Reflection from a five-inch open-circuited MS transmission line on a CVD ZnSe substrate, measured through the WG/MS transition.

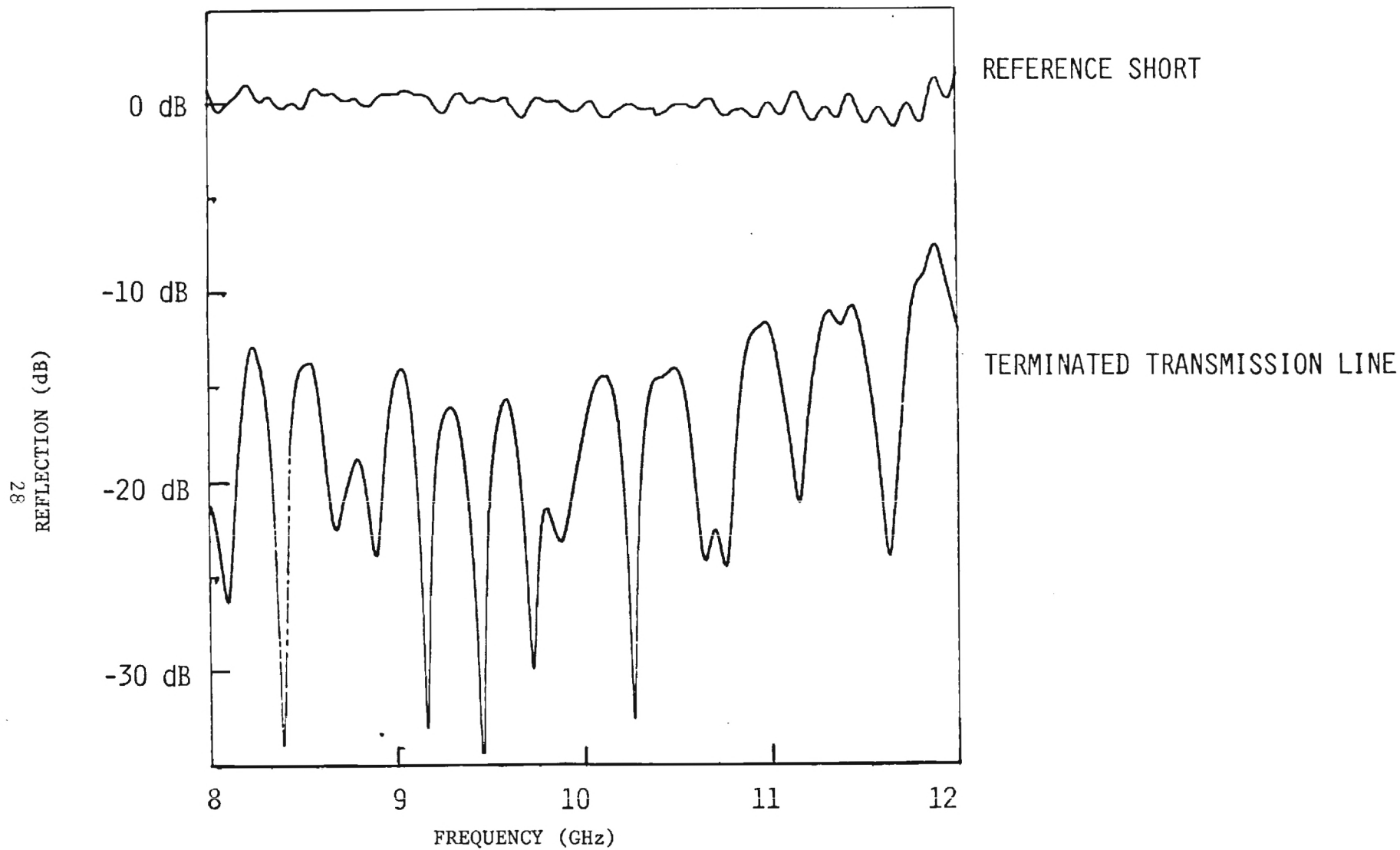


Figure 3-8(b). Reflection from a five-inch match-terminated MS transition line on a CVD ZnSe substrate, measured through the WG/MS transition.

of periodic deep nulls indicates out-of-phase summation (interference) of nearly equal signals, and the peaks indicate in-phase summation. Therefore, it can be inferred that the level of the transition reflection is about 6 dB below the peaks of the rippled traces. Near 10 GHz, the transition reflections are -20 dB or lower, which is adequate for this work. The transition has the potential to provide lower reflections, if that is required in future work.

D. Microstrip Termination

A non-reflecting termination was required for several testing functions and as one component of a non-resonant (traveling wave) array feed network.

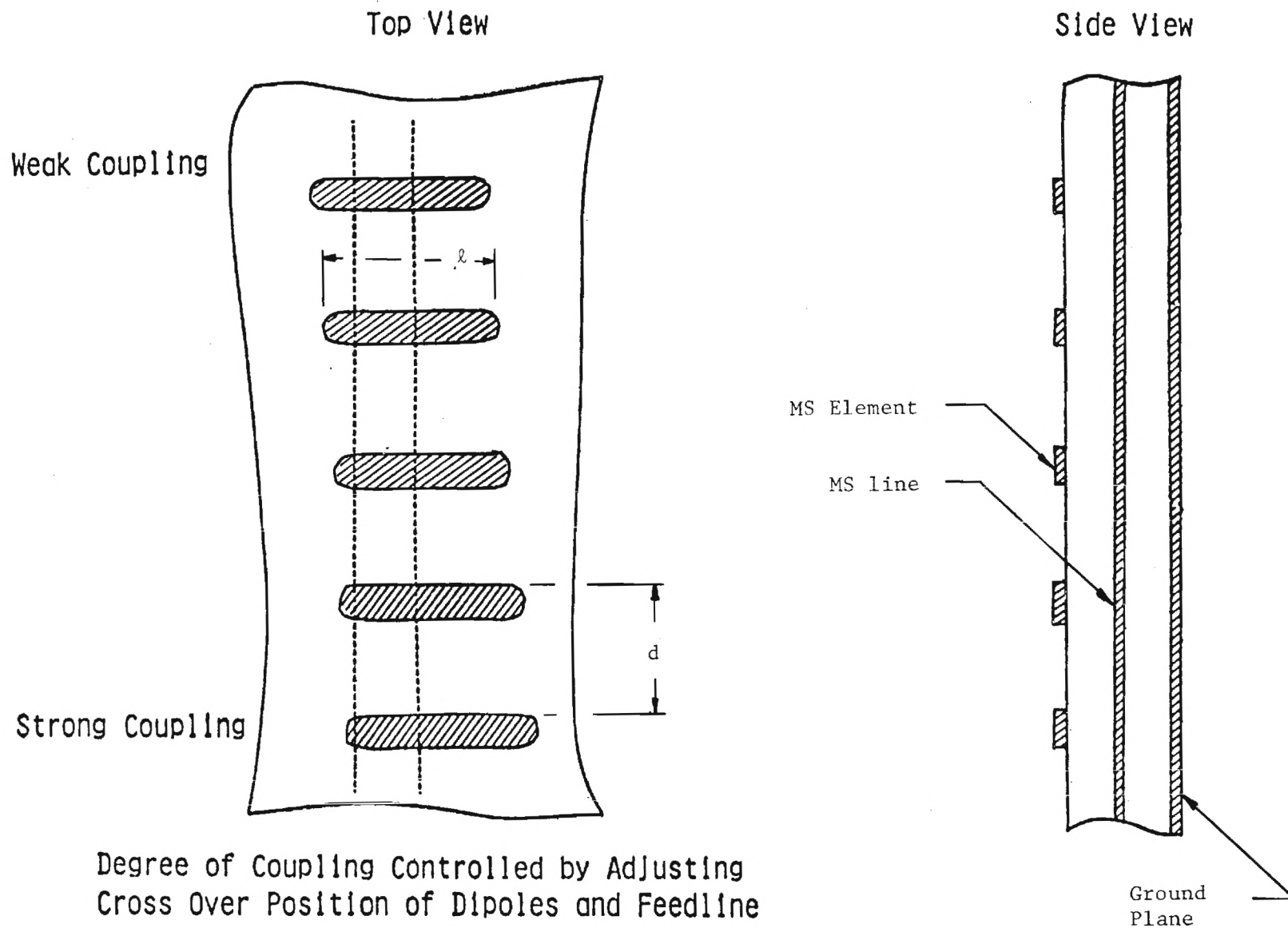
Initially, for MS lines on the low-K plastic substrates, satisfactory terminations were made using carbon and ferrite loaded plastic materials, such as Emerson and Cumming Eccosorb LS and FDS. Typically, a Vee-shaped notch was cut into a thin sheet of the absorber material. When the Vee was centered on and pressed against the MS line, reflection levels of about -25 dB could be obtained.

For MS lines on ZnSe substrates, the plastic absorbers did not couple strongly to the line and, therefore, did not provide adequate absorption. By experimentation with thin, resistive metallizations, a satisfactory termination was formed by sputtering a flared titanium patch at the end of the MS line. The thickness of the patch was not systematically optimized, but 500 Angstroms provided acceptable performance. The patch had the shape of an equilateral triangle with sides of about one inch. Reflection levels of about -20 dB were achieved.

E. Antenna Elements

The radiating elements developed for the array antenna are electromagnetically coupled, microstrip dipoles [3]. The concept is illustrated by a linear array of elements in Figure 3-9. The microstrip dipole element (MDE) is positioned asymmetrically above a microstrip transmission line. Almost any discontinuity will cause the MS line to radiate, and the MDE can be designed to operate as a controlled, radiating discontinuity.

Because the MDE is approximately the electromagnetic dual of a slot element, their radiation patterns have the same shape, but the electric and



Degree of Coupling Controlled by Adjusting
Cross Over Position of Dipoles and Feedline

Figure 3-9. Series-fed linear array electromagnetically coupled microstrip dipole elements (MDE).

magnetic fields (and polarizations) are interchanged. The pattern shape is a single broadside lobe, when the length of the element (MDE or slot) is one-half wavelength, or less. If the element is longer, the pattern is typically skewed away from broadside. The excitation of the element exhibits a resonant characteristic, as the length or frequency is varied, and the excitation is strongest when the length is approximately an integer multiple of one-half wavelength.

For the MDE array shown in Figure 3-9, the element excitation is controlled by the offset distance between the centerline of the MS line and the center of the MDE. When the element is centered over the MS line, the excitation is negligible or very weak, and for small offsets, the excitation increases with the amount of offset. The excitation is also a function of the thickness of the dielectric substrate that supports the elements above the MS line. However, it is not practical to fabricate an antenna where the substrate thickness varies from element to element, so relative excitation must be controlled by adjusting the element offsets.

In array applications, microstrip dipole or slot elements may have resonant or non-resonant lengths, and they may be positioned with resonant or non-resonant spacing. The configuration examined in this program utilizes resonant elements with resonant spacing. In such an array, all elements have approximately the same length (i.e., one-half wavelength), and the relative excitation of the elements is controlled by their position and orientation, relative to the transmission line feed. For this type of element, the objectives of the element design study are to determine (1) the resonant lengths for a given configuration, (2) the element positions relative to the feed transmission line, and (3) the resonant spacing between elements. The precise nature of the transmission line feed structure (e.g., MS line for the MDE, or waveguide for the slot) and the presence of surrounding elements in an array have a strong effect in determining the exact resonant length. In highly developed designs, changes in the array surroundings or in relative excitation require compensating changes in resonant lengths, but such refinement is beyond the scope of this program.

To prevent the formation of spurious "grating" lobes as the beam is scanned from broadside ($\theta = 0$) to a maximum $\theta_{\max}$, the element spacing must not exceed

$$d_{\max} = \frac{\lambda_0}{1 + \sin \theta_{\max}}, \quad (3-5)$$

where λ_0 is the free-space wavelength.

To form a "resonant" array, the element spacing must be a multiple of a half wavelength, λ , as measured along the transmission line. If the radiating elements are initially assumed not to load (i.e., perturb) the transmission line, the transmission line wavelength is

$$\lambda = \lambda_0 K_e^{-1/2}, \quad (3-6)$$

where K_e is the effective dielectric constant; K_e was calculated to be 6.1, using Equation (3-2), for an uncovered line, and it was measured to be about 7, for a covered line. Therefore, the resonant spacing of

$$\begin{aligned} d &= \lambda \\ &= \lambda_0 / (2.65) \end{aligned} \quad (3-7)$$

does not exceed $d_{\max}$ for any possible scan angle. For 10 GHz operation, this spacing is $d = 0.446$ inches, and this value was used in the experimental configurations. To optimize the antenna design, a more precise determination of the wavelength λ , or the effective dielectric constant K_e , will be necessary. In particular, it will be necessary to take into account the loading effect of the periodically spaced elements.

Figure 3-10 shows a schematic circuit diagram for a linear array antenna that is formed by radiating elements spaced periodically along a transmission line. The line supports a propagating wave described by $V_0 \exp(-\gamma z)$, where $\gamma = \alpha + j\beta$ is the propagation constant, α is the attenuation constant, $\beta = 2\pi/\lambda$ is the phase constant, and λ is the wavelength along the line. The elements are represented by shunt admittances $Y_n = g_n + jb_n$, and the periodic spacing is d . For a lossless, non-radiating transmission line, the attenuation constant is $\alpha = 0$. For a resonant element, the admittance is $Y_n = g_n$, and for a resonant array, the spacing is usually $d = \lambda/2$ or $d = \lambda$.

$$Y_n = g_n + jb_n$$

LOSSLESS CASE: $\alpha = 0, \beta = \frac{2\pi}{\lambda}$
 RESONANT ELEMENT: $b_n = 0$
 RESONANT ARRAY: $d = \lambda$

Figure 3-10. Circuit model for a series-fed linear array.

To achieve a resonant element, the length must be adjusted to be approximately a multiple of one-half wavelength. The element radiation pattern desired for this application requires a single half-wavelength element. The effective wavelength for this determination is neither λ_0 nor $\lambda = \lambda_0 K_e^{-1/2}$, but it is more nearly $\lambda_d = \lambda_0 K^{-1/2}$, where K is the dielectric constant of the substrate. The exact value is affected by the strength of the coupling to the transmission line, by the thickness of the substrate, and by the proximity of other radiating elements. Therefore, the approximate length for a resonant microstrip dipole element is given by

$$\begin{aligned} \ell &= \lambda_d/2 \\ &= \lambda_0/(2K^{1/2}) . \end{aligned} \quad (3-8)$$

For 10 GHz operation, the MDE length is $\ell = 0.197$ inches.

The resonant linear array forms a fan-shaped beam in the broadside direction ($\theta=0$). The sidelobe levels are determined by the relative excitation of the elements. If the elements are in-phase (i.e., resonant) and equally excited (i.e., uniform aperture distribution), the maximum sidelobe level is 13 dB below the peak of the main beam. Lower sidelobe levels are achieved by exciting the central elements more strongly than the outer elements (i.e., tapered aperture distribution). The element excitations are adjusted by changing the admittances Y_n . With the circuit model in Figure 3-10 and with a resonant array of resonant elements, a straightforward analysis of the "ladder" network shows that the input admittance is

$$Y_{in} = \sum_{n=1}^N g_n, \quad (3-9)$$

the input power is

$$\begin{aligned} P_{in} &= \sum_{n=1}^N P_n \\ &= \frac{1}{2} V_0^2 \sum_{n=1}^N g_n , \end{aligned} \quad (3-10)$$

and the relative power radiated per element is

$$\begin{aligned} \frac{P_n}{P_{in}} &= \frac{g_n}{\sum_{m=1}^N g_m} \\ &= \frac{g_n}{Y_{in}} \end{aligned} \quad (3-11)$$

Equation (3-9) provides a design constraint associated with impedance matching and gain of the antenna, and Equation (3-11) provides a constraint associated with the sidelobe requirements. A uniformly excited array is achieved by making all elements identical. For the microstrip dipole element, the information needed to design an array is resonant element conductance as a function of displacement from the center of the feed transmission line. As has been discussed, the resonant frequency of the element (i.e., when $b_n = 0$) will also vary with displacement; this is a secondary effect, but it complicates the measurement of g_n . To develop an optimum design, theoretical models should be developed to describe the variation of element admittance with frequency and displacement. For this program, the element admittance was determined from experimental measurements.

Figures 3-11, 12, and 13 show Smith chart plots of the input impedance of three different five-element arrays. The elements have lengths of $\ell = 0.20, 0.40, \text{ and } 0.50$ inches, and in each case the element spacing is $d = 0.45$ inches. The data in Figure 3-11 verify that the desired resonances are obtained near the predicted values of $\ell = 0.197$ inches and $d = 0.446$ inches, at a frequency near 10 GHz. (A resonance is indicated by a loop in the locus of impedance versus frequency, and a "good" impedance match occurs when the loop is near the center of the Smith chart.)

The best impedance match was achieved with the elements displaced from the transmission line by the amount shown in Figure 3-11. For this particular configuration, the element conductance at resonance can be calculated from Equation (3-9). The input impedance at resonance (i.e., when the loop intersects the vertical $b = 0$ line) is $Z_{in} = 0.7$, and this

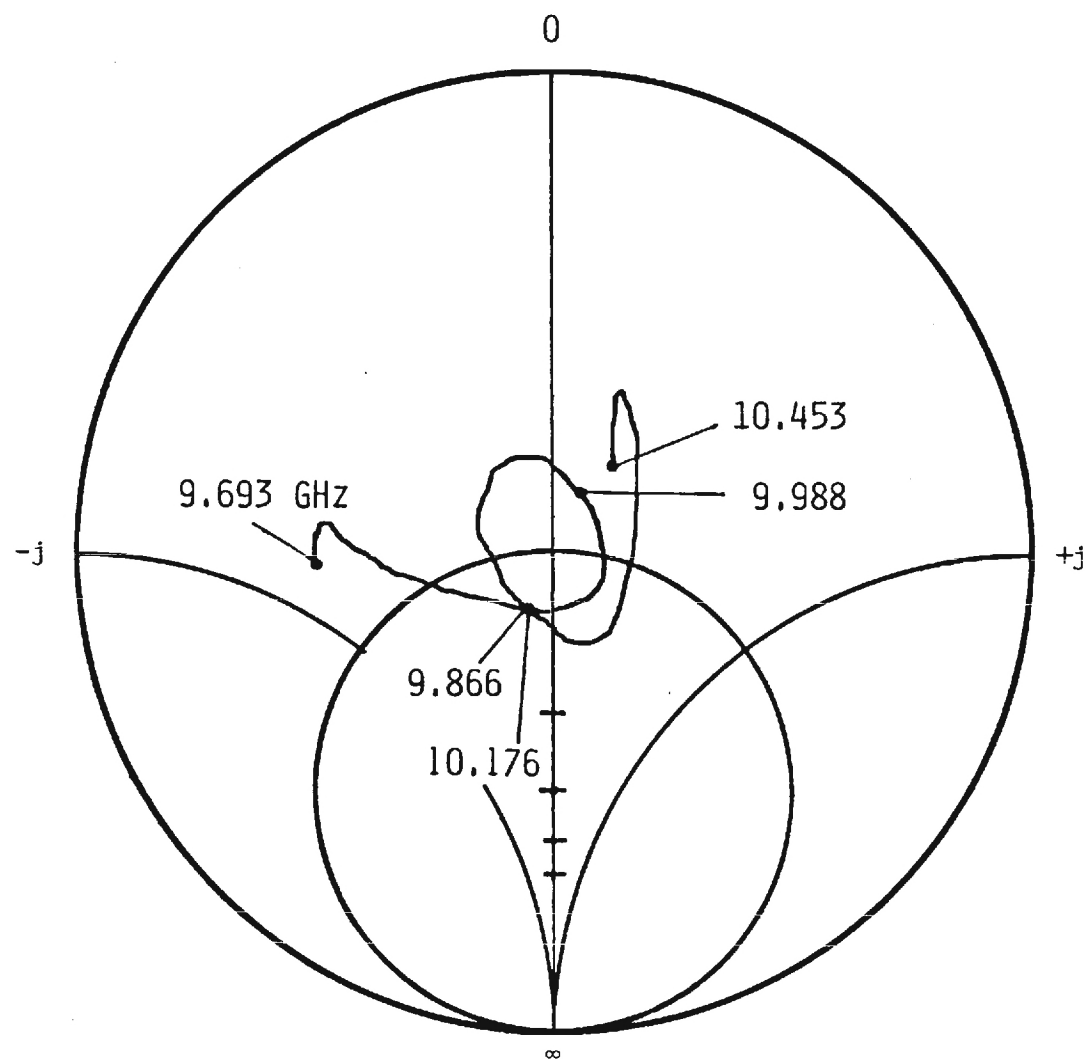
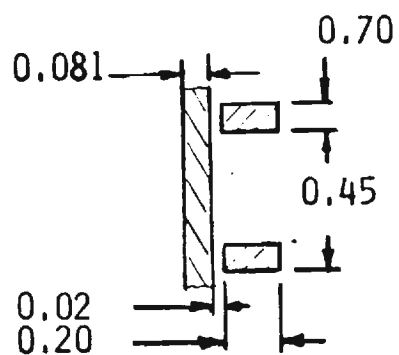


Figure 3-11. Measured impedance of five-element array of resonant half-wavelength elements.

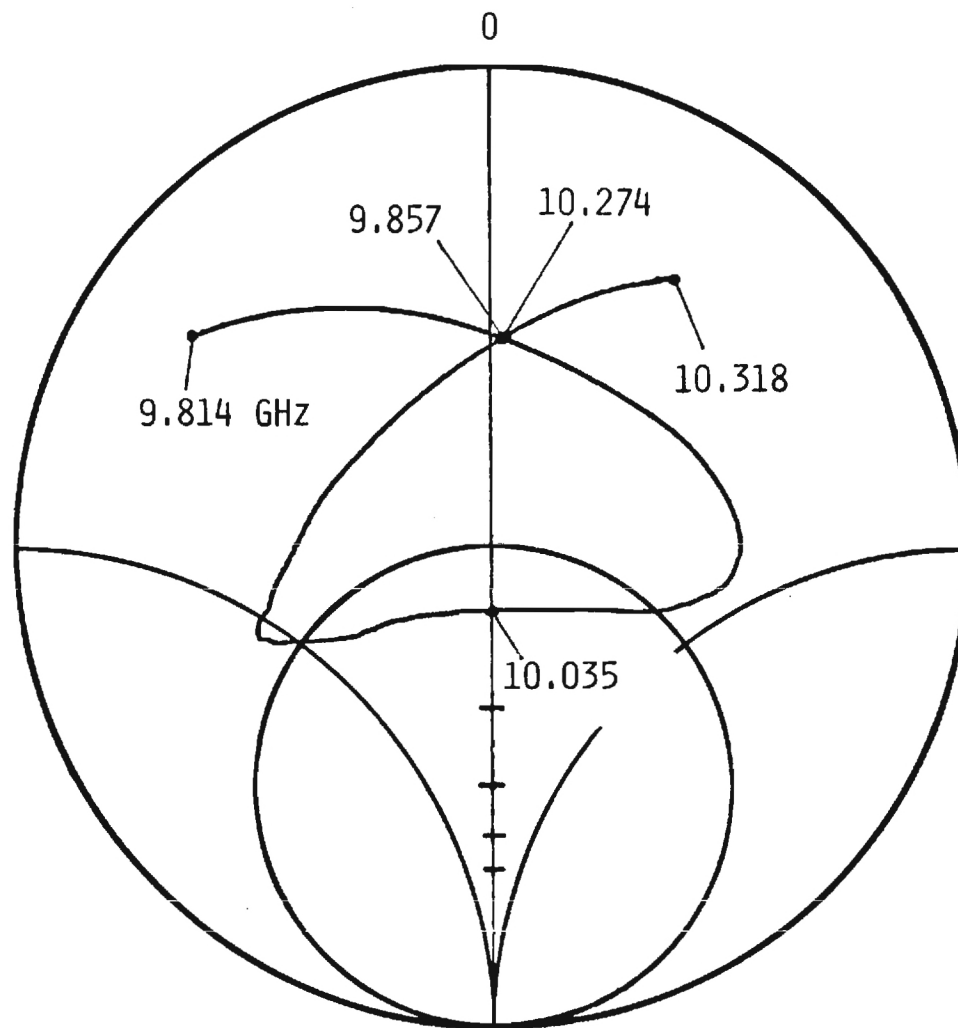
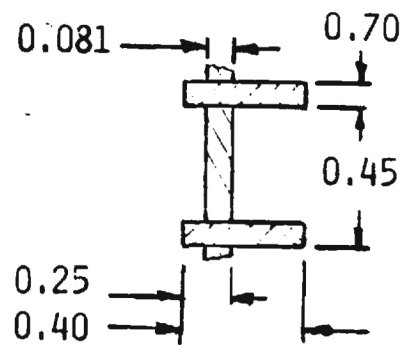


Figure 3-12. Measured impedance of five-element array of slightly short one-wavelength elements.

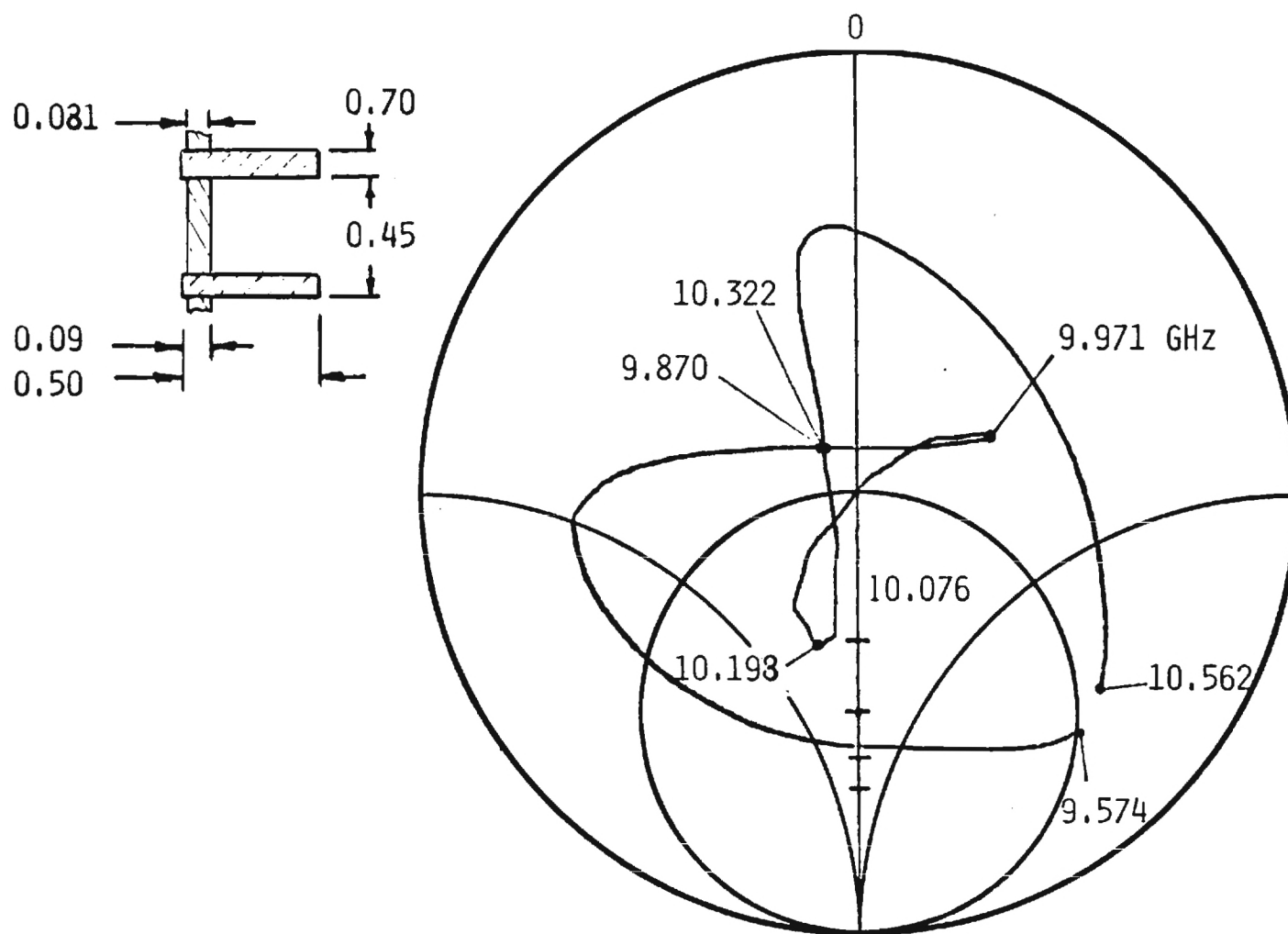


Figure 3-13. Measured impedance of five-element array of slightly long one-wavelength elements.

corresponds to an admittance $Y_{in} = 1/Z_{in} = 1.43$. Because the array consists of five identical elements, the element conductance is $g_n = Y_{in}/5 = 0.286$. Additional measurements of this type were used to determine conductances for other element displacements. However, repeatability of these measurements was not good, both because of a difficulty in manually positioning the elements relative to the transmission line, and because small air gaps tended to form between the plates of ZnSe. The 0.05 inch thick plates supplied by CVD, Inc., were used for all of these experiments, but the multilayer structures were formed by stacking and visually aligning plates, rather than as precision monolithic structures. The experiments demonstrated that an array of elements could be adjusted for well-matched resonant coupling, but precise, repeatable positioning was not possible.

Figures 3-12 and 3-13 show that the element develops a double resonance, when the length approaches a full wavelength. In Figure 3-12, the impedance locus has a single resonant loop, but the loop almost has two lobes. In Figure 3-13, two narrow, distinct loops have formed. The double resonance corresponds to two independent current distributions on the element. One distribution has a sinusoidal variation along the long dimension of the element, with a single maximum at the center; this is the dominant current on shorter, half-wavelength elements. The second distribution has a sinusoidal variation with a null at the center. On the longer, one-wavelength element, both current distributions exist, but they have slightly different resonant frequencies. The first current distribution produces the desired radiation pattern, with a single lobe in the broadside direction. The second distribution produces a double-lobed pattern, with a null in the broadside direction. When the two patterns are superimposed, a skewed beam is produced. Radiation patterns were not recorded, but by probing the field it was verified that the longer, one-wavelength elements had a skewed beam, while the half-wavelength elements had a symmetric, broadside beam. The mechanical rigidity of the stacked, multilayer structure was not considered adequate to permit the antenna to be mounted on a rotary positioner, as would be required to record radiation patterns.

Most of the experimental work undertaken on this program will need to be extended considerably in order to develop detailed design procedures,

but the multilayer structures will need to be fabricated as monolithic units. The work has certainly been successful in demonstrating that the concepts are viable and attractive.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The research conducted during this program resulted in the demonstration of a new concept for an array antenna that has good potential for application in a variety of millimeter-wave (mmW) radar systems, and especially in dual-mode infrared/millimeter-wave seeker sensors. The microstrip array is fabricated as a multilayer structure that has planar metalized circuits interleaved with a dielectric substrate. CVD, Inc. has demonstrated that monolithic multilayer structures can be formed by sequential depositions of zinc selenide substrates and platinum circuits. From this work, it can be concluded with reasonable certainty that a mmW array antenna can be incorporated as an integral part of a CVD ZnSe infrared window. The fabrication process, which uses optical polishing and photolithographic metallization, can be scaled to any mmW frequency range without the usual problems associated with surface finish and dimensional tolerances. This method for construction should make possible the development of several types of mmW microstrip array antennas that are equivalent to the "flatplate" slot array antennas that are in common use with microwave radars in monopulse seekers, terrain-following/terrain-avoidance radars, and area correlators. These are important applications for mmW systems, and substantial fabrication problems arise in scaling the mechanically machined slot arrays to the mmW range. Therefore, the work conducted on this program has important value, beyond the dual-mode seeker application.

The work discussed in this report is directly applicable to mmW antenna design, even though all the antenna experiments were conducted at X-band microwave frequencies. This is true because the entire geometry of the antenna can be easily and accurately scaled to any smaller (mmW) size by photographic reduction of masks, and because the dielectric properties of zinc selenide were measured and found to be relatively independent of frequency through the mmW range.

Only one important feasibility issue remains unresolved, and that is the attenuation associated with microstrip transmission lines formed by platinum in CVD ZnSe. After experimentation with a number of metals and processes, CVD, Inc. was successful in fabricating examples of monolithic

multilayer structures, but several spurious problems prevented the fabrication of a microstrip line that could be tested. Therefore, it is strongly recommended that work be undertaken to determine the attenuation of platinum transmission lines in CVD ZnSe substrates. This attenuation will increase with frequency and should be measured in any range of interest.

There is an almost unlimited amount of work that could be applied to develop antenna design procedures. As with slot arrays, there is an interplay between the spacing between elements, the lengths, offsets, and widths of individual elements, and the thicknesses of the various dielectric layers. This interplay must be thoroughly understood, before an antenna can be designed to difficult specifications (e.g., a low-sidelobe requirement). With slot arrays, this was accomplished first by very extensive parametric experiments and later by the development of sophisticated theoretical models. However, to justify such an investment, there must first be some successful demonstrations of complete array antennas. Therefore, the next logical steps in antenna development are to demonstrate a resonant linear array and then a planar array. For any complete array to be tested, the structure must be fabricated as a monolithic unit. To develop the linear array by an experimental process, it will be necessary to fabricate several sequences of structures, where each sequence contains several linear arrays with a single variable parameter. The three most important parameters are the spacing, lengths, and offsets of the elements. The offsets were the most difficult to characterize with repeatable experiments, where separate ZnSe plates were stacked and aligned, so a parametric study of offsets is certainly needed, when monolithic structures become available.

Several systems-related issues will eventually require attention. One is how to feed a planar array without excessive loss, and another is how electronic scanning may be incorporated. The original Georgia Tech proposal for this work [2] suggested a serpentine transmission-line (delay line) feed that could provide frequency controlled beam scanning. This and other approaches could be investigated. There is also a need to develop dual-mode sensor configurations that take advantage of the potential to incorporate a mmW antenna in an infrared window. The concepts studied in this program have great promise, and there seem to be unlimited opportunities for development.

SECTION V

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APPENDIX A
BRIEFING CHARTS



BOEING/CVD ANTENNA DEVELOPMENT PROGRAM

- TITLE - DEVELOPMENT OF DUAL IR/MM-WAVE
APERTURE ANTENNA
- CONTRACT - No. CH 6411-01 (BOEING/CVD)
 - No. 203 (CVD/GTRI)
 - No. A-3370 (GTRI/EES)
- TECHNICAL MONITOR - RAYMOND L. TAYLOR (CVD)
- PROJECT DIRECTOR - JAMES A. FULLER (EES/ECSL/EMED)
- TECHNICAL PERIOD - 30 SEPTEMBER 1982 TO 29 JULY 1983

ORIGINAL GUIDELINES FOR MMW ANTENNA

- BE INCORPORATED IN ZnSe IR WINDOW
- MINIMIZE BLOCKAGE OF IR SENSOR
- BE COMPATIBLE WITH CVD WINDOW FABRICATION
- HAVE POTENTIAL AS RADAR ANTENNA
- PROVIDE SOME FORM OF ELECTRONIC BEAM-SCANNING
- OPERATE AT 94 AND/OR 45 GHz

MM-WAVE ANTENNA DEVELOPMENT

- GOAL -

DEMONSTRATE ANTENNA CONCEPT

- APPLY MICROSTRIP ARRAY TECHNOLOGY
- INTEGRATE INTO CVD IR WINDOW (ZnSe)

- TECHNICAL REQUIREMENTS -

- DEVELOP SERIES-FED LINEAR ARRAY OF MS ELEMENTS
- DESIGN, (FAB), TEST FOR 45 GHz OPERATION
- DEVELOP ANALYTICAL MODELS

EXPERIMENTAL TASKS

- DESIGN WAVEGUIDE-TO-MICROSTRIP (WG/MS) TRANSITION
- DESIGN MS FEEDLINE
- DESIGN EM-COUPLED MS ARRAY ELEMENTS
 - FEEDLINE-TO-ELEMENT COUPLING
 - 12-ELEMENT RESONANT COLUMN
- DESIGN MS FEEDLINE TERMINATION
- MEASURE ELEMENT AND ARRAY ADMITTANCE
- MEASURE E-PLANE AND H-PLANE RADIATION PATTERNS

ANALYTICAL TASKS

- MODEL WG/MS FEEDLINE TRANSITION
 - CALCULATE RIDGED WG AND MS IMPEDANCES
 - MEASURE INPUT REFLECTION COEFFICIENT
- MODEL MS FEEDLINE
 - MEASURE DIELECTRIC PROPERTIES OF $ZnSe$
 - MEASURE MS ATTENUATION
 - CALCULATE PROPAGATION CONSTANT AND IMPEDANCE
- MODEL RADIATING ELEMENTS
 - ADAPT PUBLISHED RESULTS
(OLTMAN & HUEBNER, ELLIOT & STERN)
 - CALCULATE ARRAY PATTERNS



MICROWAVE DESIGN STAGES

<u>STAGE</u>	<u>FREQ. (GHz)</u>	<u>SUBSTRATE</u>	<u>K</u>	<u>THICKNESS (IN.)</u>	<u>Z(OHM)</u>	<u>LINE WIDTH (IN.)</u>
1	10	3M K-6098	2.45	.062	50	.229
2	10	CVD ZnSe	10	.050	50	.067
3	45	CVD ZnSe	10	.011	50	.015

SHORTED RECTANGULAR WAVEGUIDE MEASUREMENTS OF ZnSe SAMPLES

FREQUENCY: 44.3 GHz

<u>SAMPLE</u>	<u>LENGTH (IN)</u>	<u>K</u>	<u>tan δ</u>	
1	0.1857	12.0	0.045	} GOLD-PLATED
2	0.1446	10.9	0.002	
3	0.1037	12.5	0.150	
4	0.1858	11.1	0.044	
5	0.1442	10.0	0.022	
6	0.1038	10.6	0.014	

FABRY-PEROT CAVITY MEASUREMENTS OF ZnSe PLATES

FREQUENCY: 94 GHz

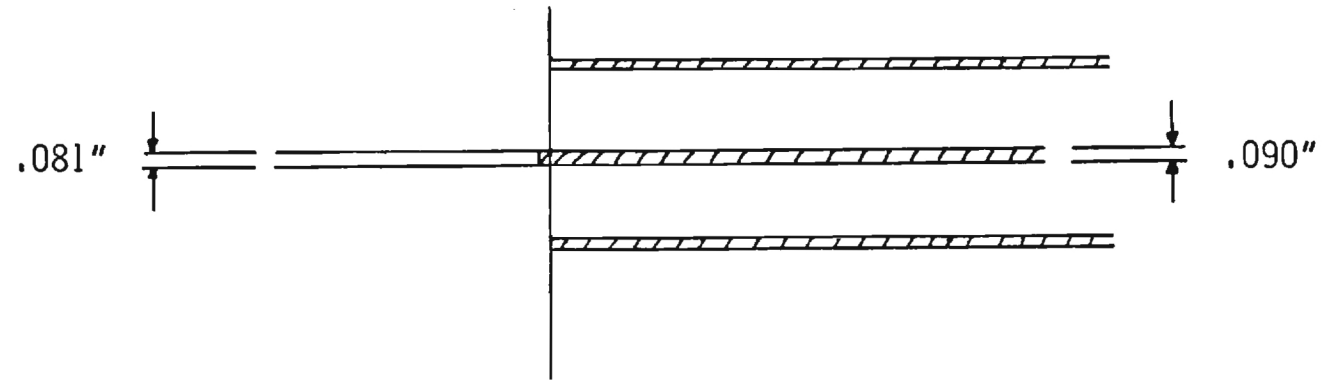
Individual Samples

Sample	Thickness (in.)	Refractive Index n	Dielectric Constant ϵ_r	Loss Tangent Tan δ
1	.054	$3.021 \pm .005$	$9.13 \pm .03$	$.0017 \pm .0005$
2	.053	$3.034 \pm .005$	$9.21 \pm .03$	$.0019 \pm .0005$
3	.047	$3.062 \pm .005$	$9.38 \pm .03$	$.0029 \pm .0005$
4	.059	$3.019 \pm .005$	$9.11 \pm .03$	*

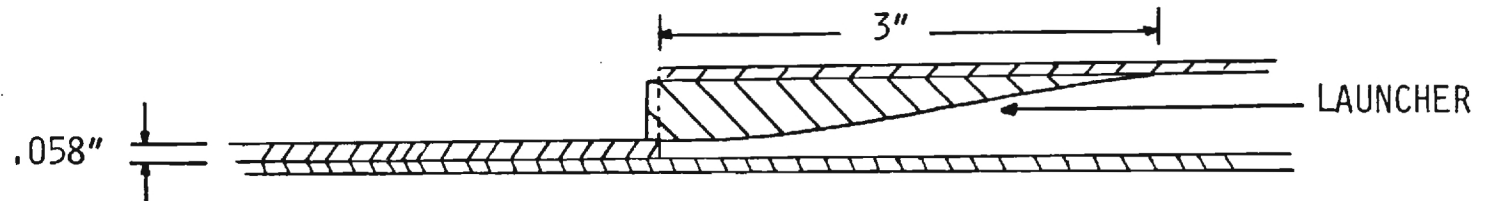
Stacks of Samples

Samples in Stack	Refractive Index n	Dielectric Constant ϵ_r	Loss Tangent Tan δ
1,2	$3.004 \pm .005$	$9.02 \pm .03$	$.0019 \pm .0005$
1,2,3	$3.036 \pm .005$	$9.22 \pm .03$	$.0025 \pm .0005$
1,2,3,4	$3.022 \pm .005$	$9.13 \pm .03$	$.0027 \pm .0005$

RIDGED WAVEGUIDE WG/MS TRANSITION

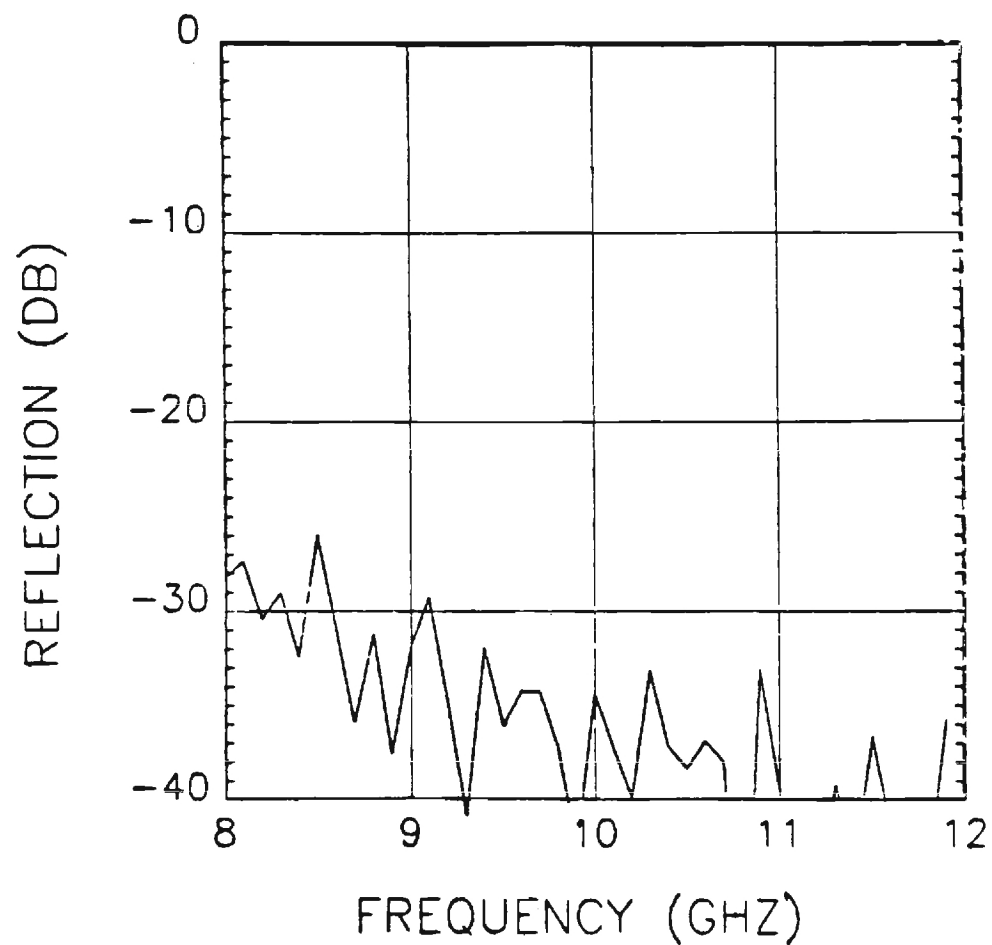


(a) TOP VIEW

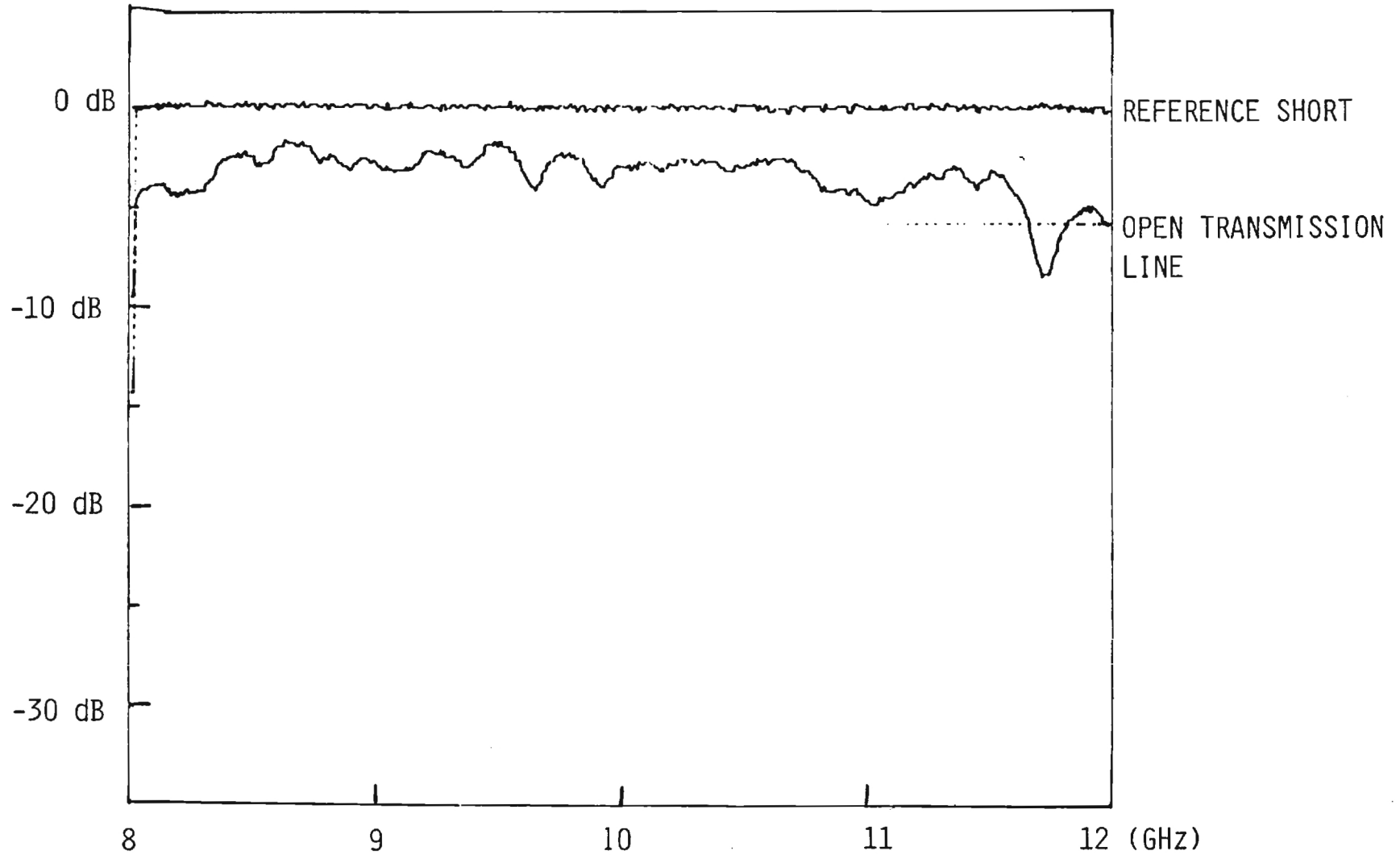


(b) SIDE VIEW

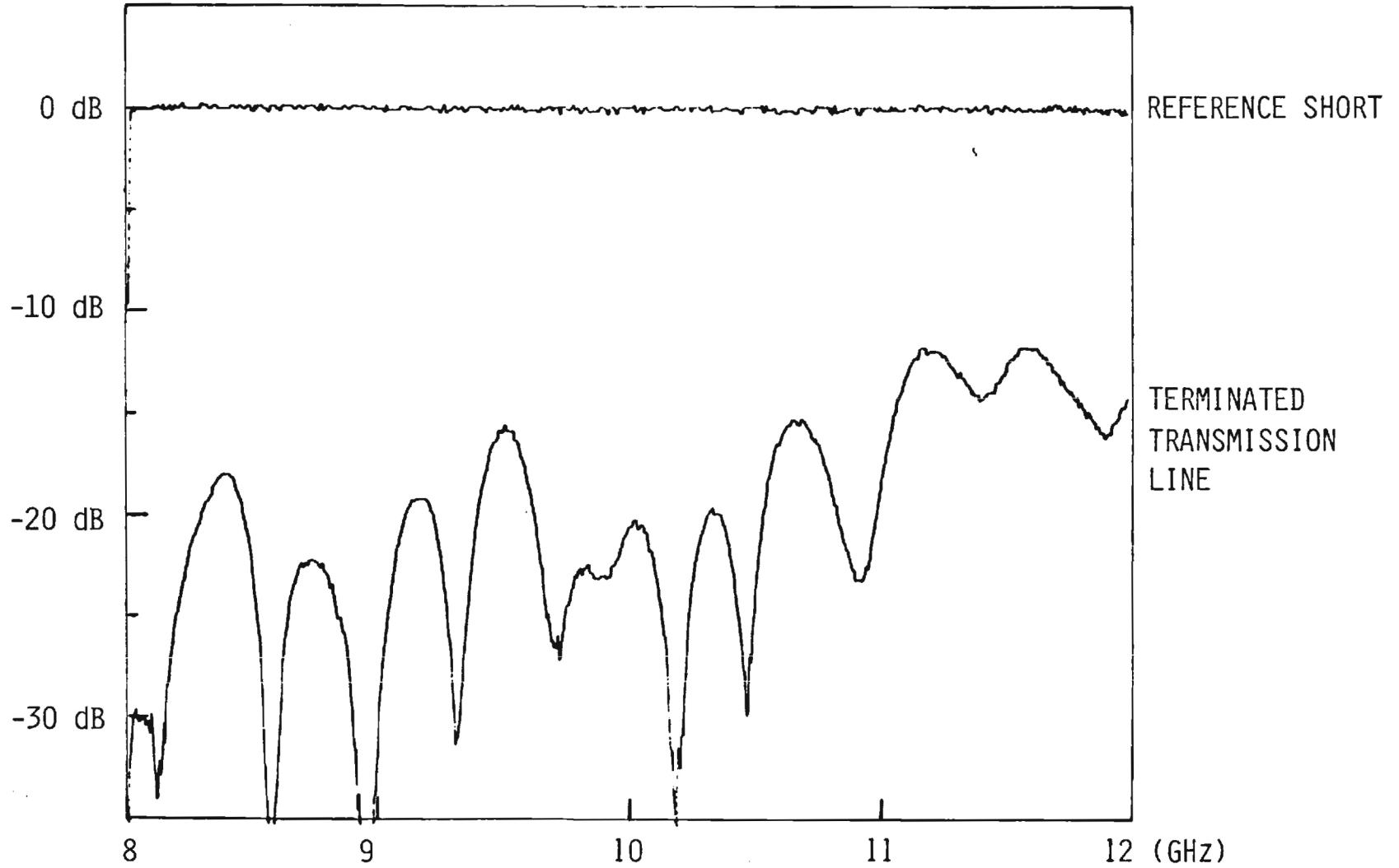
CALCULATED REFLECTION: X-BAND WAVEGUIDE LAUNCHER



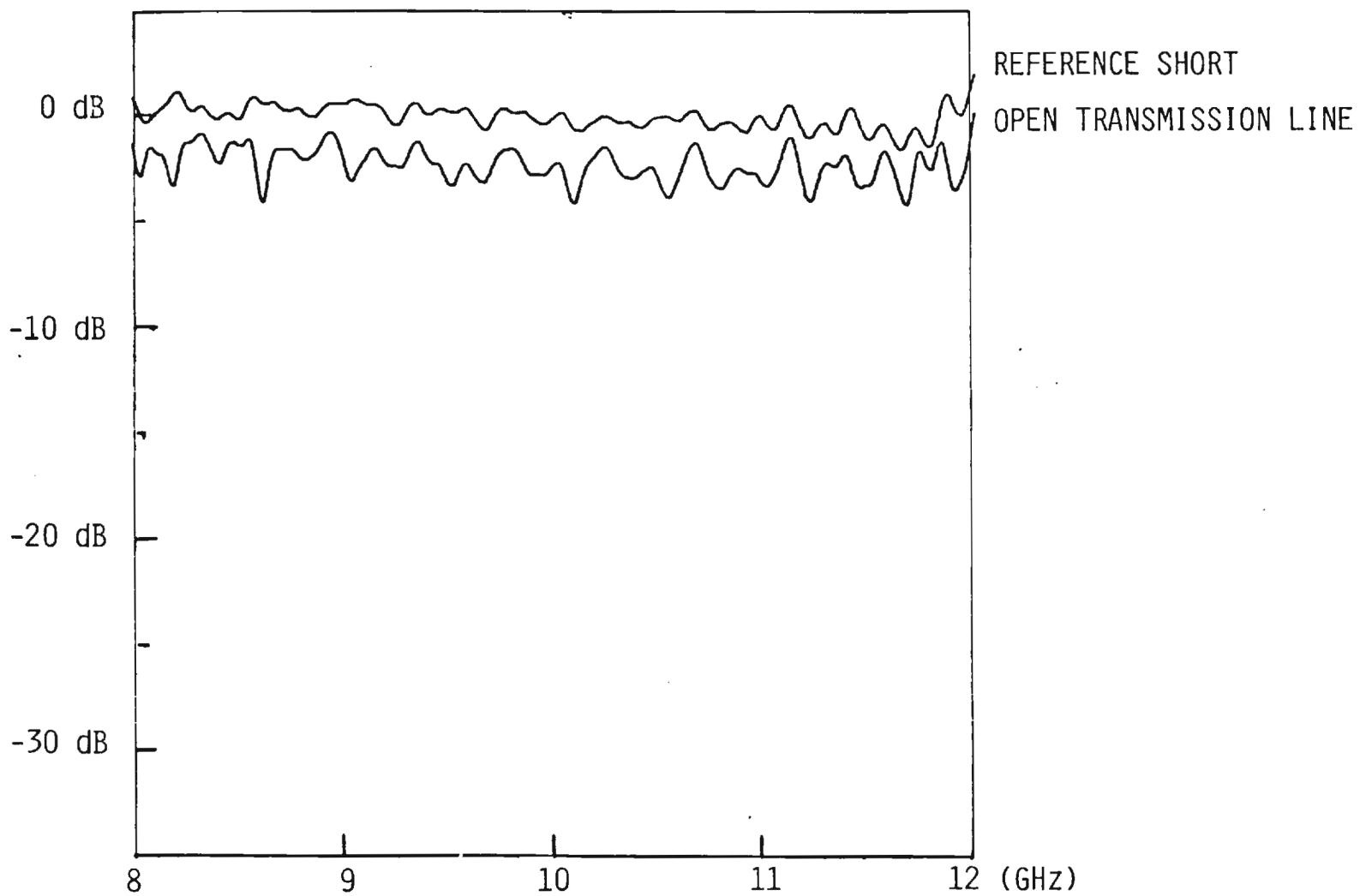
REFLECTION: OPEN TRANSMISSION LINE (K-6098)



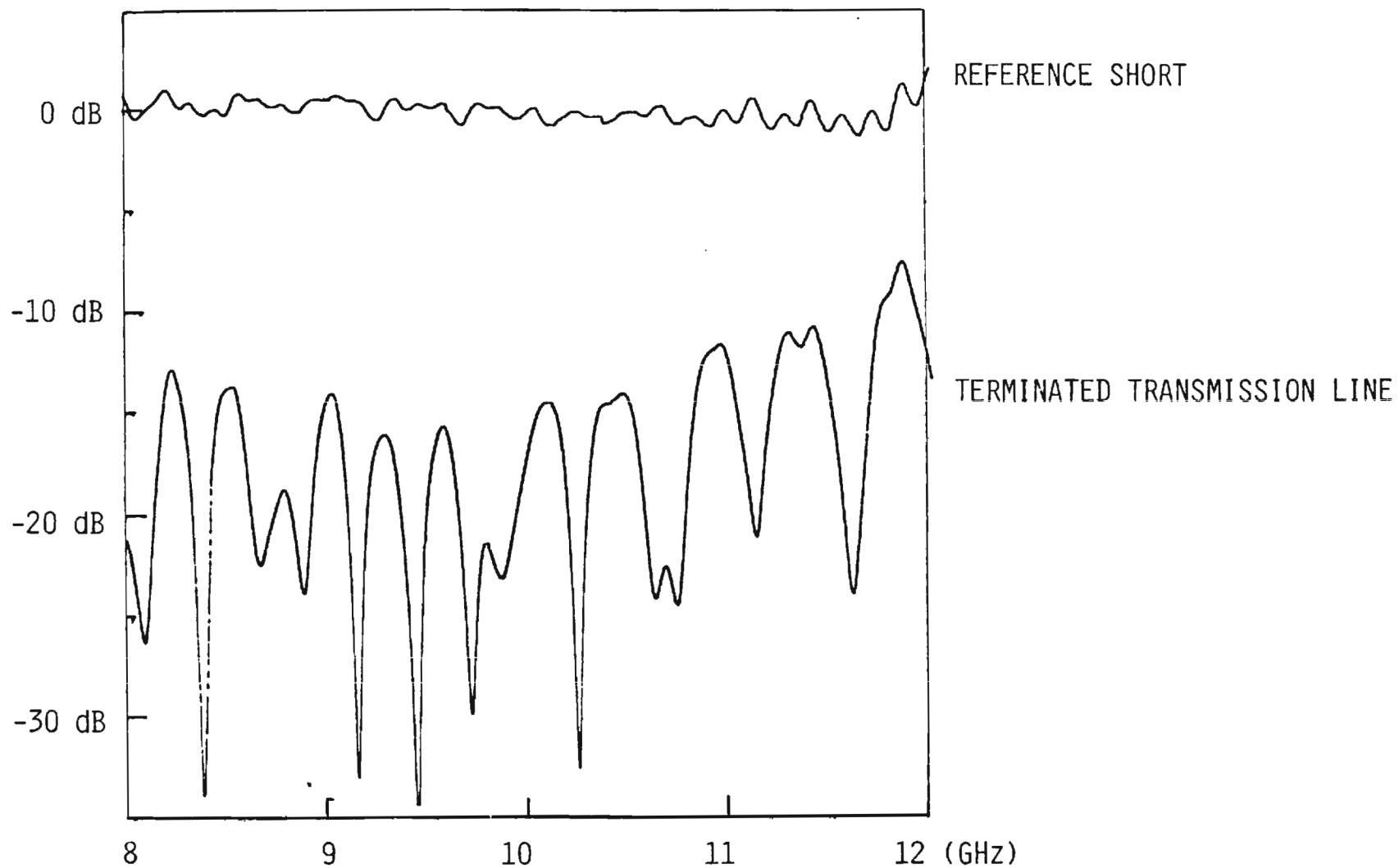
REFLECTION: TERMINATED TRANSMISSION LINE (K-6098)

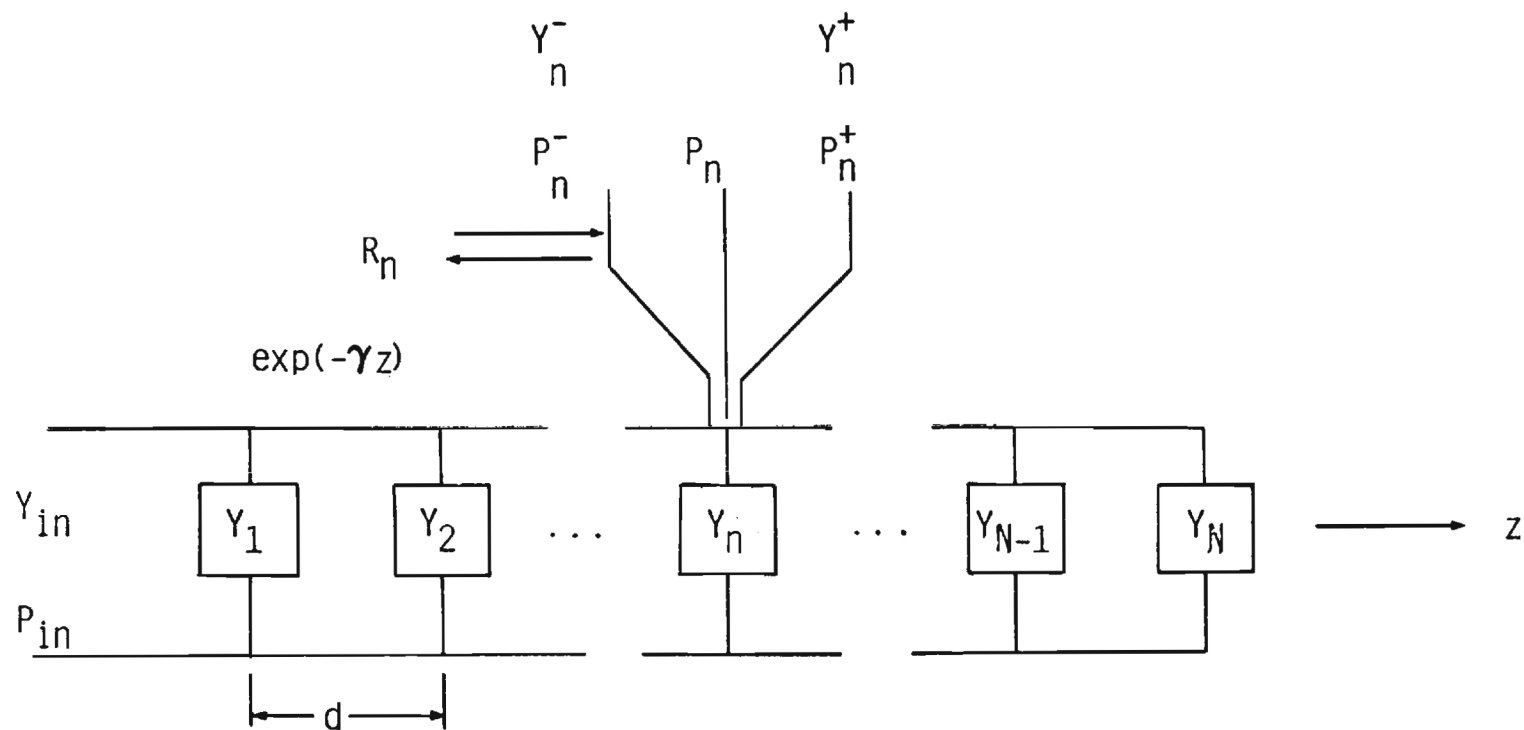


REFLECTION: OPEN TRANSMISSION LINE (ZnSe)



REFLECTION: TERMINATED TRANSMISSION LINE (ZnSe)





$$\gamma = \alpha + j\beta$$

$$Y_n = g_n + jb_n$$

LOSSLESS CASE: $\alpha = 0, \beta = \frac{2\pi}{\lambda}$
 RESONANT ELEMENT: $b_n = 0$
 RESONANT ARRAY: $d = \lambda$

ADMITTANCE CALCULATIONS

- START LADDER CALCULATION WITH LAST (N-TH) ELEMENT
 - SELECT "REASONABLE" g_N (WITH $b_N = 0$)
 - CARRY V_N AS A PARAMETER
 - RADIATED POWER: $P_N = \frac{1}{2} |V_N|^2 g_N$
 - ELEMENT PHASE: $\phi_N \propto \text{ARG}(I_N) = \text{ARG}(V_N Y_N)$
- STEP TOWARD THE INPUT
 - ADJUST g_n TO GIVE DESIRED P_n DISTRIBUTION
 - ADJUST b_n TO MAINTAIN PHASE $\phi_n = \phi_N$
(NOT NECESSARILY WITH LOSSLESS MEDIA,
WHERE TAKE $b_n = 0$)

N-1 ELEMENT

RESONANT ARRAY

$$V_{N-1} = V_N (\cosh \gamma d + Y_N \sinh \gamma d)$$



$$V_N$$

$$Y_{N-1}^+ = \frac{Y_N + \tanh \gamma d}{1 + Y_N \tanh \gamma d}$$



$$Y_N = g_N$$

$$P_{N-1}^+ = P_N^- \left[\exp(2 \mathbf{a} d) + \frac{2 |\Gamma_N|^2}{1 - |\Gamma_N|^2} \sinh (2 \mathbf{a} d) \right]$$



$$P_N$$

$$g_{N-1} = \frac{g_{N-1}^+}{P_{N-1}^+} P_{N-1}$$



$$g_N \frac{P_{N-1}}{P_N}$$

$$\text{ARG}(Y_{N-1}) = \phi_N - \text{ARG}(V_{N-1})$$



$$0$$

RESONANT ARRAY

- ASSUME: NO LOSS ($\alpha = 0$)

RESONANT SPACING ($\beta d = 2\pi$)

- INPUT POWER

$$P_{IN} = \sum_{n=1}^N P_n = \frac{1}{2} \sum_{n=1}^N |V|^2 g_n$$

$$= \frac{1}{2} |V_0|^2 \sum_{n=1}^N g_n$$

- RADIATED POWER PER ELEMENT

$$\frac{P_n}{P_{IN}} = \frac{g_n}{\sum_{m=1}^N g_m} = \frac{g_n}{g_{IN}}$$

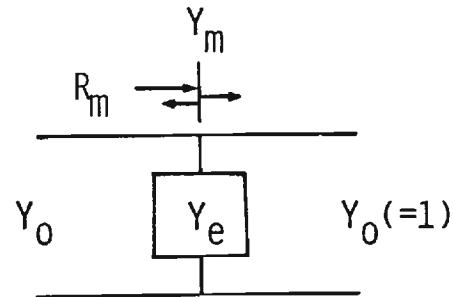
ELEMENT DESIGN

- MEASURE CONDUCTANCE AS FUNCTION OF OFFSET
(ISOLATED ELEMENT ON TERMINATED
 Y_0 TRANSMISSION LINE)
- SELECT g_n TO SATISFY

$$Y_0 = \sum_{n=1}^N g_n$$

$$\frac{P_n}{P_{in}} = \frac{g_n}{Y_0}$$

CONDUCTANCE MEASUREMENT

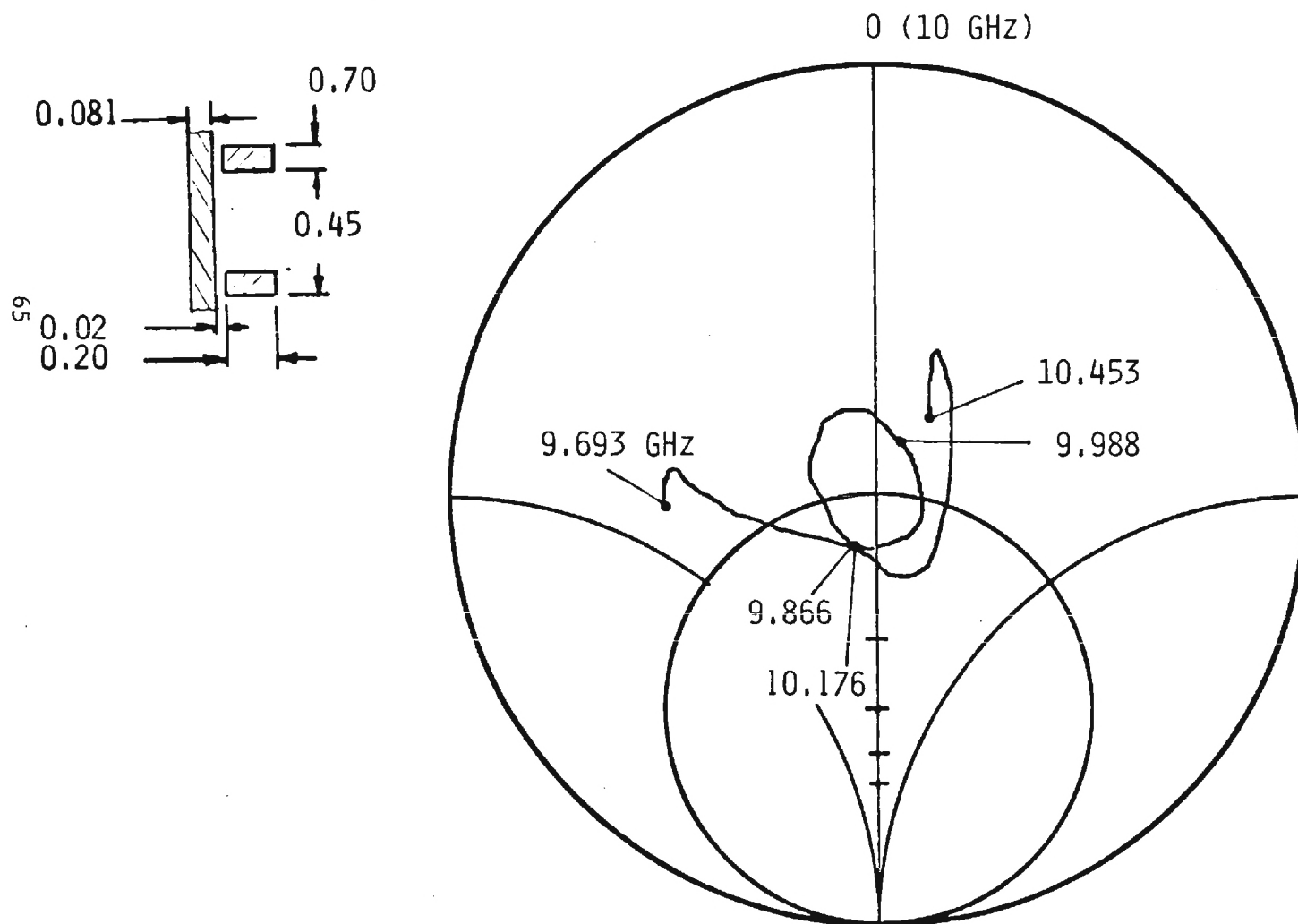


$$Y_m = Y_d + Y_o = \frac{1 - R_m}{1 + R_m}$$

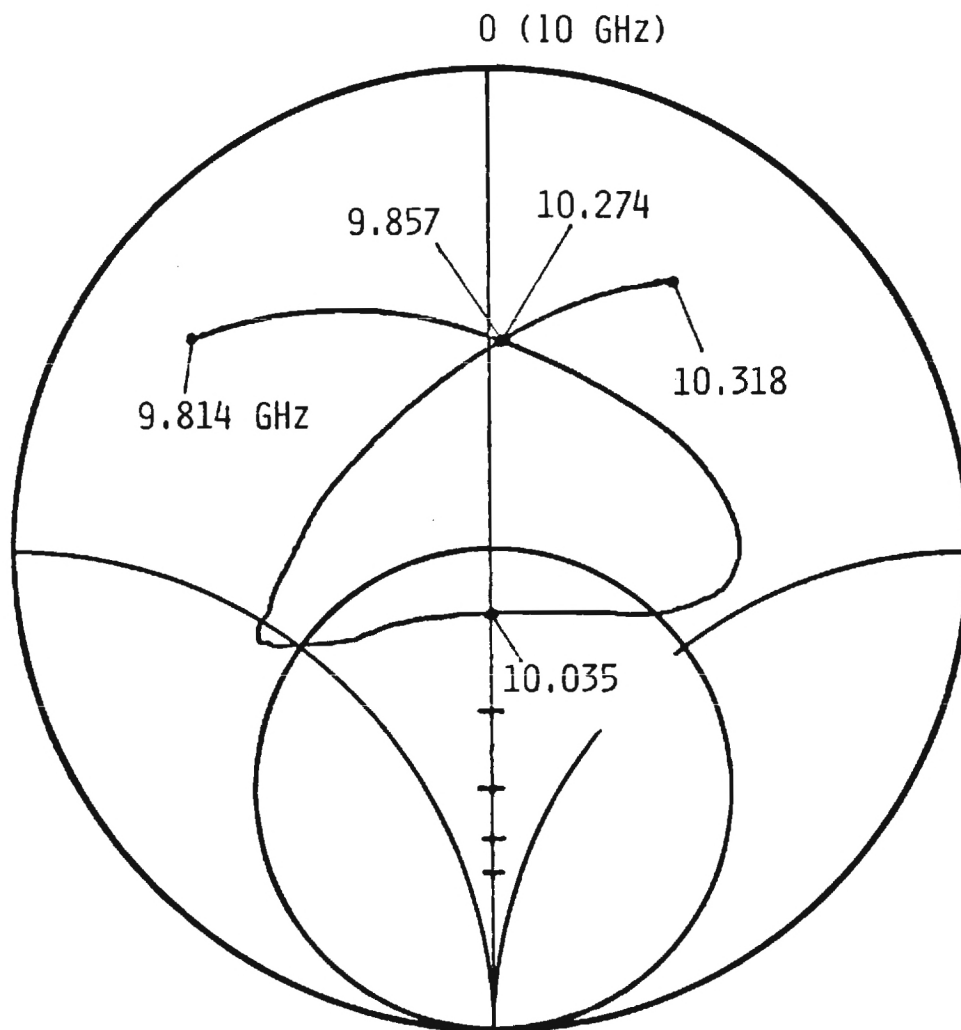
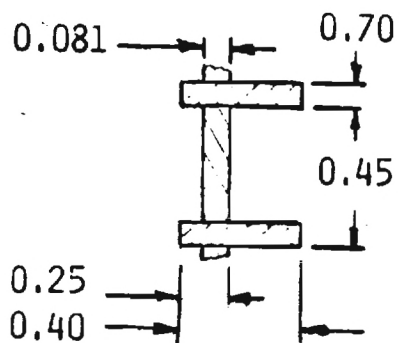
$$Y_d = \frac{-2 R_m}{1 + R_m}$$

AT RESONANCE: $R_m = \frac{-g}{1 + g}$

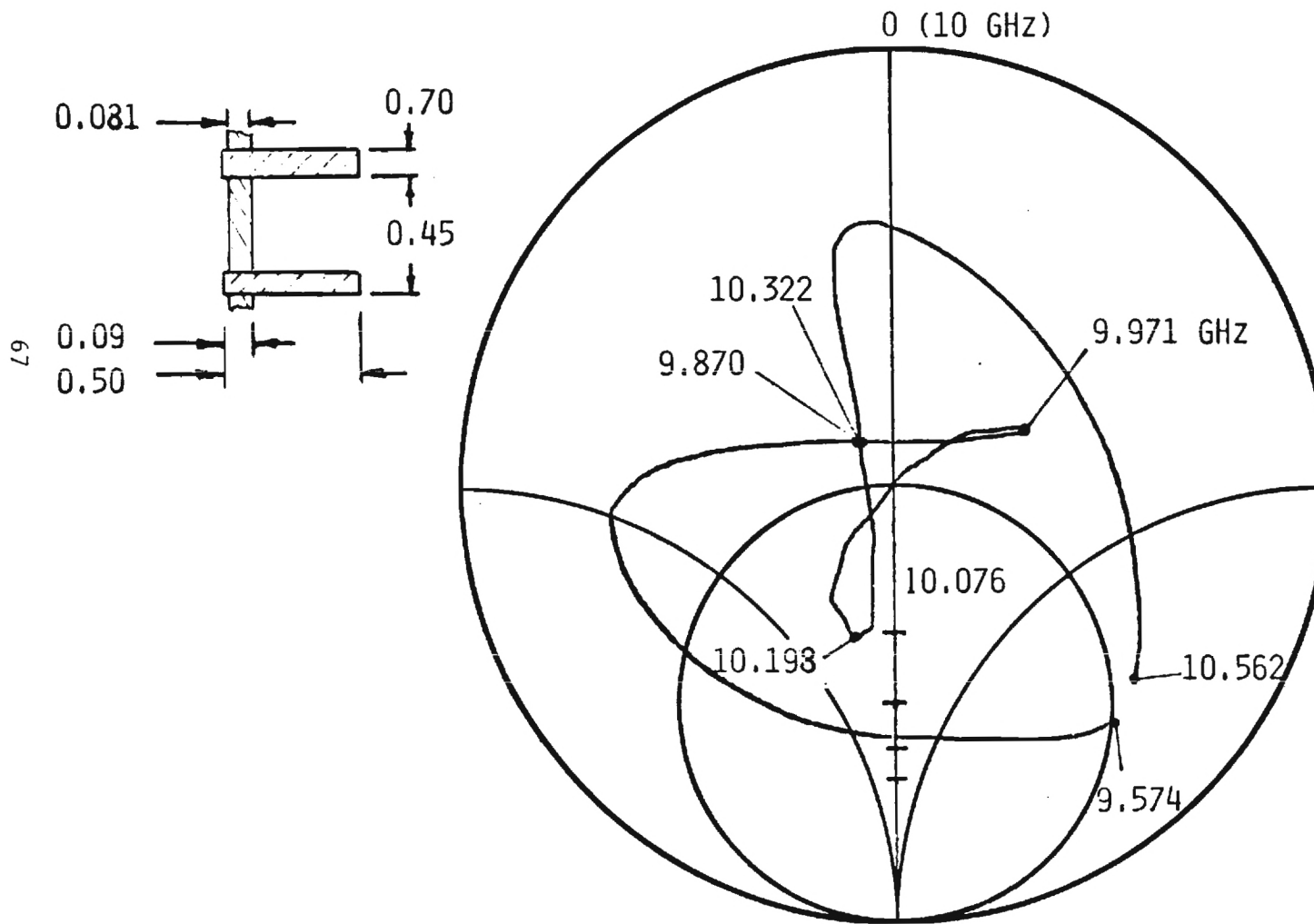
MEASURED IMPEDANCE OF FIVE-ELEMENT ARRAY



MEASURED IMPEDANCE OF FIVE-ELEMENT ARRAY



MEASURED IMPEDANCE OF FIVE-ELEMENT ARRAY



MM-WAVE ANTENNA DEVELOPMENT

SIGNIFICANCE:

WILL PROVIDE

- MM-WAVE "FLATPLATE" ANTENNAS -
 - MONOPULSE SEEKERS
 - TF/TA RADARS
 - AREA CORRELATORS
- 1-D FREQUENCY-SCANNED MMW ARRAYS -
- "DUAL MODE" MMW/IR ANTENNAS -

MM-WAVE ANTENNA DEVELOPMENT

CONCEPT

● FLATPLATE ARRAYS

DEVELOPMENT ISSUES

- THEORETICAL OR EXPERIMENTAL
BASIS FOR DETAILED DESIGN
(ELEMENT ADMITTANCE CHARACTERISTICS)

- FABRICATION PROCESSES

- FREQUENCY EXTENSIONS

● FREQUENCY-SCANNED ARRAYS

- ABOVE PLUS

- SERPENTINE FEED DEVELOPMENT

● DUAL-MODE ANTENNAS

- ABOVE PLUS

- GROUND-PLANE THINNING

APPENDIX B

OPEN RESONATOR MEASUREMENTS OF
CVD ZnSe DIELECTRIC PROPERTIES



ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
A Unit of the University System of Georgia
Atlanta, Georgia 30332

ELECTROMAGNETICS LABORATORY
MILLIMETER WAVE TECHNOLOGY DIVISION

March 4, 1983

Memorandum

TO: Jim Fuller, ECSL/EMED
FROM: Ron Bohlander and George Kirkman, EML/MMD
SUBJ: Optical Constants of ZnSe

This is to bring you up to date on measurements we have made of the ZnSe samples you provided on your project A-3370. One of us (G.F.K.) has made measurements of the refractive index n (or dielectric constant ϵ_r) and of the loss tangent $\tan \delta$ of the samples in a semi-confocal Fabry-Perot cavity, using the method described by K. H. Breeden and J. B. Langley in the Rev. Sci. Instrum. 40, 1162-3 (1969).

Recently in our investigation, inconsistent results were obtained when we attempted to repeat our first measurements. For example, results for n varied between 3 and 3.5 and for $\tan \delta$ between 0.001 and 0.020, and the size of random effects like instrumental noise could not explain this variation. In addition, we obtained results for stacks of ZnSe plates and again there were considerable variations depending on the thickness of the stack. This was not expected since the plates were flat enough to stack well and to appear to be like a homogeneous sample to a sufficient approximation.

We have, however, more recently identified and removed the cause of this confusion; namely, higher-order modes. With no material in the cavity, higher-order modes are suppressed by virtue of the size of the flat mirror in the semi-confocal arrangement. This mirror is small enough that higher-order modes leak around the mirror and are not contained by

the cavity. The problems arose because the ZnSe samples are much wider than this mirror and are able themselves to reflect the higher-order modes with relatively high efficiency due to the high dielectric constant of the material. This was confirmed by scanning the moving mirror of the cavity and finding spurious resonances. Bogus results can be explained then as being a measurement of the wrong resonance when the ZnSe was in the cavity.

This problem was eliminated by adding further higher-order mode suppression in the form of an absorbing collar around the radiation beam within the cavity. As an additional precaution, the E-H tuner that is used to match signals into the cavity was always adjusted to about the same level of null reflection with the sample in the cavity to try to eliminate possible effects of the material on the coupling part of the cavity factor. The results given on the attached table were obtained with this arrangement, and much better agreement between the samples and the various stacks is shown. The uncertainties indicated in the Table are those due to random effects only. One may note that there is some residual inconsistency between results which is larger than the random errors and which may be due to any of the following causes: (1) the individual samples may in fact have slightly different optical properties, (2) the results from the stacks of samples may be affected in a minor way by the thin air-gap interfaces between samples, and (3) there may be some additional residual perturbation on the cavity or on the cavity coupling due to the high dielectric constants of the samples. There is not sufficient information at present with which to establish the relative importance, if any, of these suggested mechanisms.

One further problem has been noted. In the case of sample #4, the Q of the cavity increased slightly with the sample in the cavity. In terms of a loss tangent, this would imply a non-physical, slightly negative value ($\tan \delta \sim - .001$). We can only speculate that the most likely explanation is that the sample may be perturbing the coupling in and out of the cavity in a way that the E-H tuner does not fully compensate.

Nevertheless, from previous experience we feel that it is safe to conclude that the loss tangent of the ZnSe samples ($\tan \delta \lesssim .003$) and that a value of the index of refraction in the range 3.00 to 3.08 can be inferred. The average value observed was 3.03_4 .

xc: John Cotton
Joe Newton
Vernon Brady

Table of Fabry-Perot Cavity Measurements of ZnSe Plates
Frequency: 94 GHz

Individual Samples

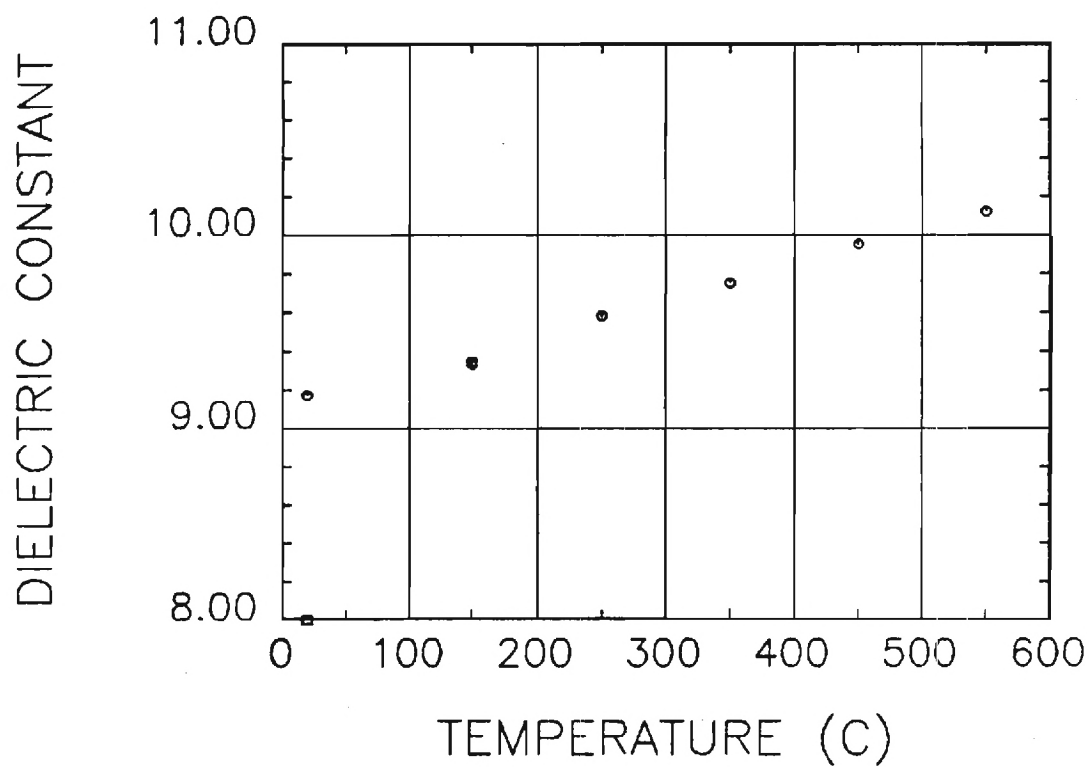
Sample	Thickness (in.)	Refractive Index n	Dielectric Constant ϵ_r	Loss Tangent Tan δ
1	.054	$3.021 \pm .005$	$9.13 \pm .03$	$.0017 \pm .0005$
2	.053	$3.034 \pm .005$	$9.21 \pm .03$	$.0019 \pm .0005$
3	.047	$3.062 \pm .005$	$9.38 \pm .03$	$.0029 \pm .0005$
4	.059	$3.019 \pm .005$	$9.11 \pm .03$	*

Stacks of Samples

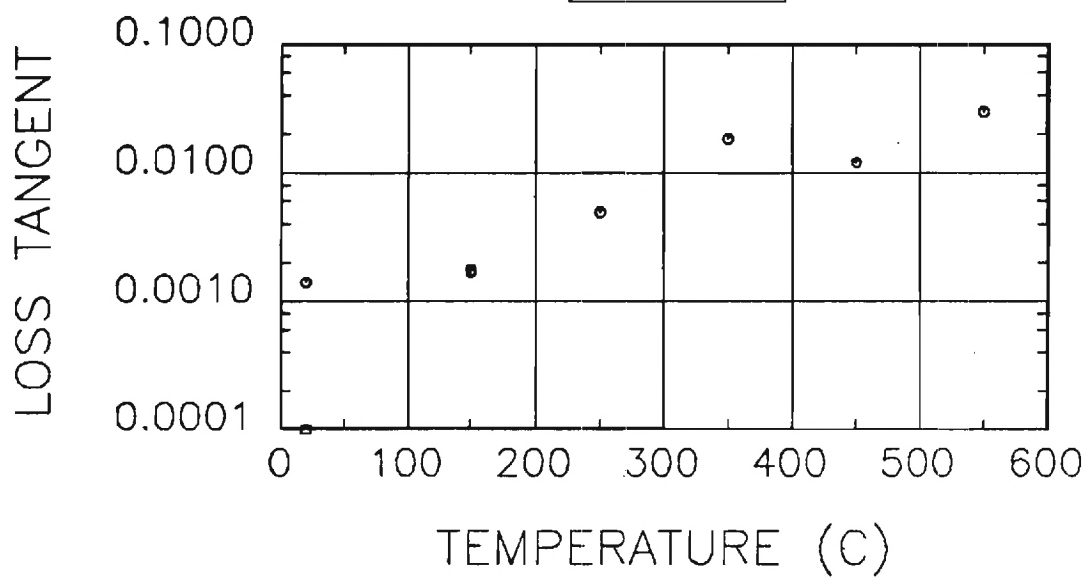
Samples in Stack	Refractive Index n	Dielectric Constant ϵ_r	Loss Tangent Tan δ
1,2	$3.004 \pm .005$	$9.02 \pm .03$	$.0019 \pm .0005$
1,2,3	$3.036 \pm .005$	$9.22 \pm .03$	$.0025 \pm .0005$
1,2,3,4	$3.022 \pm .005$	$9.13 \pm .03$	$.0027 \pm .0005$

APPENDIX C

HIGH-TEMPERATURE MILLIMETER-WAVE MEASUREMENTS
OF CVD ZnSe DIELECTRIC PROPERTIES

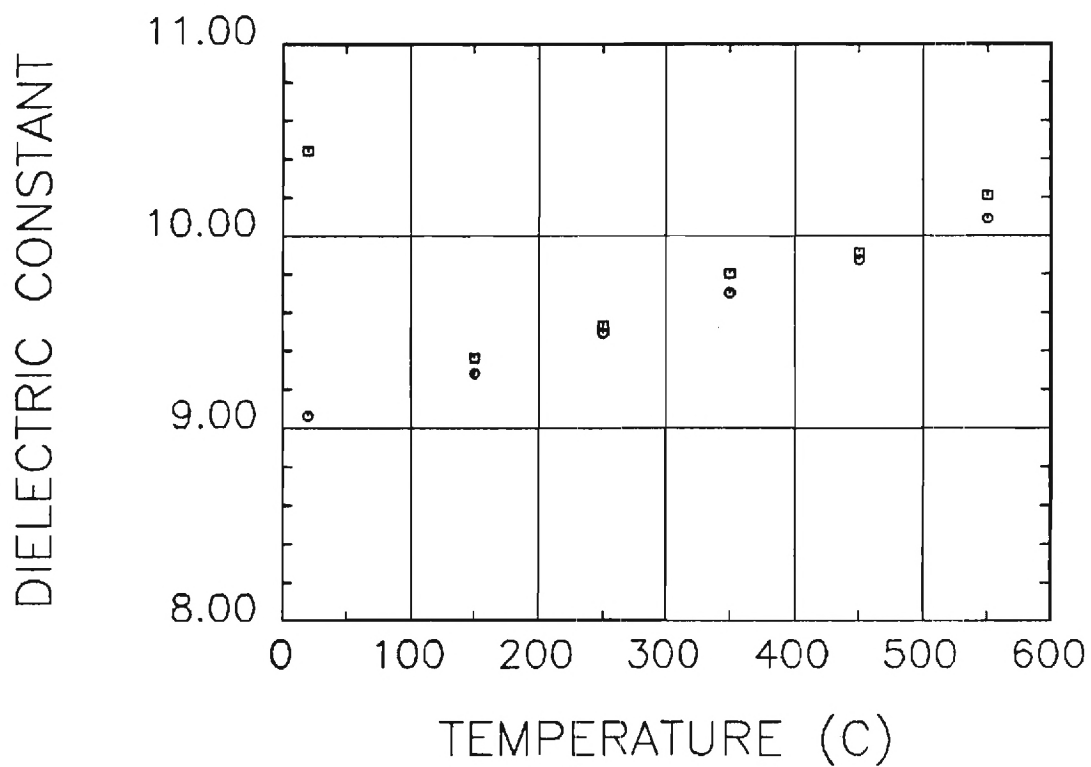


28.9 GHZ

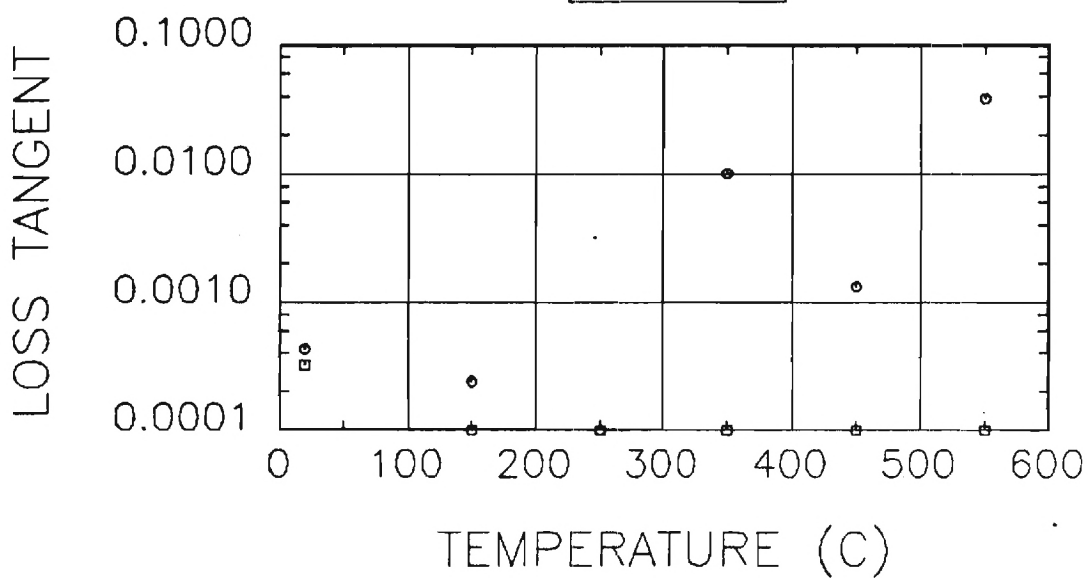


SAMPLE ID. ■ ZSA1A
• ZSB1A

Figure C-1 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 28.9 GHz.

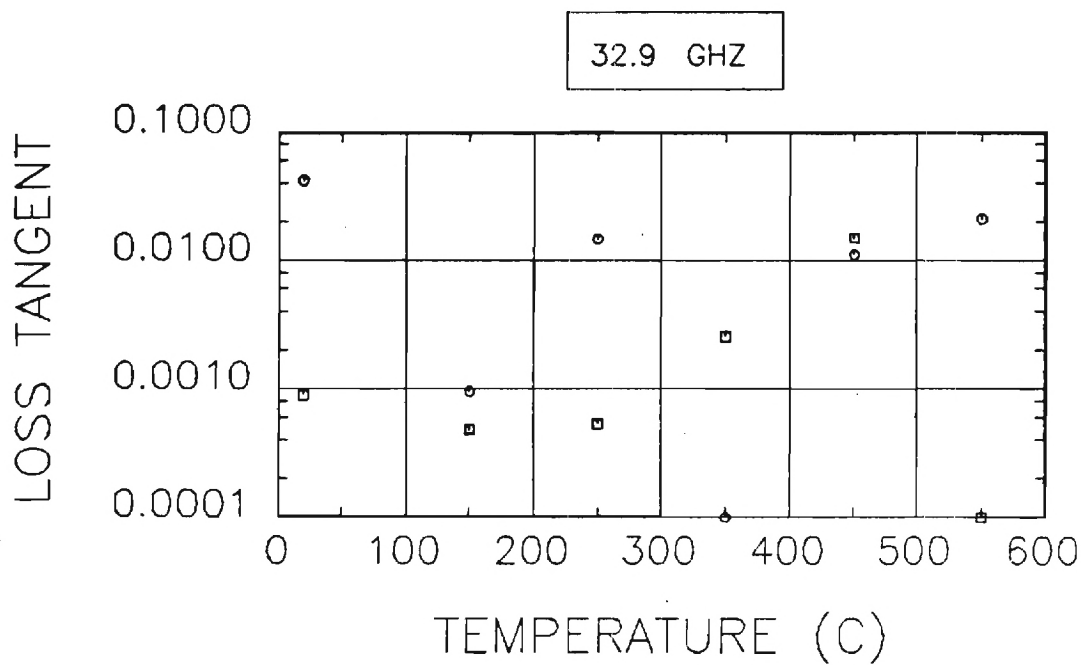
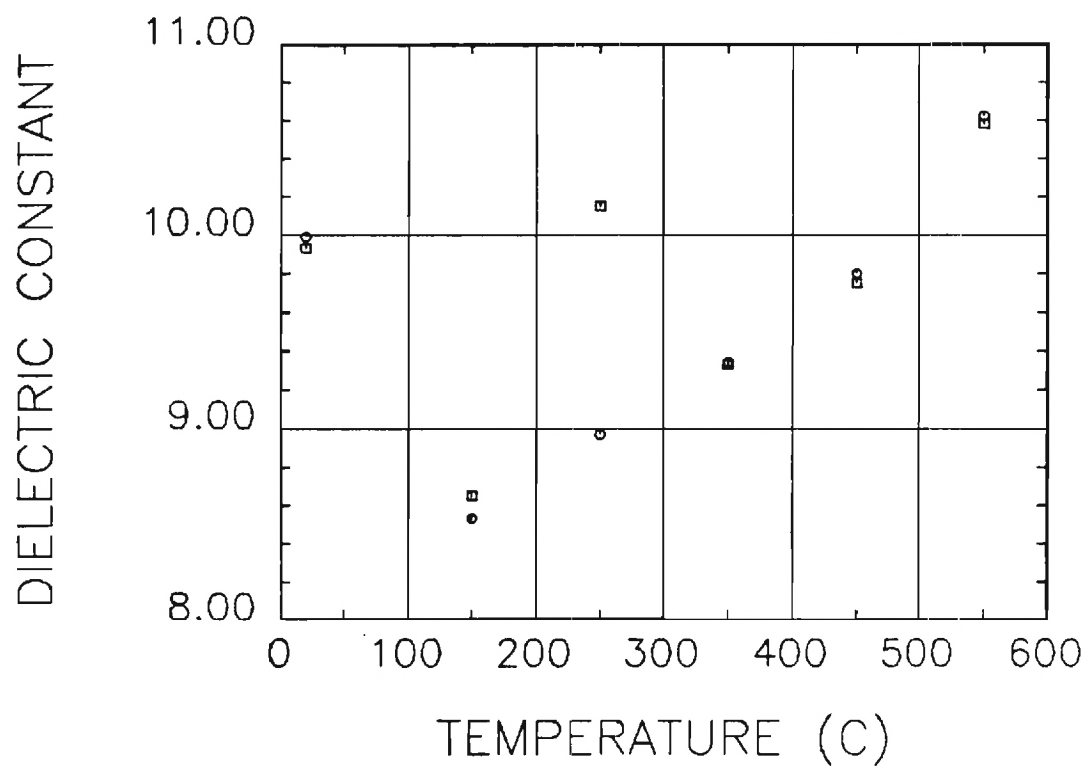


30.7 GHZ



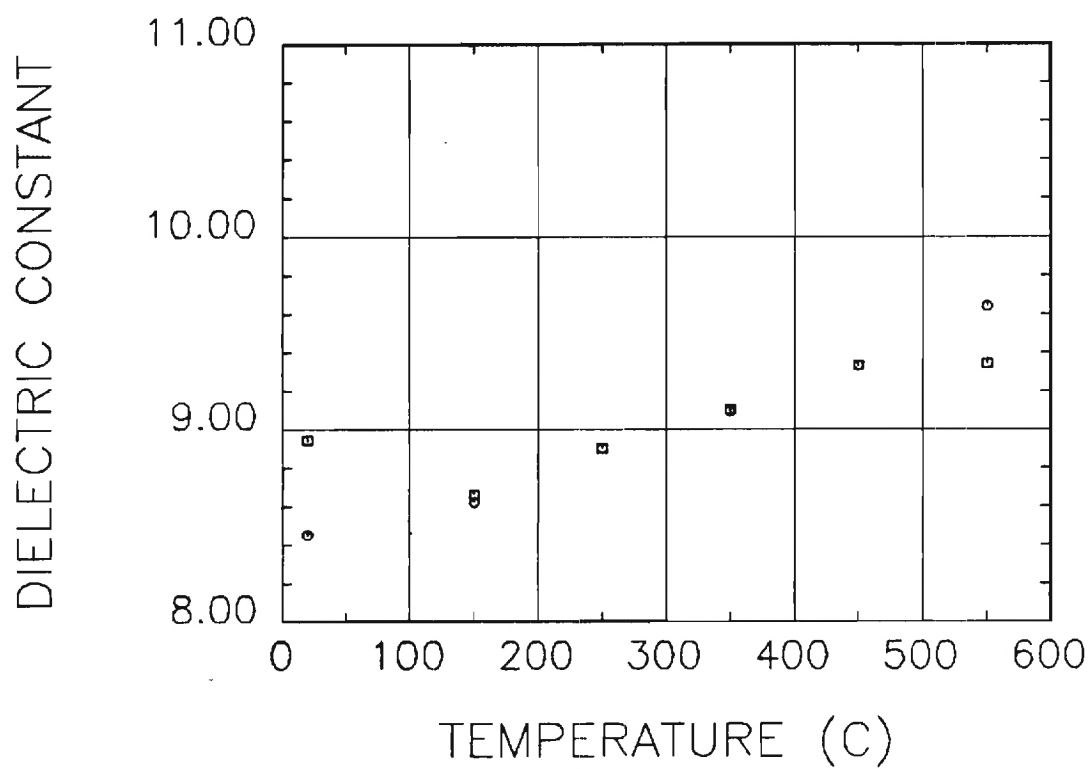
SAMPLE ID. □ ZSA1A
• ZSB1A

Figure C-2 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 30.7 GHz.

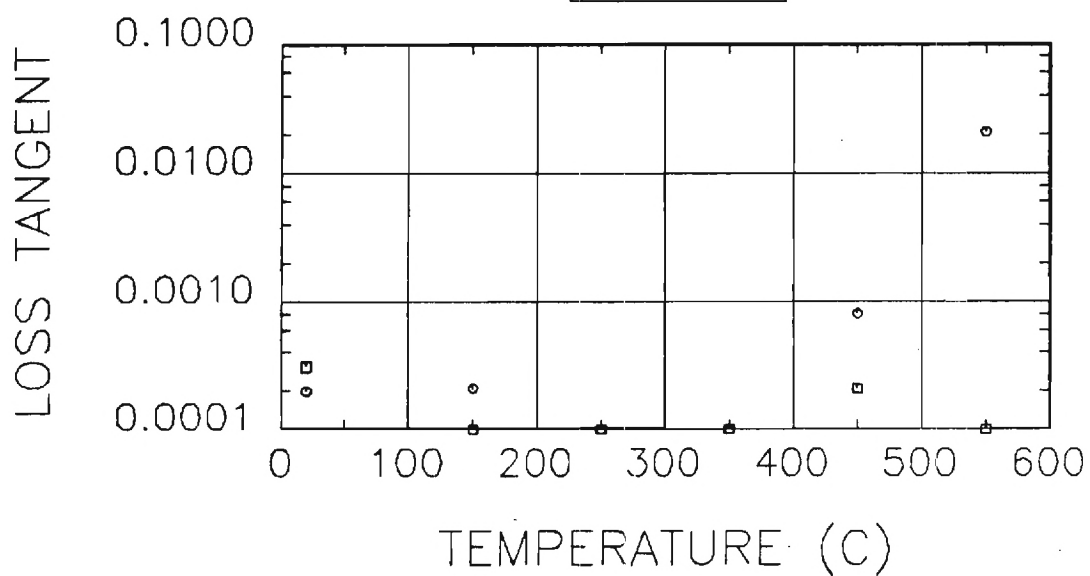


SAMPLE ID. □ ZSA1A
○ ZSB1A

Figure C-3 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 32.9 GHz.

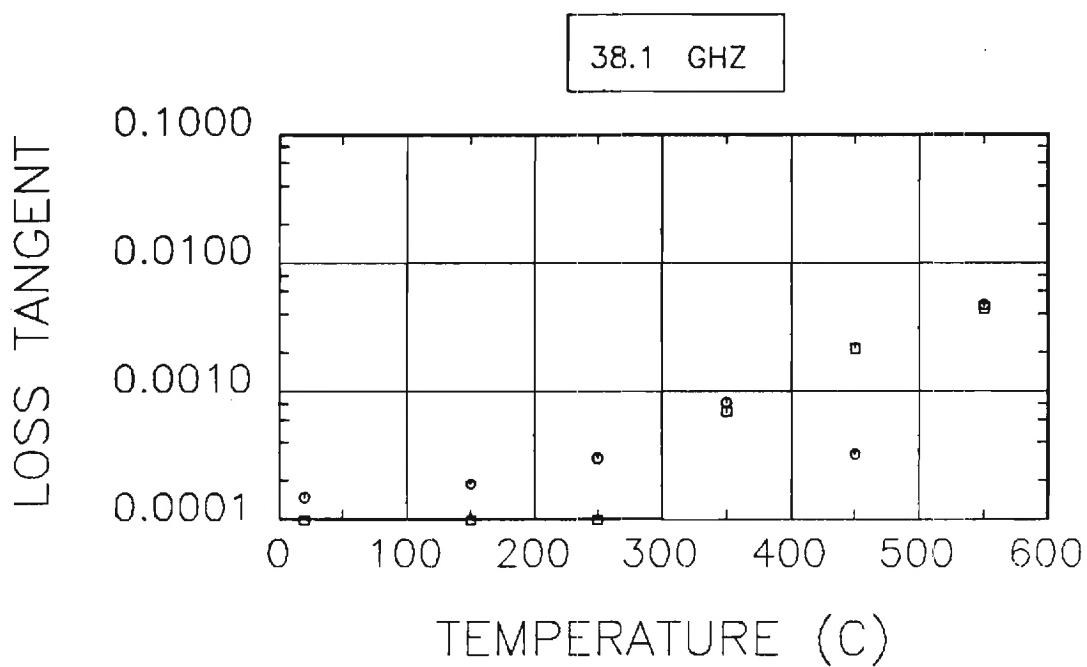
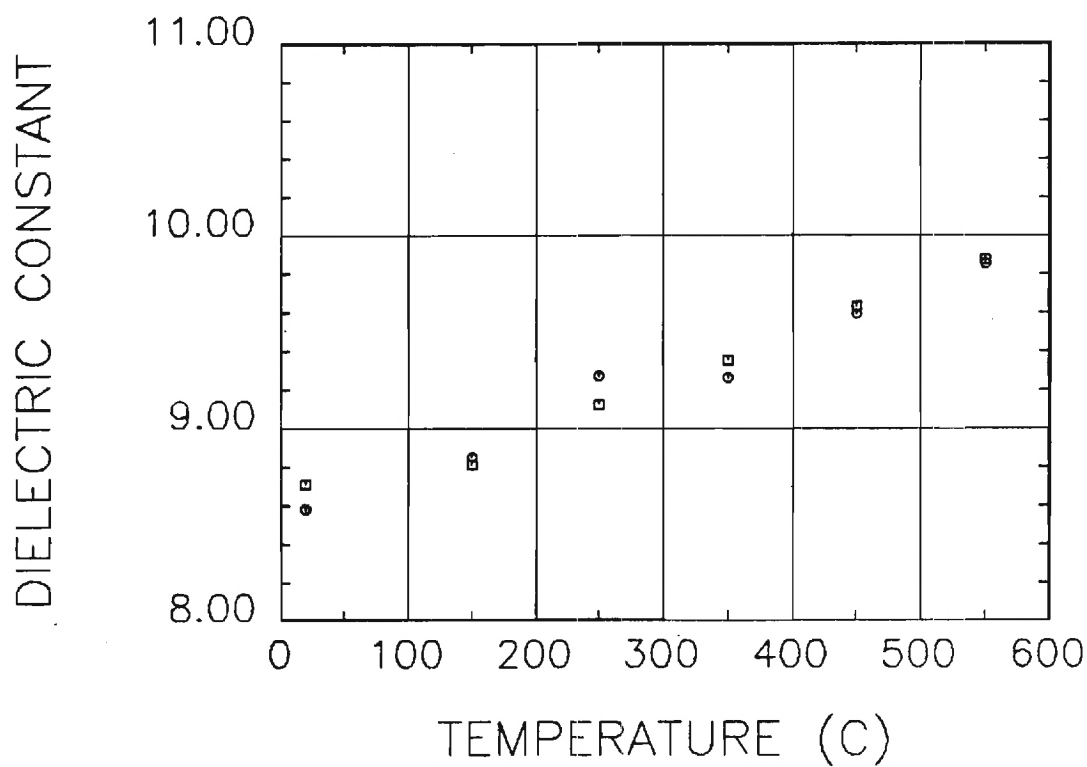


35.5 GHZ



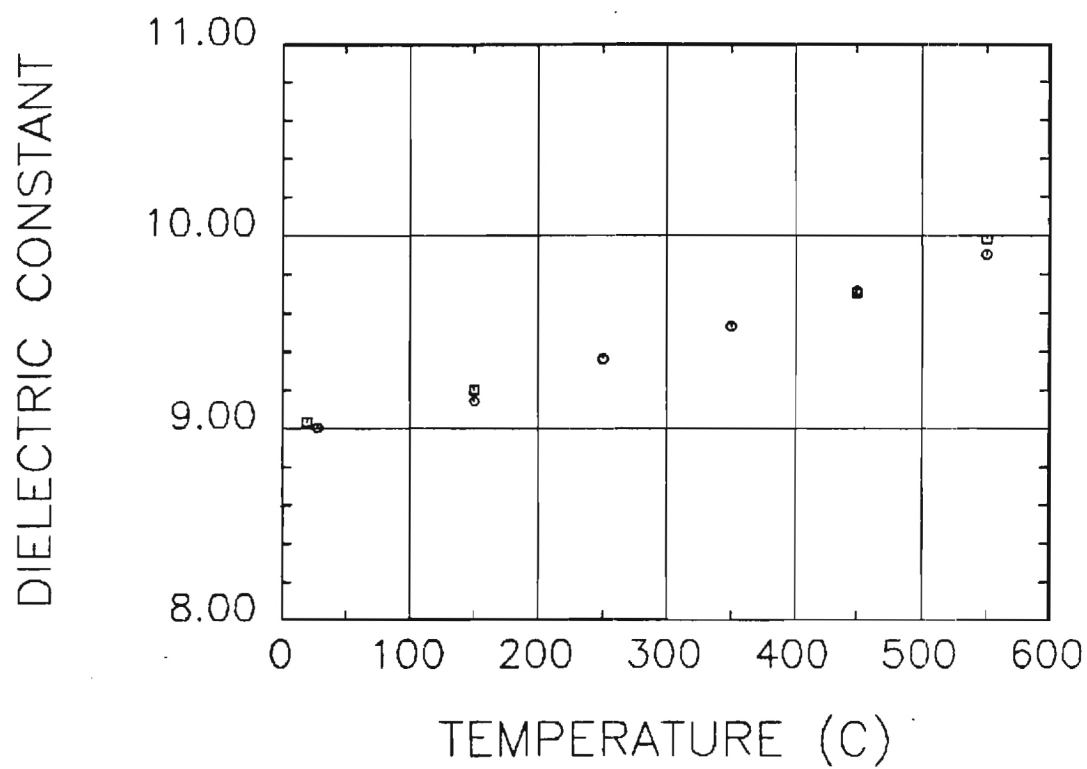
SAMPLE ID. □ ZSA1A
○ ZSB1A

Figure C-4 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 35.5 GHz.

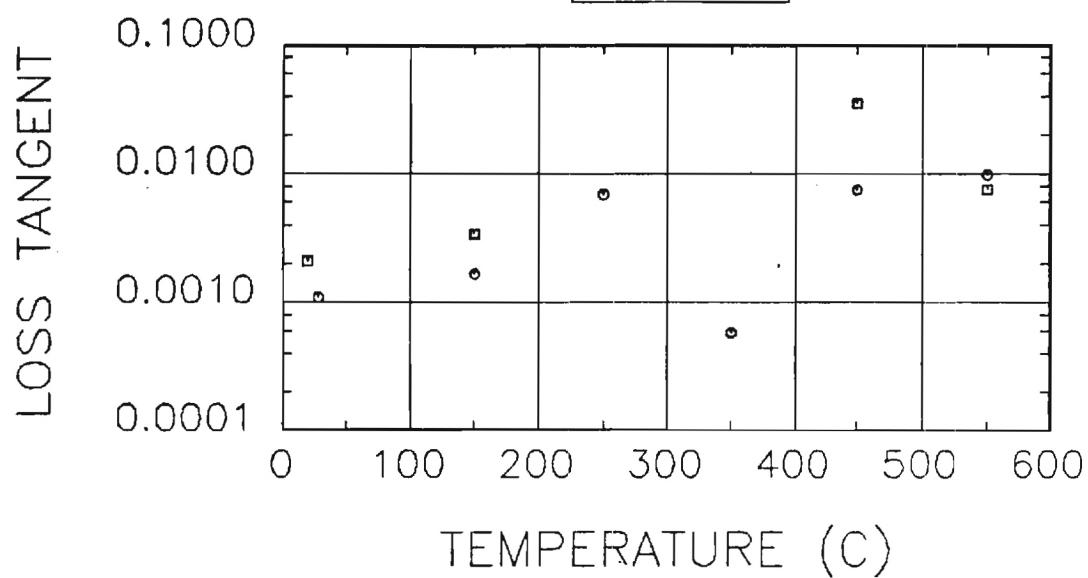


SAMPLE ID. □ ZSA1A
○ ZSB1A

Figure C-5 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 38.1 GHz.

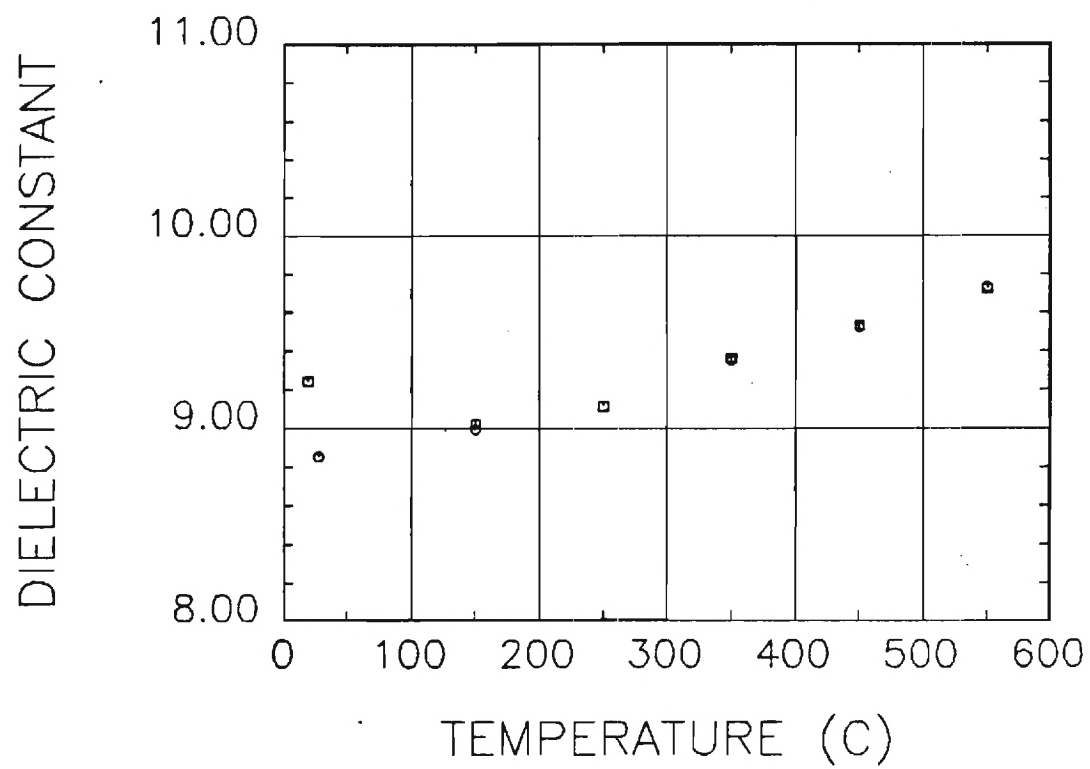


29.2 GHZ

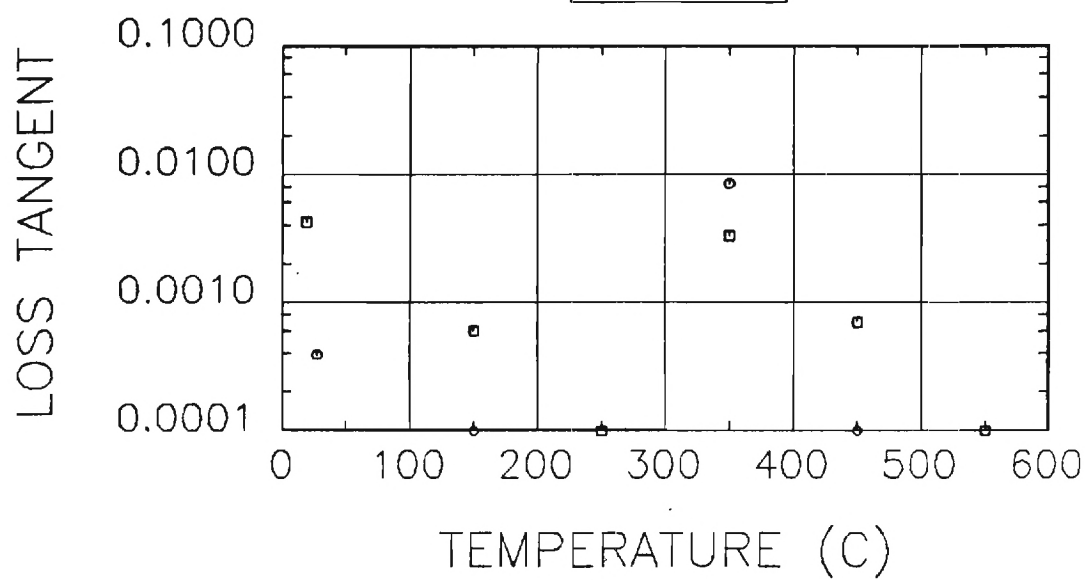


SAMPLE ID. □ ZSC1A
○ ZSD1A

Figure C-6 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 29.2 GHz.

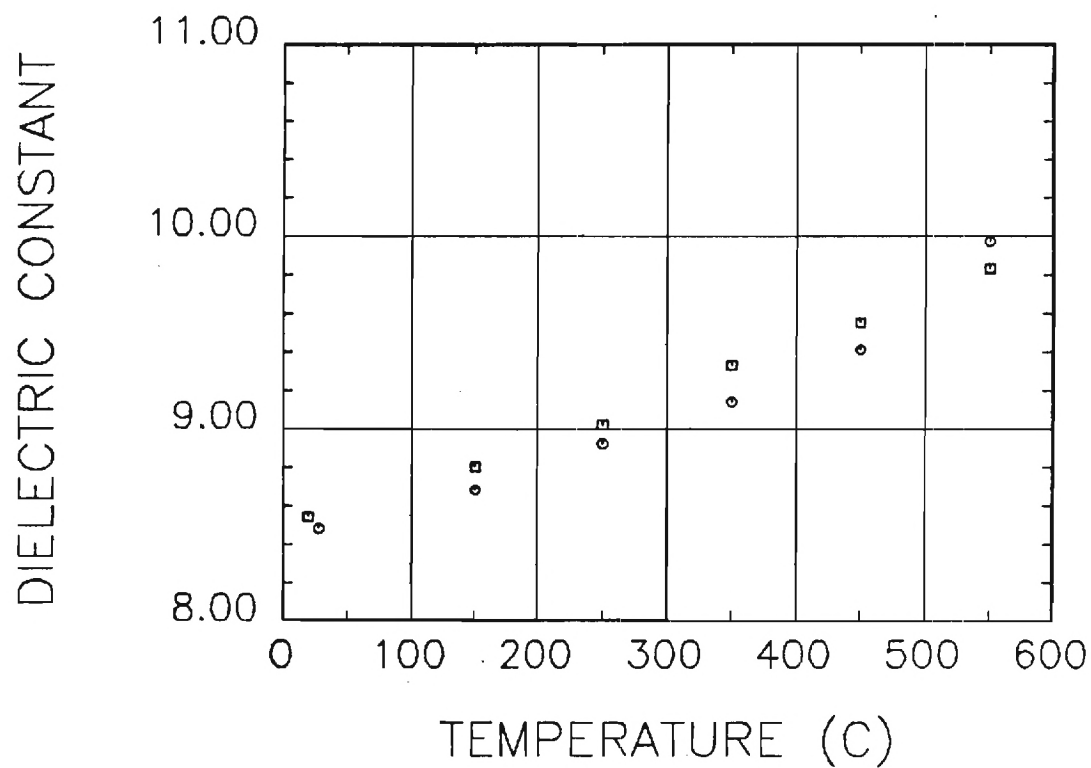


31.2 GHZ

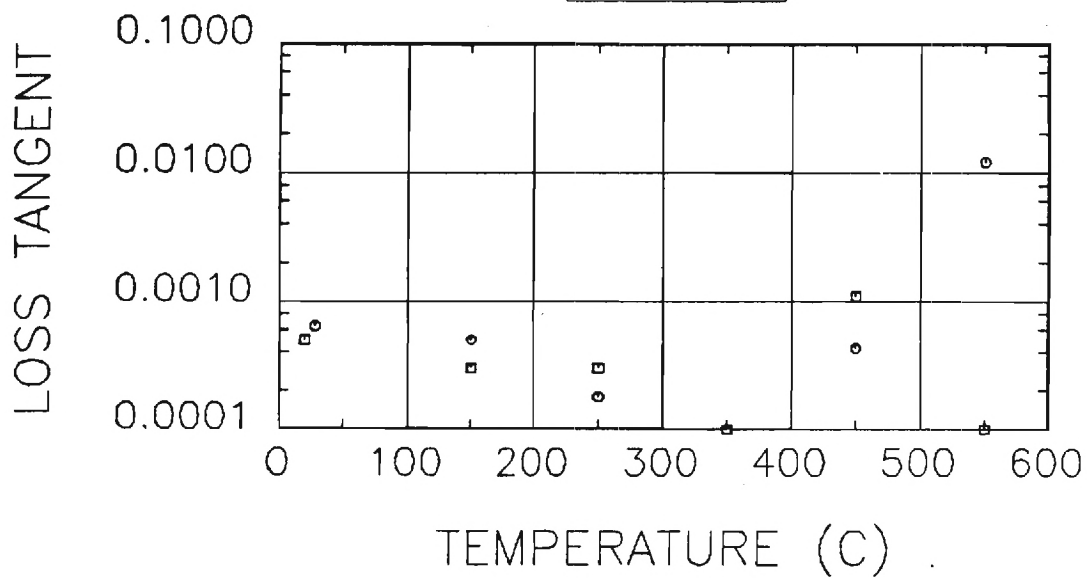


SAMPLE ID. ■ ZSC1A
● ZSD1A

Figure C-7 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 31.2 GHz.

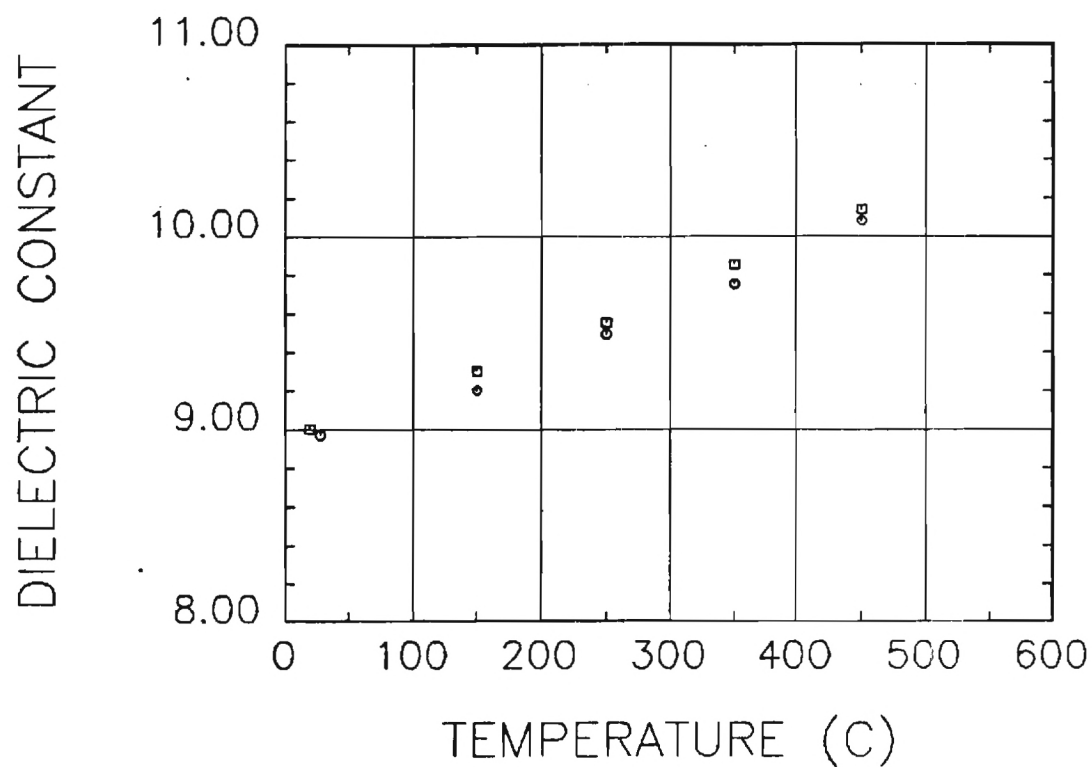


33.6 GHZ

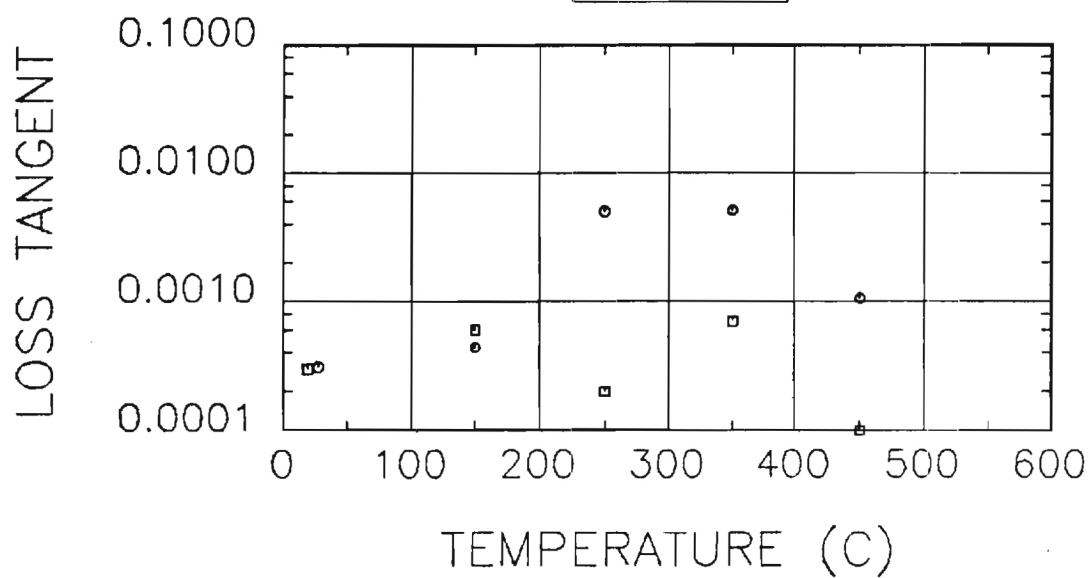


SAMPLE ID. □ ZSC1A
 • ZSD1A

Figure C-8 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 33.6 GHz.

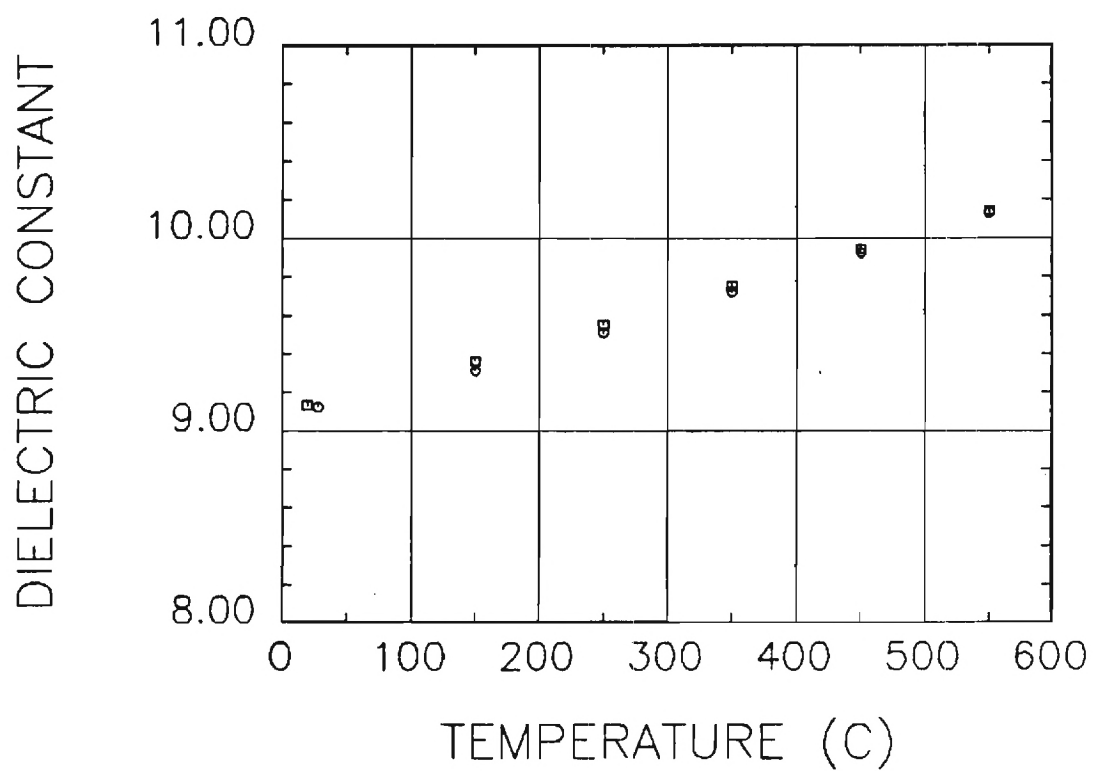


36.1 GHZ

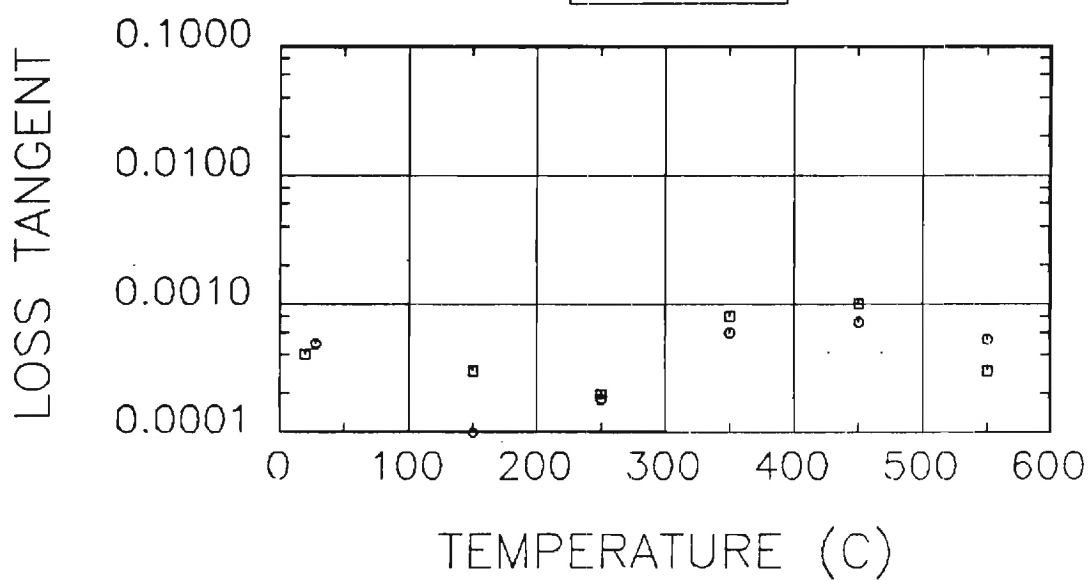


SAMPLE ID. ■ ZSC1A
○ ZSD1A

Figure C-9 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 36.1 GHz.



39.8 GHZ



SAMPLE ID. □ ZSC1A
○ ZSD1A

Figure C-10 . Dielectric properties of chemical-vapor deposited zinc selenide (CVD, Inc.) at 39.8 GHz.