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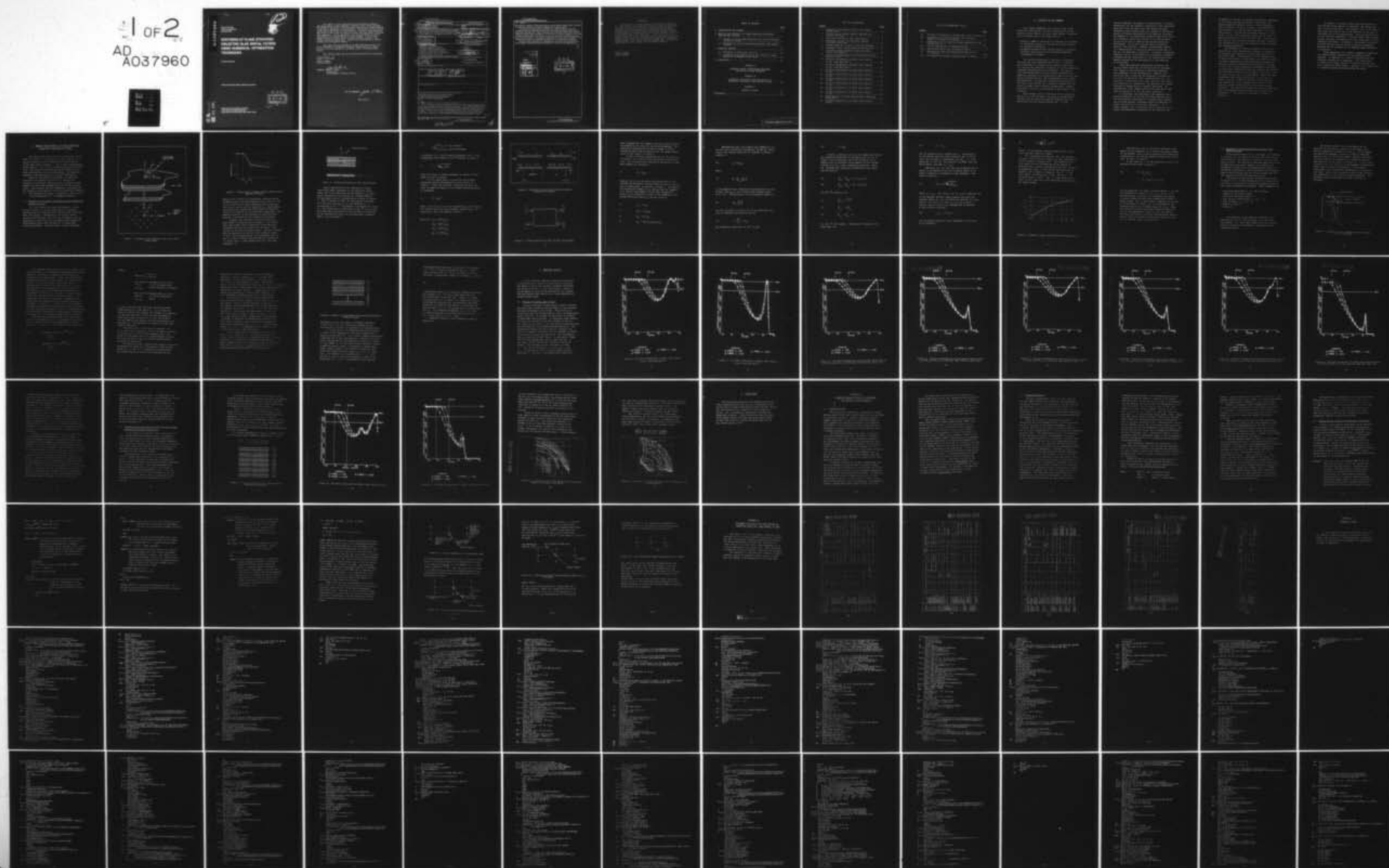

RADC-TR-76-408
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December 1976

SYNTHESIS OF PLANE STRATIFIED DIELECTRIC SLAB SPATIAL FILTERS USING NUMERICAL OPTIMIZATION TECHNIQUES

Raytheon Company

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ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

This report is a full description of an optimization technique from which spatial filters composed of dielectric layers can be designed. The purpose of the filter is to allow energy radiated by an antenna aperture to pass nearly unaffected in the broadside or near broadside direction while significantly attenuating all other radiation. Because of these properties, this filter is very useful for possible limited scan applications as grating lobe suppressors. In this application, the principle benefit to the Air Force would be in allowing the use of larger elements in the aperture thereby reducing the total number of expensive control elements. This reduces the overall antenna cost. There are also applications to smaller antennas such as monopulse trackers.

This report has been reviewed by the RADC Information Offices (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the General public, including foreign nations.

This technical report has been reviewed and approved for publication.

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The synthesis of plane stratified dielelectric slab spatial filters using numerical optimization techniques is presented. The stratified dielectric slab spatial filter is a unique concept for element pattern control on large planar arrays in that it gives protection for the array in the fashion of a radome. However, because of the relatively limited number of low loss microwave dielectrics, the synthesis of practical spatial filters must

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proceed in a manner which guarantees that the final configuration consists of materials which are readily available and reproducible.

A numerical optimization technique of stratified dielectric filter synthesis has been developed which provides this guarantee while simultaneously attaining the required spatial and frequency bandwidth response. Using the optimization technique, an eleven layer filter design for use with a large mechanically scanned array has been obtained which has greater than 10 dB rejection in an angular stopband of 36 deg and less than 0.3 dB transmission loss in an angular passband of 10 deg around broadside.

An up to date tabulation of available low loss microwave dielectrics and complete computer program listings are given in the Appendices.

EVALUATION

This report is a full description of an optimization technique from which spatial filters composed of dielectric layers can be designed. The purpose of the filter is to allow energy radiated by an antenna aperture to pass nearly unaffected in the broadside or near broadside direction while significantly attenuating all other radiation. Because of these properties, this filter is very useful for possible limited scan applications as grating lobe suppressors. In this application, the principle benefit to the Air Force would be in allowing the use of larger elements in the aperture thereby reducing the total number of expensive control elements. This reduces the overall antenna cost. There are also applications to smaller antennas such as monopulse trackers.

Peter R. Franchi

PETER R. FRANCHI
Project Engineer

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1. INTRODUCTION AND SUMMARY

This report summarizes the study of a stratified dielectric slab spatial filtering technique to provide element pattern control on large planar arrays. Specifically, the objectives of the study were to:

- Develop a computer optimization technique for synthesis of stratified dielectric slab spatial filters subject to realistic constraints.
- Synthesize optimum filter designs subject to required rejection characteristics and frequency bandwidth requirements at X-band.

The stratified dielectric slab spatial filtering technique was first described by Mailloux[1], wherein the properties of filtering in the spatial domain were outlined and the analytical synthesis of filters possessing Chebyshev characteristics was presented. The present work extends Mailloux's earlier results by providing a numerical technique for synthesizing filters with arbitrary spatial characteristics. As a consequence of the method developed here, the physical constraints encountered in practical filter design (e.g., material availability and layer thickness) may be directly parametrized, thereby providing a practical filter design as the output of the synthesis.

The principle point of departure of the analytical approach to filter synthesis, as typified by Mailloux's results, and the numerical approach presented here, is associated with the ultimate design goal. In the analytic approach, the degree of specification is limited, essentially, by the algebraic complexity of the constituant equations, with the result that the design goal must necessarily have limited scope with respect to the overall degree of freedom associated with the physical structure. For example, in the analytical procedure given by Mailloux, this effective restriction results in the specification of the filter only in terms of the desired electrical performance. To be sure, this may lead to practical spatial filter designs. However, the procedure results in a specification of dielectric materials which may, or may not, be obtainable in practice. In effect, no material selection control is provided by the analytical synthesis procedure and the practicality of the synthesized filter depends strongly on the availability of the materials so determined.

Using the numerical optimization technique, the overall design goals may be factored into the procedure. With respect to the selection of dielectric material, this procedure is also deterministic. However, as a particular goal, we may ask the optimizer to select one or all of the materials from a predetermined list. By judiciously constructing this list, such that only available materials are represented, the optimizer will always synthesize a design which is readily fabricated. By interference, such a design would be low cost due to the specific selection of "off the shelf" materials.

In principle, the advantage of the numerical optimization technique is that the available solution set is not artificially constrained to a limited space, spanned only by those physical parameters which are ammenable to direct inclusion in an analytical expression. It is clear, however, that in practice, not all physical (electrical and mechanical) properties of the structure can be modeled to provide a reasonable optimization parameter. In particular, during the course of this study, the design parameters material density, tensile strength, sheer strength, dielectric strength, and machinability were found to be of second order importance for typical applications. For low loss microwave materials in the range $1<\epsilon_r<25$, these properties either varied little, or were not determinable from available data. Consequently, the scope of the synthesis procedure has been limited to the consideration of material selection, layer thickness, and frequency bandwidth.

The synthesis procedure developed in this study proceds from a wave transmission analysis of scattering of incident plane waves by infinite plane stratified dielectric slabs. An equivalent circuit representation of the layered media is constructed, and from the scattering matrix description of the constituent networks representing junction discontinuities and length of transmission line, a wave transmission formalism is obtained. A single wave transmission matrix $\underline{\underline{A}}$, relating the incident and reflected traveling wave voltages at the filter input to those at the output, is constructed. Since the power transmitted with respect to one volt at the input is simply $(1/A_{11})^2$, we operate directly on this quantity, and optimize the filter response with respect to the desired rejection characteristics over the frequency bandwidth. The optimization algorithm used is a modification of the RAZOR search technique due to Bandler and MacDonald.[2] The synthesis procedure is given in Section 2.

In section 3, an eleven layer stratified dielectric slab spatial filter design is presented. The design goal was to achieve less than .1 db insertion loss in the spatial pass band, and greater than 10 db rejection in the spatial stop band over a 4% frequency band. Since the permittivity of most microwave materials is constant from S band through X band, the layer thicknesses are given normalized to center frequency wavelength. In addition, the designs synthesized are such that the spatial extent of spurious passbands produced for TM incidence by the Brewster angle phenomenon is minimized.

Three appendices are included. Appendix A summarizes the modified RAZOR algorithm and associated computer programs. In Appendix B, a table of available low loss microwave dielectrics is presented. This table gives a summary of microwave materials currently available and their properties (where known). Appendix C is a compilation of computer programs developed during the study.

2. ANALYSIS AND SYNTHESIS OF PLANE STRATIFIED DIELECTRIC SLAB SPATIAL FILTERS

The plane stratified dielectric slab spatial filter shown in Figure 1 is configured in such a manner as to provide a multiplicative element pattern modification of the type shown in Figure 2 for a large planar phased array antenna. The filter is assumed flush with the array face. Both relative permittivity and thickness of the slabs are arbitrary, and assumed uniform. All media are assumed to have permeability $\mu_o (=4\pi x10^{-7}$ henries/m).

Basic to the problem of synthesis of stratified dielectric slab spatial filters is the analysis of arbitrary transversely infinite layered dielectric sheets subject to plane wave incidence with TE and TM polarizations. This analysis and the fundamental limitations of the dielectric slab spatial filter are presented in Section 2.1. The synthesis technique is presented in Section 2.2.

A time dependence $e^{j\omega t}$ is assumed throughout.

2.1 Analysis of Plane Wave Scattering by Plane Stratified Dielectric Sheets

It is well known that the electromagnetic fields in the vicinity of a large planar array of radiating apertures may be decomposed into linearly polarized plane wave constituents. Consequently, for spatial filter analysis and synthesis, the array may be removed, and the properties of the filter may be examined with respect to monochromatic plane wave incidence on a transversely infinite structure. Since arbitrary linearly polarized

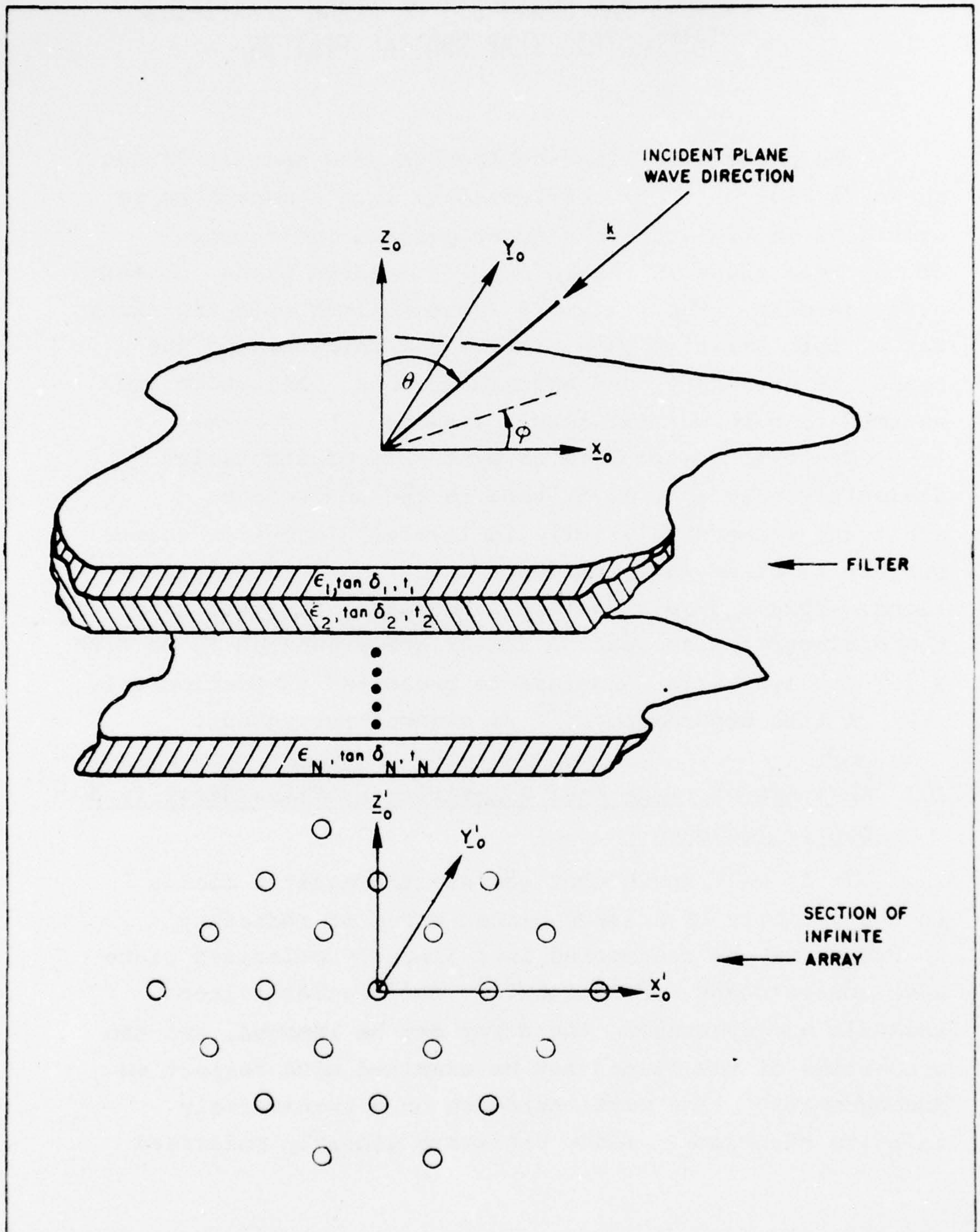

Figure 1 - Dielectric Slab Spatial Filter over Planar Phased Array

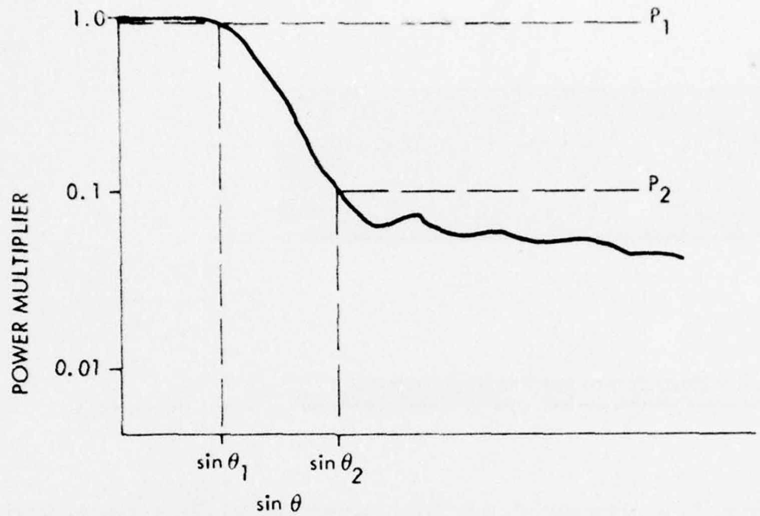

Figure 2 - Multiplicative Element Pattern Modifier for Spatial Filtering

waves in the vicinity of a dielectric interface may be decomposed into TE and TM components with respect to the surface normal which remain decoupled upon scattering, the analysis may be further simplified by independently determining the transmission and reflection characteristics of the device for the individual components. The complete solution is then obtained by applying superposition to reconstitute the fields in all regions.

Consider then the plane stratified dielectric sheet shown in cross-section in Figure 3. For convenience and without loss of generality plane waves are considered incident only from $Z>0$ at an angle θ with respect to the surface outward normal. We wish to determine the magnitude and phase of the reflected fields at $Z=0^+$, and the magnitude of the transmitted field at $Z=-D^-$ for both incident polarizations as a function of incidence angle θ; layer permittivity, ε_r^i; and layer thickness, t_i.

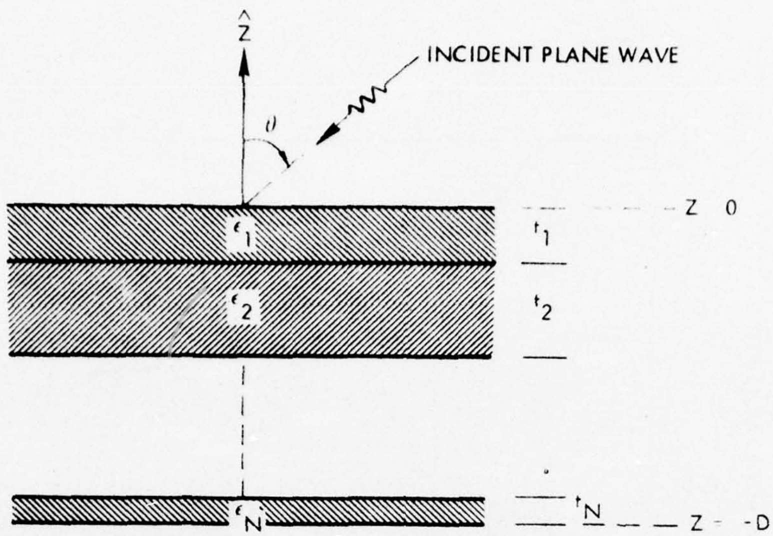

Figure 3 - Stratified Dielectric Slab Cross-Section

Having specialized to the scattering of plane waves which remain decoupled at the dielectric interfaces, the field problem may now be reduced to an equivalent transmission line problem in a standard manner. The equivalent circuit representation is shown in Figure 4. The i^{th} dielectric layer of the physical structure, with relative permittivity ε_{r_i} and thickness t_i, is represented by the i^{th} transmission line segment of length t_i. The characteristic admittance of the i^{th} line is the wave admittance associated with the dielectric properties of the corresponding layer for the particular incidence angle θ, and is given as

1) $$Y_i = \begin{cases} \kappa_i/\omega\mu_o, & \text{for TE incidence} \\ \omega\varepsilon_{ri}\varepsilon_o/\kappa_i, & \text{for TM incidence} \end{cases}$$

In equation (1), w is the angular frequency, and κ_i, the longitudinal wave number in the i^{th} medium, is given as

2) $$\kappa_i = \frac{\omega}{c}\sqrt{\varepsilon_{ri} - \sin^2\theta}$$

since the filter is assumed embedded in vacuum. c is the speed of light in vacuum.

It is a simple matter to construct the voltage scattering matrix representation of the circuit in Figure 4. Given any lossless, reciprocal two port network, as shown in Figure 5, the voltage scattering matrix is defined by

3) $$\underline{V}^- = \underline{\underline{S}}\,\underline{V}^+$$

where $\underline{V}^-$ and $\underline{V}^+$ are the vector representation of scattered and incident traveling wave voltages, respectively. By definition, then, the elements of $\underline{\underline{S}}$ are

4a,b,c,d) $$S_{11} = V_1^-/V_1^+\big|_{V_2^+\equiv 0}$$
$$S_{22} = V_2^-/V_2^+\big|_{V_1^+\equiv 0}$$
$$S_{12} = V_2^-/V_1^+\big|_{V_2^+\equiv 0}$$
$$S_{21} = V_1^-/V_2^+\big|_{V_1^+\equiv 0}$$

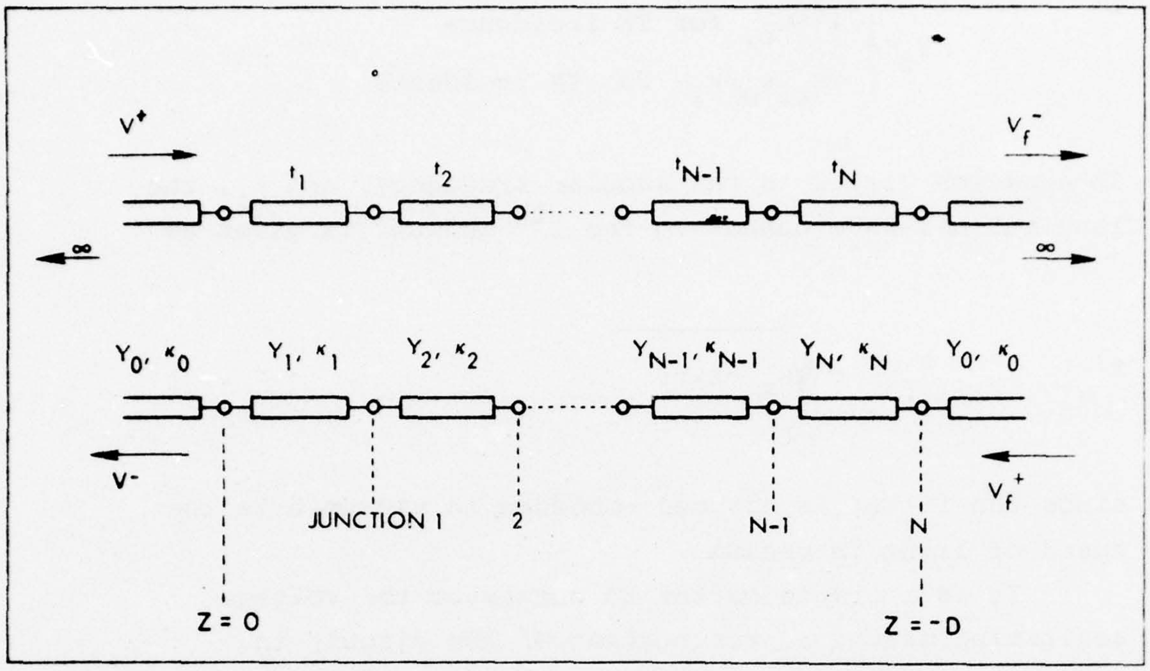

Figure 4 - Equivalent Circuit for Arbitrary Layered Dielectric Structure

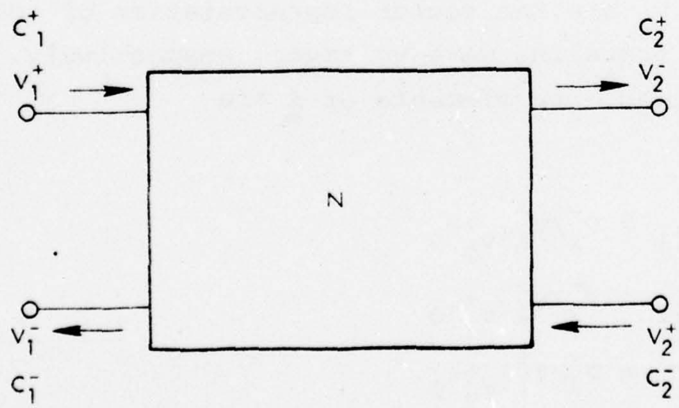

Figure 5 - Voltage Labeling at Ports of Two Port Network

Each transmission line segment, and each junction may be represented by its two port scattering parameters. By appropriate manipulation of port voltages, a single scattering matrix may be obtained for the network equivalent of the circuit in Figure 4.

A more convenient representation of the circuit is in terms of its traveling wave transmission characteristics. The traveling wave voltages at the ports of a two port network are related by

5) $$\underline{C}_1 = \underline{\underline{A}}\,\underline{C}_2$$

where $\underline{C}_1$ and $\underline{C}_2$ are the vector representations of the incident and scattered traveling wave voltages at ports 1 and 2, respectively, as defined in Figure 5. By properly associating the elements of $\underline{C}_1$ and $\underline{C}_2$ with the elements of $\underline{V}^-$ and $\underline{V}^+$, the elements of the wave transmission matrix, $\underline{\underline{A}}$, are obtained in terms of the elements of the voltage scattering matrix $\underline{\underline{S}}$, and are given as

6) $$A_{11} = 1/S_{21}$$

7) $$A_{12} = -S_{22}/S_{21}$$

8) $$A_{21} = S_{11}/S_{21}$$

9) $$A_{22} = (S_{21}S_{12}-S_{11}S_{22})/S_{21}$$

Representing each line segment and junction by its two port wave transmission parameters, $\underline{\underline{A}}_i^d$ and $\underline{\underline{A}}_i^j$, respectively, the cascade connection of networks in Figure 4 results in

10) $$\underline{C}_o = \underline{\underline{A}}\ \underline{C}_{fs}$$

where

11) $$\underline{\underline{A}} = \underline{\underline{A}}_o^j \prod_{i=1} \underline{\underline{A}}_i^d\ \underline{\underline{A}}_i^j$$

is the complete wave transmission representation for the network, and $\underline{C}_{fs}$ is the traveling wave voltage vector at $Z = -D^-$. In particular, for no excitation from $Z<-D$

12) $$\underline{C}_{fs} = \begin{Bmatrix} C_{fs}^+ \\ 0 \end{Bmatrix}$$

and the transmission coefficient of the equivalent network is obtained from equation (10) as

13) $$T = \frac{C_{fs}}{C_o^+} = 1/A_{11}$$

The reflection coefficient at $Z=0^+$ is then

14) $$\Gamma = A_{21} T$$

Formally, equations (13) and (14) completely specify the scattering properties of the equivalent circuit in Figure 4 for monochromatic TE or TM incidence, and it remains only to determine the parameters of the various junction and line length transmission matrices. These are obtained from elementary transmission line theory and are given as

15) $$A^j_{i_{11}} = A^j_{i_{22}} = (Y_i + Y_{i+1})/2Y_i$$

16) $$A^j_{i_{12}} = A^j_{i_{21}} = (Y_i - Y_{i+1})/2Y_i$$

for the i^{th} junction, and

17) $$A^d_{i_{11}} = e^{-j\kappa_i t_i}$$

18) $$A^d_{i_{22}} = 1/A^d_{i_{11}}$$

19) $$A^d_{i_{12}} = A^d_{i_{21}} = 0$$

for the i^{th} line segment. Examination of equation (16) shows that for

20) $$Y_i = Y_{i+1}$$

the off-diagonal matrix elements are 0. Consequently, at any spatial angle for which equation (20) is satisfied, the junction is transparent, and $A^j_{11_i} = 1$. From equations (1) and (2), this equality can occur only for TM incidence, provided $\varepsilon_i \neq \varepsilon_{i+1}$.

Equations (1), (2), and (20) may be manipulated to result in an expression for the incidence angle, θ, at which a junction is transparent to TM incidence. This angle is given as

21) $$\theta_T = \sin^{-1}\sqrt{\frac{\varepsilon_i}{1+\varepsilon_i/\varepsilon_{i+1}}}$$

where $\varepsilon_i \neq \varepsilon_{i+1}$. For either $\varepsilon_i=1$, or $\varepsilon_{i+1}=1$, equation (21) is the familiar Brewster angle formula, and gives the smallest angle, $\theta_T = \theta_\beta$, for which the junction is transparent. For both $\varepsilon_i \neq 1$ and $\varepsilon_{i+1} \neq 1$, θ_T is also a spatial angle at which total transmission is obtained at the junction, provided.

22) $$\varepsilon_{i+1} < \varepsilon_i/(\varepsilon_i-1)$$

For the layered dielectric sheet embedded in free space, θ_T is bounded by

23) $$\sin^{-1}\sqrt{\frac{\varepsilon'}{\varepsilon'+1}} < \theta_T < 90^\circ$$

where ε' is the smaller relative permittivity of the first and last dielectric layers.

As a consequence of equation (20), the layered dielectric sheet will have regions of high transmission to TM incidence at angles $\theta > 45^\circ$. From equation (23), this region of high transmission may be reduced by selecting the dielectric constants of the outer layers to be moderately large. A plot of the left hand side of equation (23) is shown in Figure 6. For $\varepsilon' = 3$, the lower bound in equation (23) is 60°, and for $\varepsilon' = 5$, the lower bound is 65.9°. For $\varepsilon' > 5$, the slope of the curve is very slow, and little advantage is gained from the larger values.

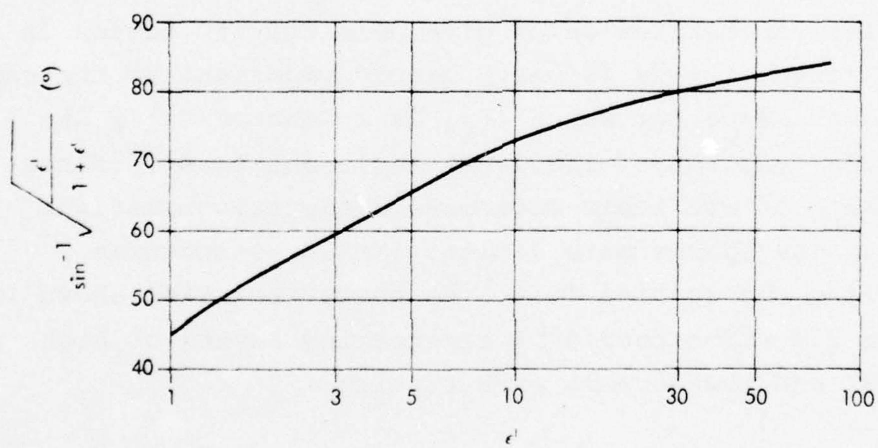

Figure 6 - Brewster's Angle versus Relative Permittivity, ε'

The principle task in stratified dielectric slab spatial filter synthesis is to reduce the spatial extent of the Brewster angle related passbands while maximizing transmission in the desired spatial passband near broadside, as shown in Figure 2.

At any junction, i, of the equivalent circuit, the reflection coefficient is given as

25) $$\Gamma_i^j = A_{i_{12}}^j / A_{i_{11}}^j$$

$$= (Y_i - Y_{i+1})/(Y_i + Y_{i+1})$$

and the magnitude, for small incidence angles θ, is large for permittivity ratios $p = \varepsilon_i/\varepsilon_{i+1} >> 1$, or $p << 1$. To achieve spatial filtering it is therefore, desireable to select geometries which give permittivity ratios in these ranges. This is particularly important in the case of TM incidence for which $|\Gamma_i^j|$ is a monotonically decreasing function of incidence angle out to θ_T. Since the range of available microwave dielectric materials lies in the approximate limits, $1 < \varepsilon < 25$, structures providing the spatial filtering characteristics shown in Figure 2 must be formed by alternating layers of high ($\varepsilon_i > 3$) and low ($\varepsilon_i \approx 1$) permittivity.

2.2 Synthesis of Plane Stratified Dielectric Slab Spatial Filters

The principle objective of this study is to develop a technique for the synthesis of practical plane stratified dielectric slab spatial filters for use with large planar arrays. The particular technique developed is one of numerical optimization wherein it is possible to synthesize filters which are optimized with respect to electrical performance in both the spatial and frequency domains while constraining the solution space such that only practical filter configurations result.

The spatial filter matrix characterization given in equation (11) of the preceding section is constructed such that all electrical and physical parameters effecting filter performance are modeled. These parameters are

- Plane wave polarization, i.e., TE or TM with respect to the filter normal
- Plane wave incidence angle, θ
- Slab relative permittivity, ε_i, $i=1,\ldots,N$
- Slab thickness, t_i, $i=1,\ldots,N$
- Number of slabs, N
- Frequency, f

The objective of the synthesis procedure is to determine the set of permittivities, $\{\varepsilon_i\}$, and slab thicknesses, $\{t_i\}$, which best match the filter performance to the desired performance in both spatial and frequency domains.

The desired spatial filter performance may be specified by the spatial variation of the power transmission coefficient as shown in Figure 7. In the figure, the desired performance is given in terms of forbidden regions since, in the spatial domain, specific functional variation control of the measure is limited by physical realizability, as was shown in Section 2.1. In the region $0<\sin\theta<\sin\theta_1$, the filter is to be maximally transmissive, within P_1db of perfect transmission. In the region $\sin\theta_2<\sin\theta<1$, the transmission coefficient is to be less than P_2db. And in the intervening region, $\sin\theta_1<\sin\theta<\sin\theta_2$, the transmission is to be monotonically decreasing. The forbidden region diagram may be fixed or varying in frequency.

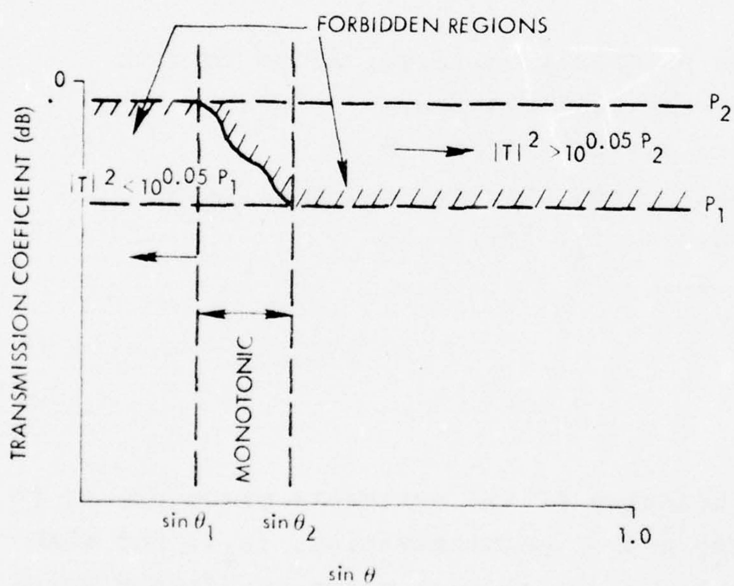

Figure 7 - Forbidden Region Diagram of Desired Spatial Filter Performance

For incident waves which are TE with respect to the surface normal, the transmission characteristics of the dielectric interfaces are monotonically decreasing functions of incidence angle. Hence, for applications in which only H-plane element pattern or grating lobe control is required, spatial filters are readily synthesized according to the prescription in Figure 7, provided the slab thicknesses are not so large as to introduce spurious far out passband as described by Mailloux[1]. However, for the case of E-plane control, or the more general case of providing control in two dimensions, the filter performance is fundamentally limited by the Brewster angle associated phenomena as discussed in Section 2.1. Consequently, the synthesis procedure developed here has been specifically designed to limit the spatial extent of the far out passband which occurs for TM incidence while simultaneously maximizing transmission in the passband around normal incidence.

From the above considerations, the formal statement of the synthesis goal is to minimize the function U over a properly defined multidimensional feasible region in $\{\varepsilon_i\}$ and $\{t_i\}$. The function U is defined as

25) $$U = \mathrm{Max}\{\min_{\substack{0<\theta<\theta_1 \\ f_l<f<f_h}} (|T(\theta,f)| - 10^{.05p_1}), 0\} + \mathrm{Max}\{\max_{\substack{\theta_2<\theta<\theta_s \\ f_l<f<f_h}} (|T(\theta,f)| - 10^{.05p_2}), 0\}$$

where

$$\text{Max}\{a,b\} = \begin{cases} b, & \text{for } b>a \\ a, & \text{for } a>b \end{cases}$$

$$\underset{\substack{0<\theta<\theta_1 \\ f_1<f<f_h}}{\text{Min}} (x(\theta,f)) = \text{minimum value of } x(\theta,f) \text{ in the two dimensional space, bounded as indicated}$$

$$\underset{\substack{\theta_2<\theta<\theta_s \\ f_1<f<f_h}}{\text{Max}} (x(\theta,f)) = \text{maximum value of } x(\theta,f) \text{ in the two dimensional space}$$

f_1 and f_h are the lower and upper frequency bounds, respectively; θ_s is the angle, $\theta_s > \theta_2$ at which the slope of $|T(\theta,f)|$ with respect to θ changes from negative to positive; and $T(\theta,f)$ is the voltage transmission coefficient given by equation (13) for TM incidence. For the special case wherein only TE polarization is of interest, $\theta_s = 90^\circ$ and $T(\theta,f)$ is taken as the TE transmission coefficient.

The effect of the first term in equation (25) is to force the transmission loss in the spatial passband to be less than P_1 db over the frequency band. The effect of the second term is to simultaneously maximize the filter rejection over the spatial region $\theta_2<\theta<\theta_s$ and drive θ_s toward 90°.

To ensure that the ultimate filter design represents an optimum, yet practical, configuration, the feasible region in $\{\varepsilon_i\}$ and $\{t_i\}$ is bounded and discontinuous. The allowed values of slab relative permittivity are taken from a table of available, low loss microwave materials, and are bounded by $\varepsilon_r = 1$ (vacuum) and a moderately large value available in practice ($\varepsilon_r=25$ is a practical upper bound at X band). The allowed values of slab thickness are continuous in a range guaranteeing a design which may be fabricated using current manufacturing techniques for large surfaces. A lower bound of .020" inches is representative, and an upper bound of 1.0" is a reasonable engineering limit for x band designs.

In principle, the filter synthesis may proceed from this point without further restrictions on the solution space. However, as was discussed in Section 2.1, the desired filtering characteristics are best achieved for permittivity ratios $\rho>>1$, or $\rho<<1$, at the dielectric interfaces. Such ratios are obtained by constructing the filter with alternating layers of high ($\varepsilon_i>3$) and low ($\varepsilon_i \approx 1$) permittivities. Consequently, the synthesis procedure is designed to consider only filters of the type shown in Figure 8, which consist of N dielectric layers with permittivities $\{\varepsilon_i\}$, i = 1,...,N, and thicknesses $\{t_i\}$,i = 1,...,N separated by N-1 layers of air or low permittivity ($\varepsilon_r \approx 1$) dielectric.

In the figure, the high permittivity layers are shown to have arbitrary ε_i. It was found during the course of this study that the synthesis procedure typically resulted in a disposition of permittivities which is nearly symmetric about the geometric center of the filter. Since this is not at all unreasonable in light of the results obtained by Mailloux[1], and since it is

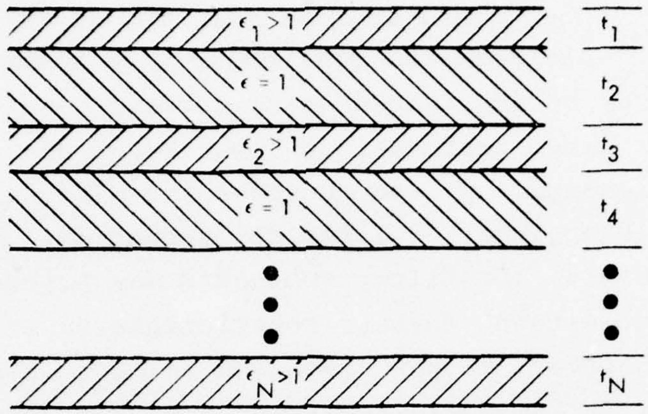

Figure 8 - Generic Configurations for Stratfied Dielectric Spatial Filters

desirable to limit the number of different materials in the filter, the last restriction imposed on the solution space disposes the permittivities symmetrically.

In broad outline, the numerical synthesis procedure is based on the RAZOR search optimization described by Bandler and MacDonald(2). For a given incident polarization, (typically TM for most applications), frequency and bandwidth, desired spatial performance criterion (e.g. Figure 7), and number, N, of high permittivity dielectric layers, a modified pattern search is conducted to locate local and/or global minima of the function U (equation (25)) within the bounded feasible region of $\{\varepsilon_j\}$, $\{t_i\}$, where the ε_j are symmetrically disposed with $j = 1,\ldots,N/2$; and the t_i are the thickness parameters of each filter layer with $i=1,\ldots,2N-1$ (thicknesses of both high and low permittivity layers are considered). An estimate $\{\varepsilon_j^o\}$, $\{t_i^o\}$ is used to initiate the search. If the pattern search does not locate a minimum of U which satisfies a predetermined measure of success, f_ε, that is

26) $$U > f_\varepsilon$$

a new pattern search is initiated by randomly perturbing the estimate $\{\varepsilon_j^o\}$, $\{t_i^o\}$ with large steps along the multidimensional coordinate axes. After a set number of evaluations of U, or after a set number of failures, as defined by equation (26), the procedure concludes, identifies the cause of termination, and provides the best estimate $\{\varepsilon_j\}$, $\{t_i\}$ as defined by the minimum value of $U-f_\varepsilon$. If a success is recorded, i.e., $U<f_\varepsilon$, the procedure terminates and provides the solution set $\{\varepsilon_j\}$, $j=1,\ldots,N/2$, and $\{t_i\}$, $i=1,\ldots,2N-1$.

A detailed account of the procedure is given in Appendix A.

3. NUMERICAL RESULTS

In this section, numerical results are presented. In the first part, results are given which illustrate the manner in which the synthesis technique approaches the optimum solution. In the second part, a spatial filter design is given which provides far out sidelobe and quantization lobe control for a large mechanically scanned planar array.

3.1 Synthesis of Seven Layer Filters

Figures 9 through 16 show typical results obtained for seven layer filter at various stages of the synthesis procedure developed in this study. The synthesis is carried out only for TM polarization since, as demonstrated above, filtering of incident TE waves does not present a significant design problem. In obtaining these results, slab relative permittivities were allowed to take on any value in the range $1<\varepsilon_i<25$, and thus the configurations are not practical in the sense defined previously. The synthesized designs are given only to illustrate the result of repeated application of the procedure to obtain the desired filtering characteristic. The performance goal is indicated on each figure. In the spatial range, $0<\theta<10^{\circ}$, the transmission loss is less than 1db. In the range, $25^{\circ}<\theta$, the desired rejection is 10 db or greater. The frequency band is 4% about 11.8 GHz.

The initial estimates $\{\varepsilon_j\}$, j=1,2, and $\{t_i\}$, i=1,...,7 were taken from the filter design given by Mailloux[1]. The outer high permittivity slabs have

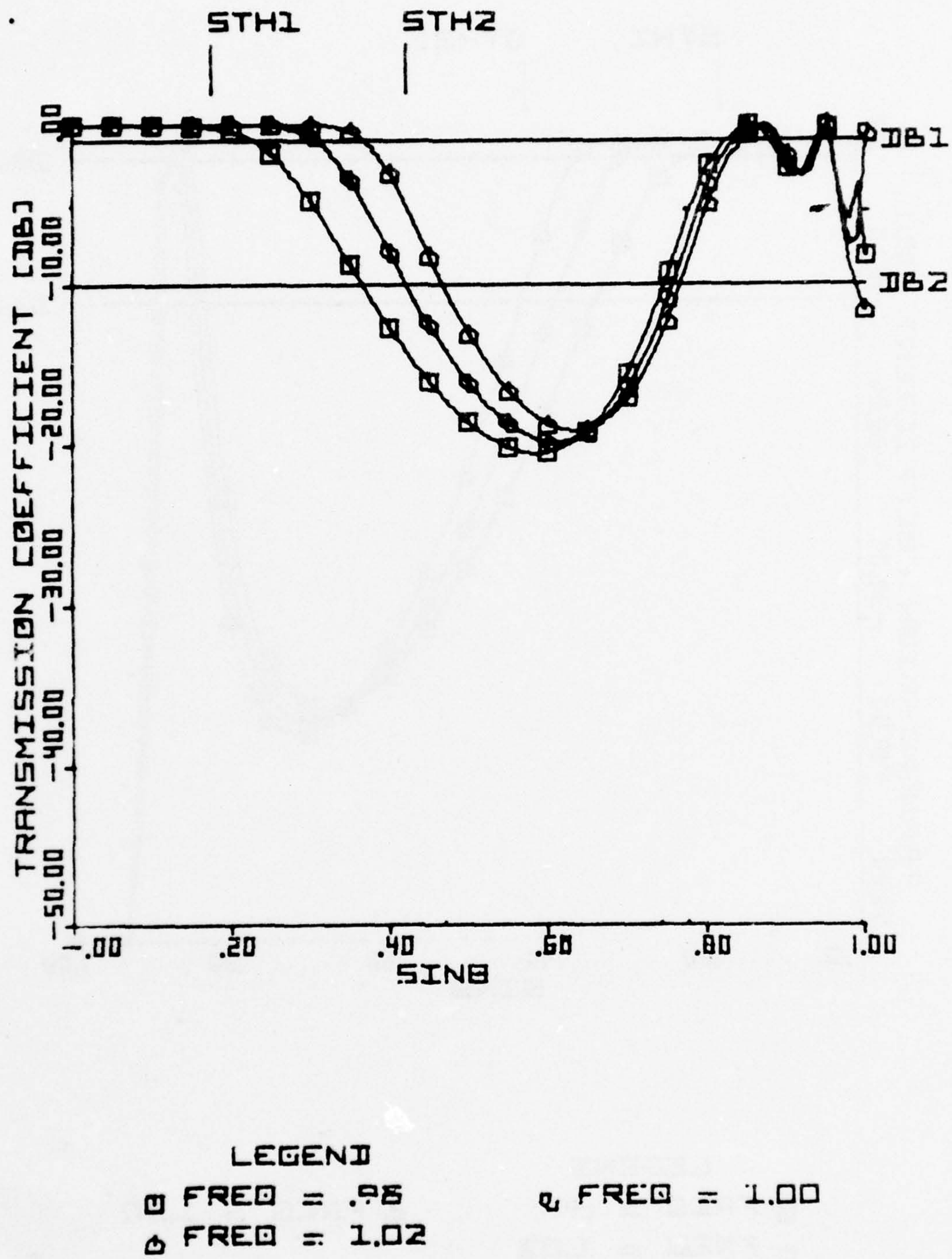

Figure 9 - TM Power Transmission of Seven Layer Spatial Filter (from Mailloux[1])

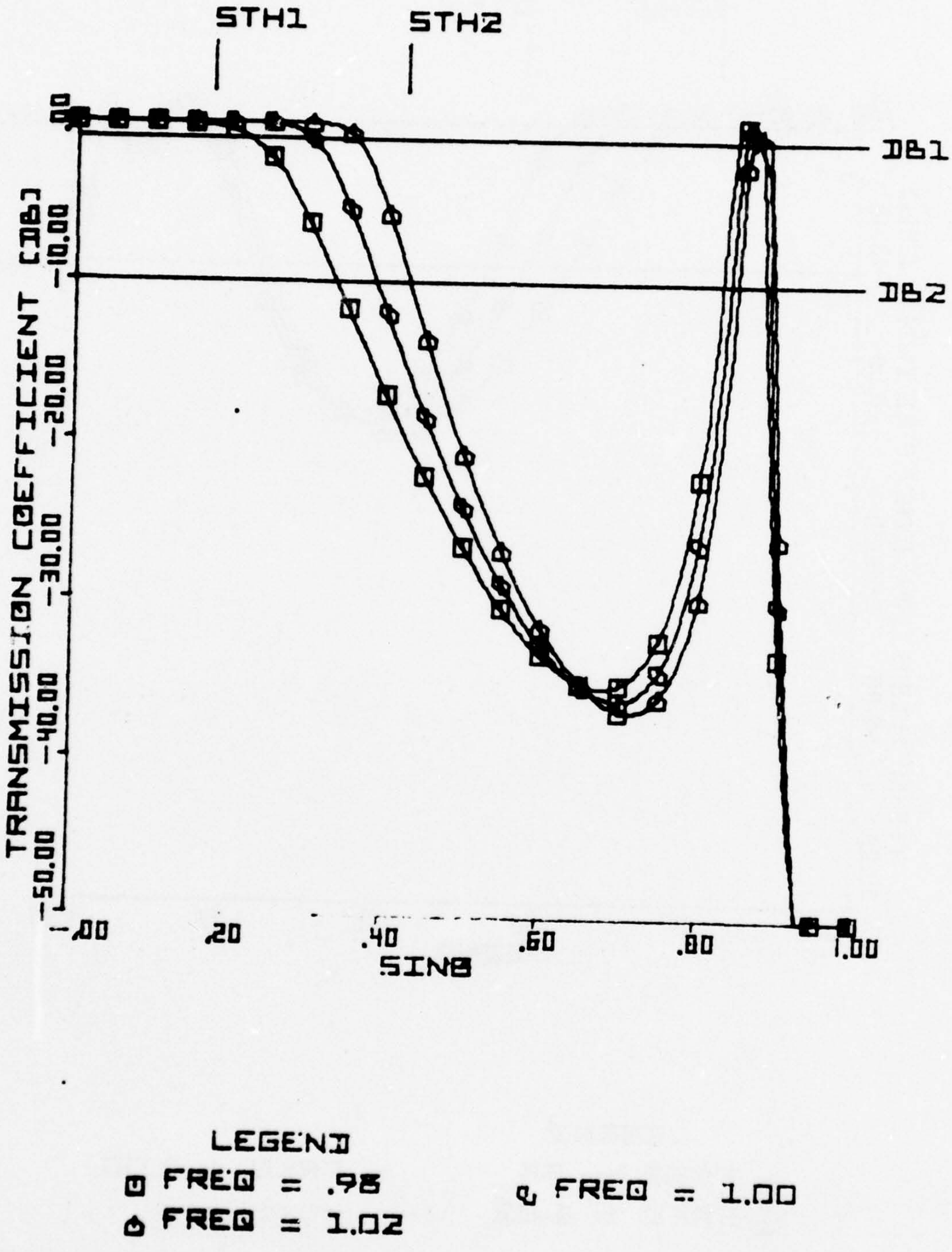

Figure 10 - TE Power Transmission of Seven Layer Spatial Filter (from Mailloux[1])

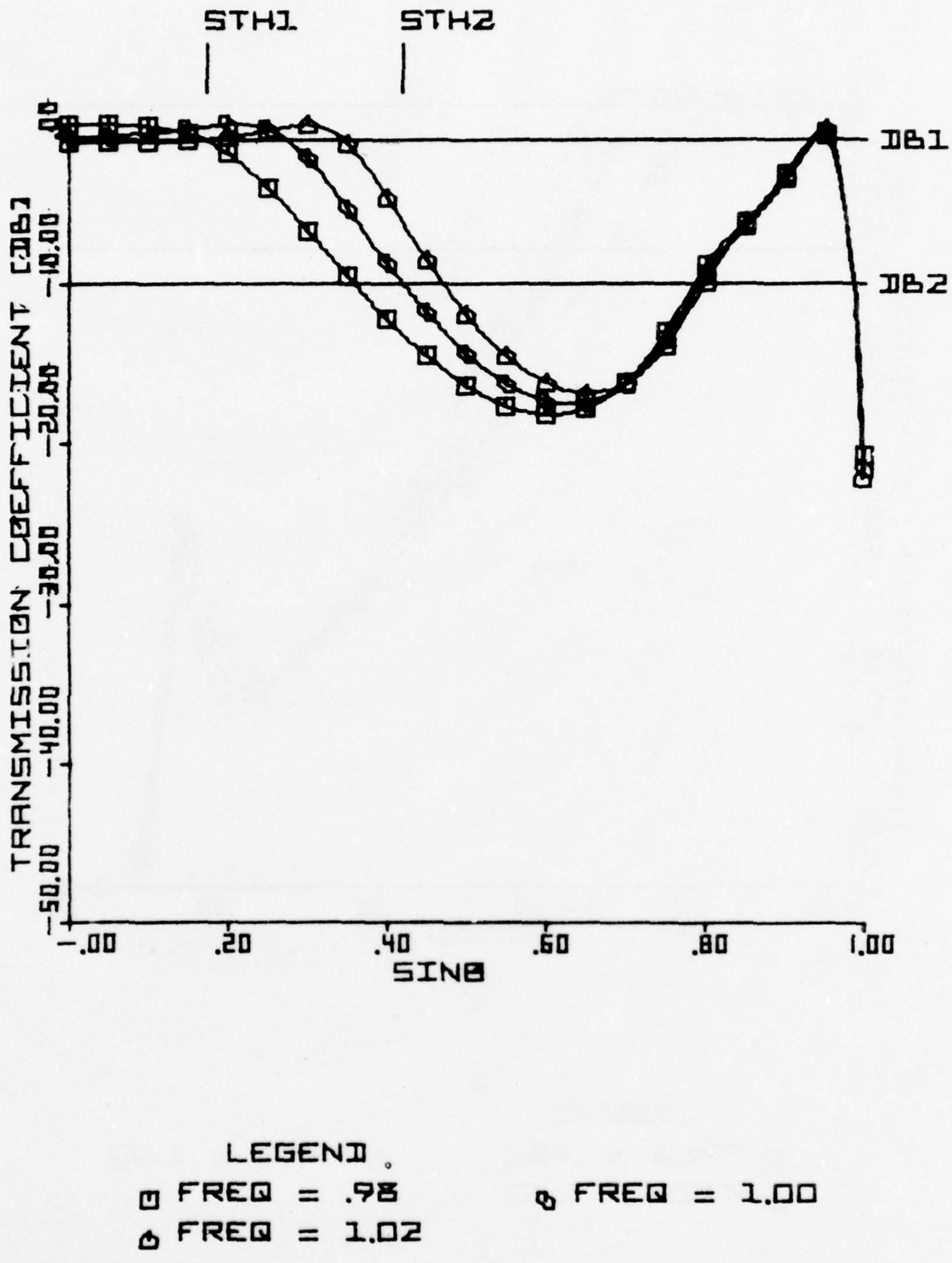

Figure 11 - TM Power Transmission of Seven Layer Spatial Filter
ε_1=3.95, ε_2=14.91, $\{t_i\}$={.142,.440,.046,.500,.057,.965,.129}

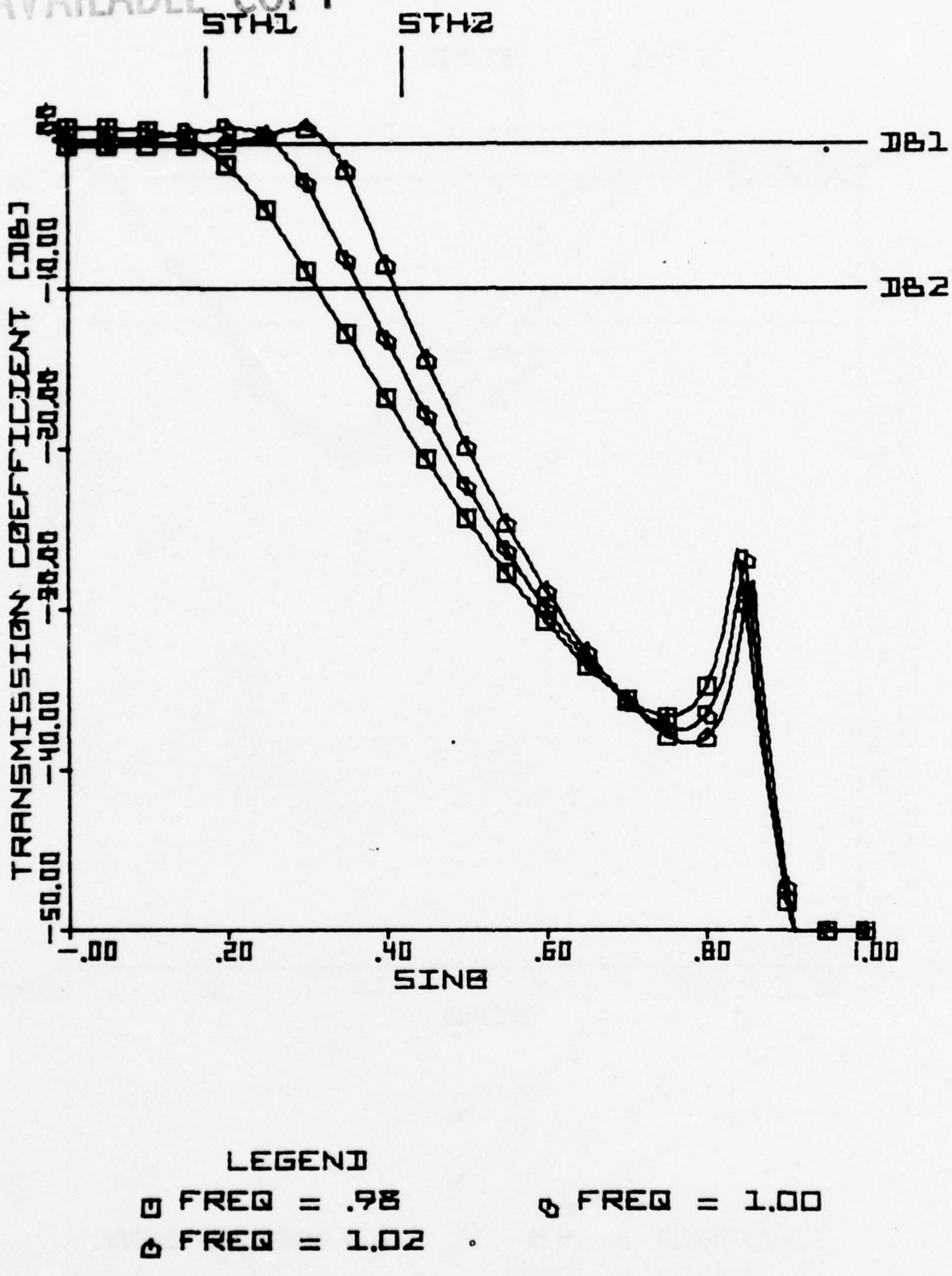

Figure 12 - TE Power Transmission of Seven Layer Spatial Filter
$\varepsilon_1=3.95, \varepsilon_2=14.91, \{t_i\}=\{.142,.440,.046,.500,.057,.965,.129\}$

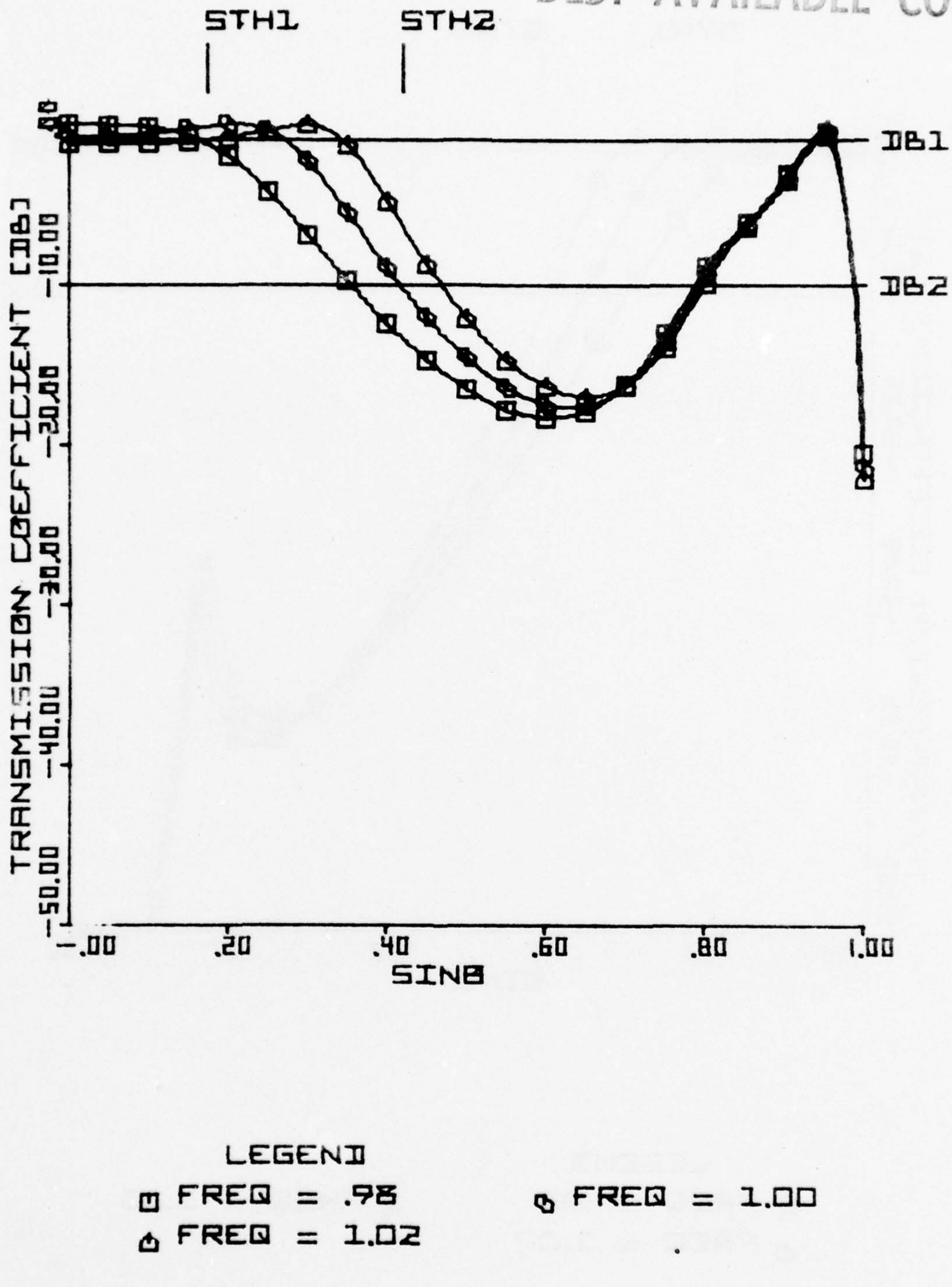

Figure 13 - TM Power Transmission of Seven Layer Spatial Filter
$\varepsilon_1=3.93, \varepsilon_2=14.93, \{t_i\}=\{.139,.440,.046,.500,.057,.965,.129\}$

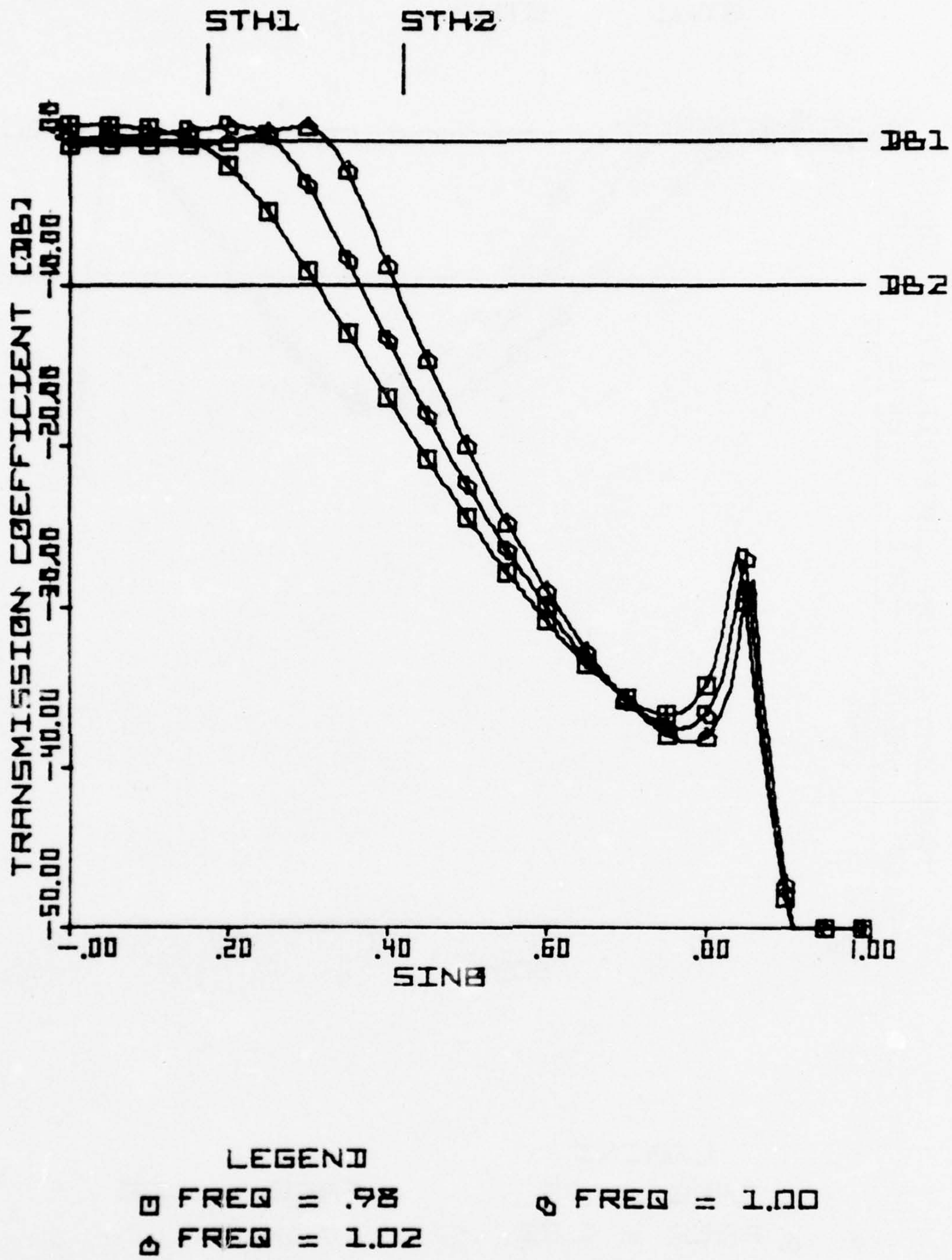

Figure 14 - TE Power Transmission of Seven Layer Spatial Filter
$\varepsilon_1=3.93, \varepsilon_2=14.93, \{t_i\}=\{.139,.440,.046,.500,.057,.965,.129\}$

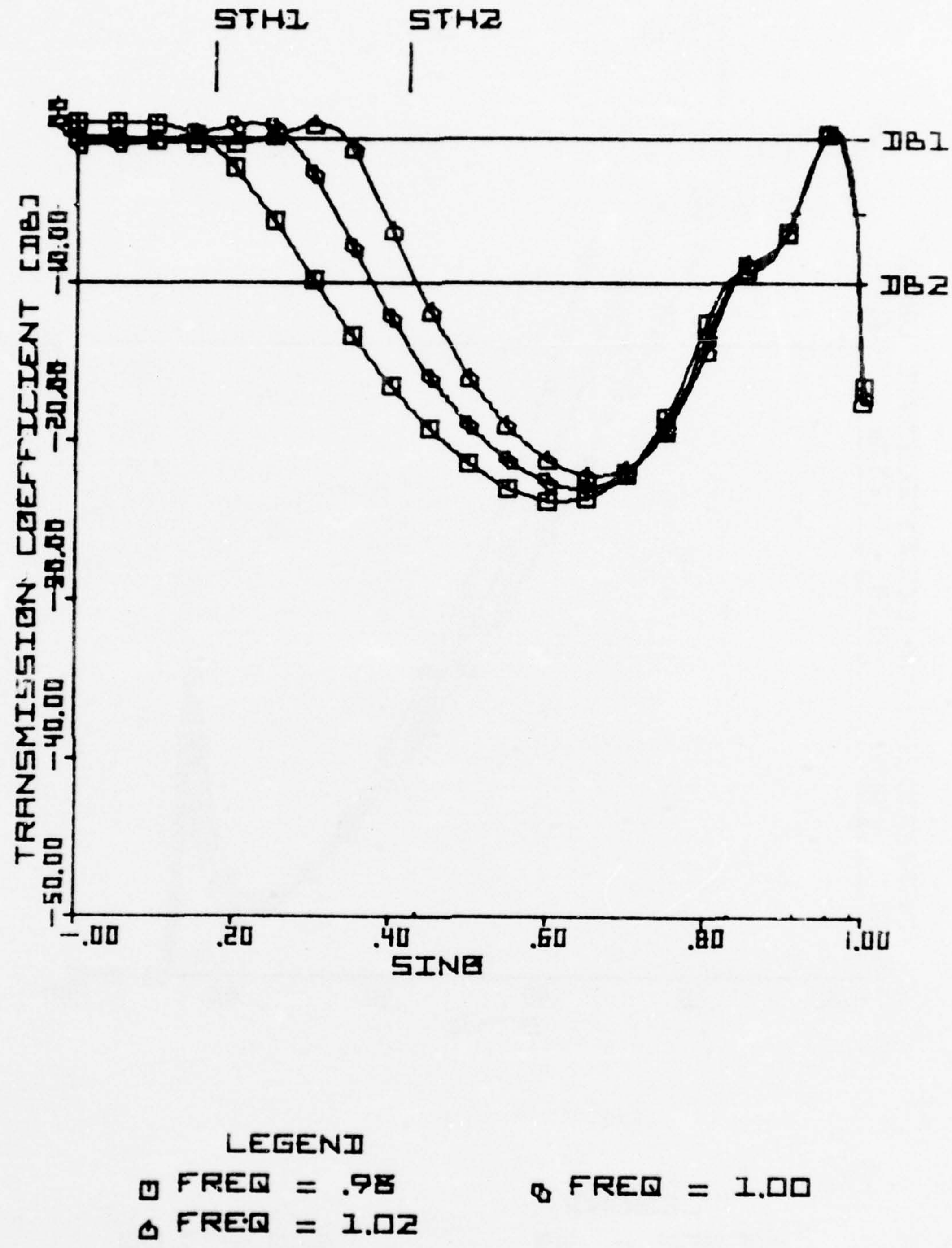

Figure 15 - TM Power Transmission of Seven Layer Spatial Filter
ε_1=7.27, ε_2=18.75, $\{t_i\}$=\{.114,.449,.051,.483,.050,.947,.074\}

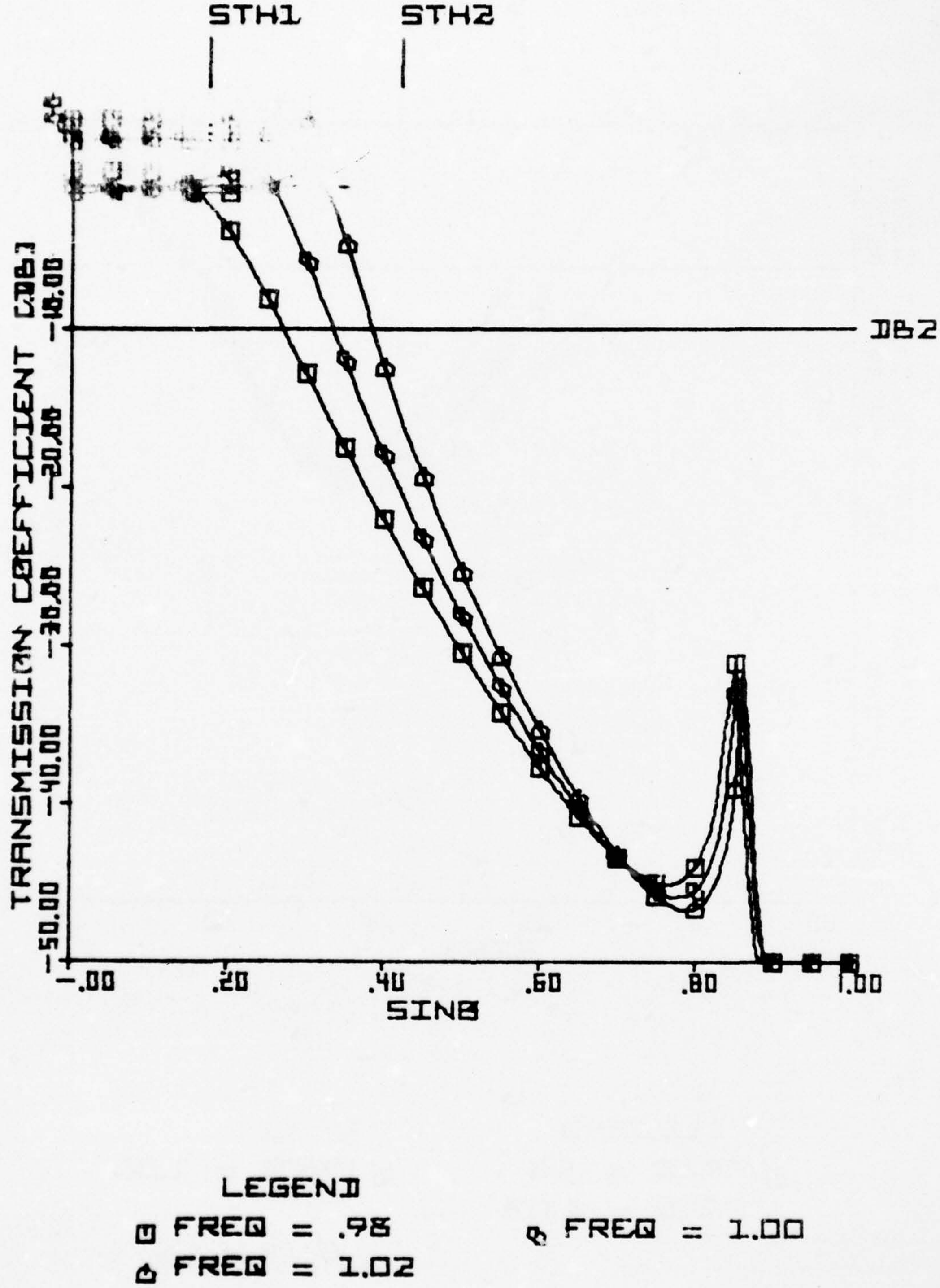

Figure 16 - TE Power Transmission of Seven Layer Spatial Filter
ε_1=7.27, ε_2=18.75, $\{t_i\}$={.114,.449,.051,.483,.050,.947,.074}

ε_1=3.08, and the inner high permittivity slabs have ε_2=15.14. The layer thicknesses are $.25/\sqrt{\varepsilon_i}$ inches in the high permittivity slabs, and 1.0" in the intervening regions which are assumed to be free space. The performance of this filter for TM and TE incident polarizations is shown in Figures 9 and 10, respectively. For TM and TE incidence, the filter provides the required low transmission loss in the spatial passband and over the entire frequency band. However, the spatial stopband is very narrow for TM incidence and a spurious farout passband appears for both polarizations near 60° incidence angle. The goal of the numerical optimization technique is to eliminate the spurious passbands for both polarizations and extend the spatial stopband for TM incidence.

Figures 11 and 12 show the filter response after 200 evaluations of the function U. It is evident that the synthesis procedure is obtaining greater stopband extent at the expense of transmission loss in the passband. For both polarizations, the spurious passband has been significantly reduced. The thickness distribution and relative permittivity have been significantly altered.

After 400 evaluations of the function U, the synthesized filter response is as shown in Figures 13 and 14. Little change has occurred with respect to the previous result, and it is clear that a continued search in the immediate vicinity will not obtain the desired result. Using the current best estimate as the starting point, a large step size is introduced for the pattern search to drive the result away from the local minimum. And, after an additional 200 function evaluations, the performance shown in Figures 15 and 16 is obtained, which satisfies the design goals. In particular, the extent of the stopband has been increased from the original 16°, beginning at $\theta=32^{\circ}$, to 31° beginning at $\theta=26^{\circ}$. Although significant transmission loss has been introduced in the passband, it may be removed by further optimization in the vicinity of the current best estimate. It is particularly interesting to note that the farout TM incidence passband peak has been moved well outside the first layer Brewster angle and the width at the 5 db points has been reduced from 30° for the original design to 15°.

3.2 An Eleven Layer Spatial Filter for Use with a Large Mechanically Scanned Planar Array

In this section a practical filter design for use with a large planar non-scanning array is presented. Since the permittivity of most microwave materials is constant from S band to X band, the thickness parameters determined by the synthesis procedure are given normalized to the free space wavelength at the center frequency of the operating band, and the design may be considered universal for this frequency range.

The design goal is to provide a minimum farout ($\theta>25^{\circ}$) sidelobe and quantization lobe reduction of 10 db for a large, mechanically scanned, two-dimensional planar array of vertically polarized rectangular apertures over a 4% frequency band. The array possesses full search track capability and requires a 10° spatial passband with maximum transmission loss of .ldb. The required coverage sector is 360° azimuthally, and -5° to 50° vertically. An SOJ threat is postulated to be uniformly distributed in azimuth within 20° of the horizon.

To provide the required rejection over the full coverage sector, the filter design must limit the Brewster angle associated passband to angles greater than 55^{o}. Practical filters providing a 30^{o} E-plane stopband may be synthesized using eleven or more layers.

Figure 17 shows an illustration of an eleven layer filter which satisfies the design goals. The filter is constructed using four well known dielectric materials: stycast Hi-K ($\varepsilon_1=\varepsilon_{11}=5$), an Emerson Cumming loaded cross-linked polystrene; Trans-Tech DA-9 Alumina ($\varepsilon_3=\varepsilon_9=9.5$); stycast Hi-K 500F loaded thermoset hydrocarbon; and ($\varepsilon_2=\varepsilon_4=\varepsilon_6=\varepsilon_8=\varepsilon_{10}=1.02$). The layer thicknesses are given normalized to free space wavelength at center frequency.

The filter performance is shown in Figures 18 and 19 for E and H plane incidence, respectively. In the

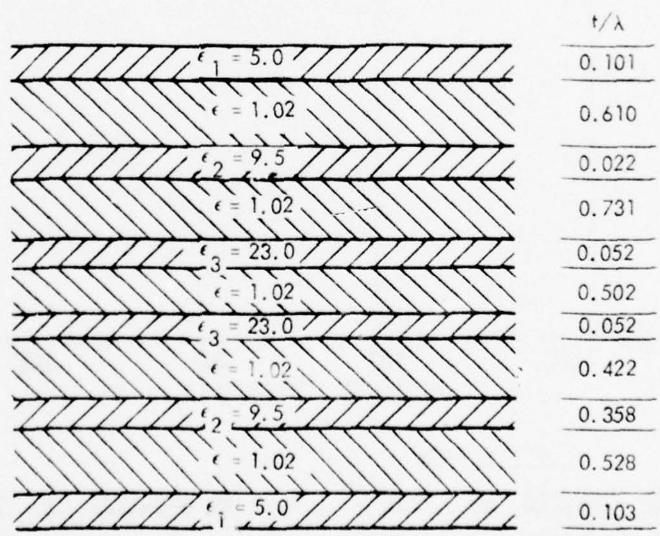

Figure 17 - Cross Section of Filter Synthesized by Numerical Optimization

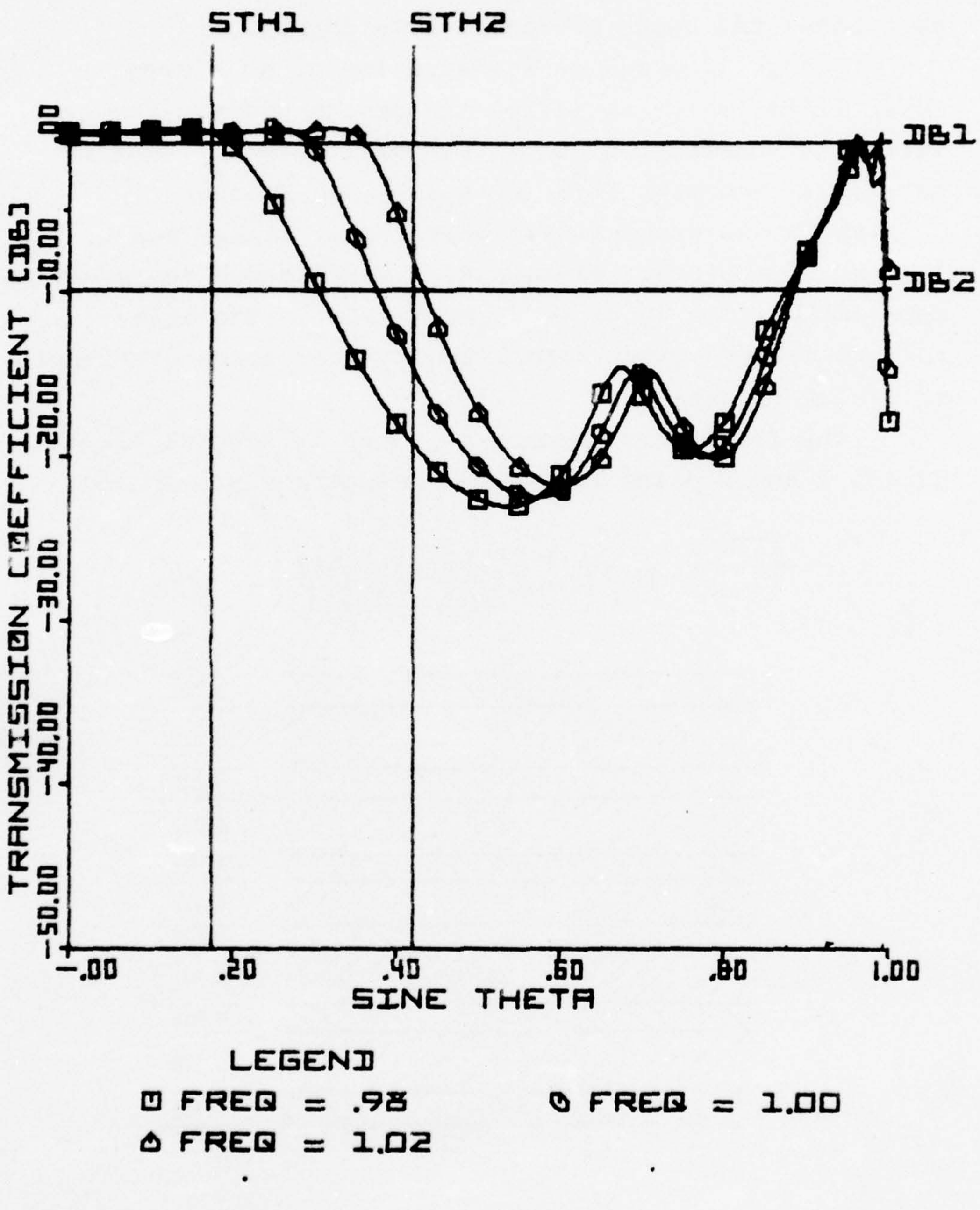

Figure 18 - TM Power Transmission of Eleven Layer Spatial Filter

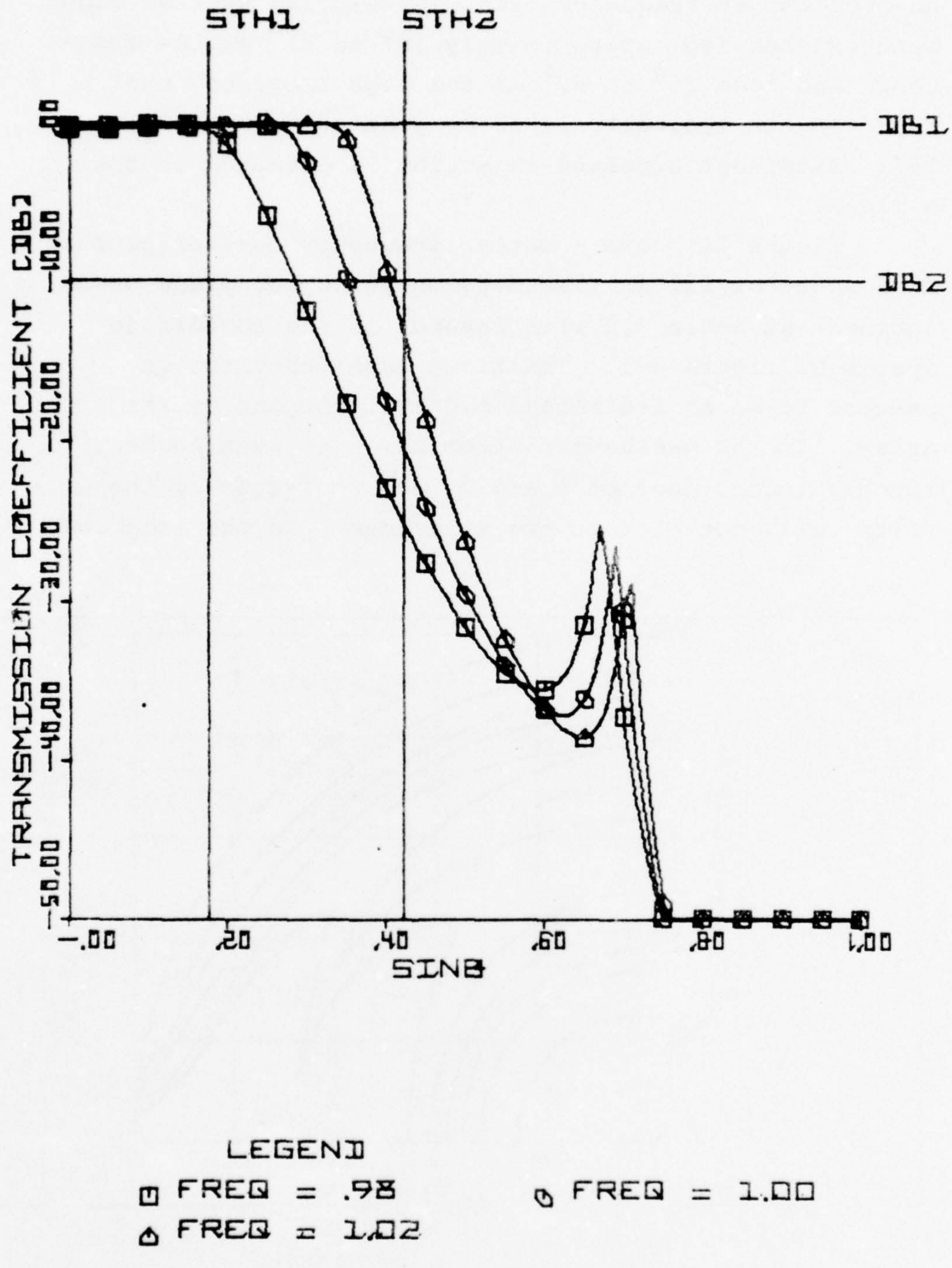

Figure 19 - TE Power Transmission of Eleven Layer Spatial Filter

spatial passband, the transmission loss is less than .15 db over the 4% frequency band. The E-plane spatial stopband extends from approximately 18° to 61° at low frequency and from 26° to 62° at the high frequency and rejection is typically 14 db or greater from 30° to 55°. Excellent stopband rejection is obtained in the H-plane.

Figure 20 shows a center frequency contour plot in sine space of filter transmission in db for plane waves incident at angle θ,Ø with respect to the coordinate system of Figure 2-1. The plane wave generator is assumed to be an X-directed magnetic current on the array. In the passband, transmission is seen to be roughly independent of θ and Ø, and consequently the filter will not distort the main beam. In the stopband,

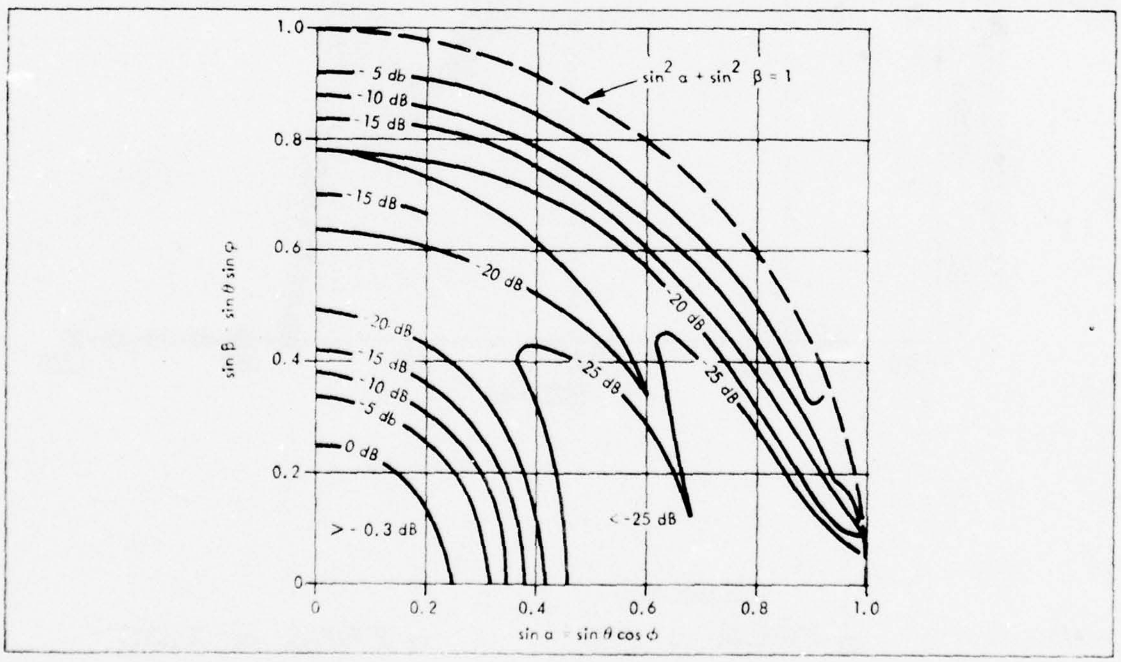

Figure 20 - Transmission of Fields Generated by X-Directed Magnetic Currents on the Array

the rejection is greater than 10 db except in the vicinity of the near in stopband edge for $\emptyset=90^{\circ}$. Over most of the stepband, the rejection considerably exceeds 14 db. The Brewster angle associated passband does not extend to angles, $\emptyset$, below 33°, thereby reducing the SOJ threat/

The isolation between nominal (or transmitted) field polarization, and the cross polarization generated by the filter is shown in Figure 21. As expected, the peak cross polarized signal is generated in the vicinity of $\emptyset=45^{\circ}$, $\theta=20^{\circ}$, and in the farout passband region.

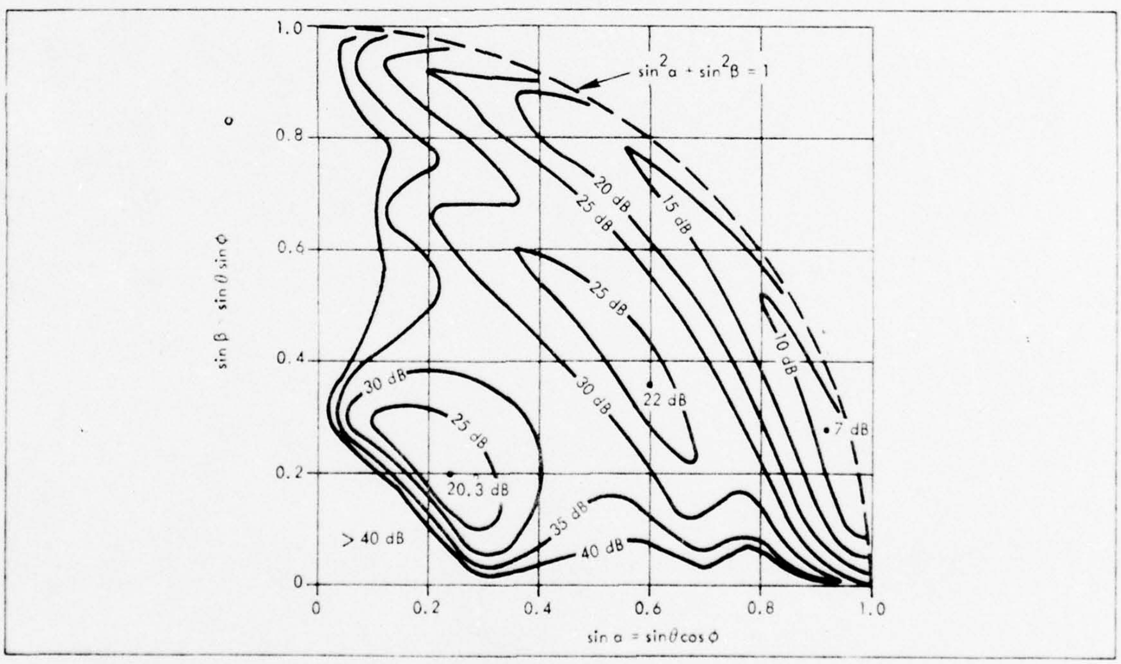

Figure 21 - Isolation of Cross Polarized Signal Generated by the Layered Medium

4. CONCLUSIONS

The stratified dielectric slab spatial filter synthesis technique given here results in practical filter designs which provide considerable element pattern control for large mechanically scanning and limited scanning arrays. For a hypothetical mechanically scanned two dimensional antenna, a filter design has been presented which reduces farout sidelobes and quantization lobes by more than 10 db in a region extending from 26° off the antenna normal to 61°.

APPENDIX A

A MODIFIED RAZOR OPTIMIZATION PROCEDURE FOR SPATIAL FILTER SYNTHESIS

A.1 Program Abstract

The optimization program is a federation of three modules named FILTER, RXS, and RZS which will be described as functional entities. FILTER is the main program segment containing in addition, a subroutine named U which computes the objective function to be optimized, and DISPLA, a utility subroutine which surpresses the automatic carriage return and line feed after printing a prompting message.

The main program permits the user to input all pertinent parameters such as: the number of slabs of the spatial filter, the initial dielectric constants and thicknesses, tolerance ranges over which the optimization is to seek its improved values, the frequency ranges over which the filter is to operate, the sine theta and transmission coefficient values which characterize the pass/stop bands and the performance in db, as well as the parameters ALPHA, LIMIT, EPSMIN, RHO, ETA, KAPPA, DELTA, FEPS which govern the conduct of the optimization process itself.

Sufficient flexibility has been incorporated into the main program to allow the user to select a TRACE option which permits witnessing the deliberations of the optimization by a printout of all perturbated components and their effect on the objective function. In addition, the program has been structured so that only a minor alteration by the user, if he so desires, will enable him to treat special filter configurations like symmetric filters, quarter wave length layer filters and so on.

The second module RXS consists of a single subroutine RXTX which returns the complex-valued transmission coefficient RT used only by the function U. RT results from the matrix multiplication of junction and line length wave transmission matrices, and as this coefficient is computed many times by the function U (even for a single perturbation), great care has been exercised in the construction of the algorithm for the total wave transmission matrix computation.

The last module RZS consists of six subroutines named RAZOR, FINISH, PATSER, BOUND, EXPLR, PATMV, with FINISH and BOUND serving in ancillary capacities of determining whether the perturbations have produced a minimization of the objective function and secondly ensuring that no perturbation is allowed to exceed its prescribed range. RAZOR is the subroutine which in conjunction with PATSER, PATMV, EXPLR executes the optimization technique described by of Bandler and Macdonald[2]. In its broad outline the technique is to conduct a pattern search (PATSER) around a base point by perturbing in turn each of the components of the base point. If the search exposes a new point for which the objective function has been minimized to within a tolerance specified by FEPS, RAZOR returns this new point to the main program and terminates its activities. Otherwise, a point in the vicinity is randomly selected as a provisional base point around which explorations are undertaken as before. If there is no improvement, the process is repeated for as many times as specified by KAPPA with a closer randomly selected provisional base point.

A.2 Program Description

The main program TEST 1 calls for user input of NS, the number of non-air dielectrics, the associated dielectric constants, slab thicknesses, and the high and low constraints on the perturbation vector PHO. In addition, the frequency range over which the filter is to perform is input as are the sine theta and transmission coefficient values characterizing the pass/stop bands and performance in db.

Thus, for a spatial filter with six non-air dielectrics configured symmetrically, 6 would be entered for NS in response to the prompt NR SLABS=?. Also 3 values (IP=(NS+1)/2) of non-air dielectric constants and 11 values (NSLAB1=2*NS-1) of air and non-air thicknesses would be input. The dimensionality of the perturbation vector PHO would then be 14 (K=IP+NSLAB1), and whose initial contents would be the 3 dielectric constants and 11 thicknesses. The next two input parameters would be two sets of K (here, 14) values for low and high perturbation constraints to be placed on the permissible ranges of the PHO vectors components. Typically, a low of 1 and a high of 25 have been placed on the PHO components associated with dielctric constants, a low of .02 and high of 1.0 for those components associated with non-air dielectric thicknesses, and a low of .1 and a high of 2.0 for air thicknesses. In response to the prompt for frequency range, the user enters 3 values for low frequency, high frequency, frequency increment normalized to center frequency; for example .98, 1.02, .02 would cover three frequencies. The next six values to be entered are concerned with the filter's performance. The value specified for DB1 determines the low cutoff figure for transmission coefficient in the passband and the values entered for SN1 and SNINC1 in response to the prompt STH1 and INCR=? define the spatial limit of the passband and the sequence of points within the passband which are to be evaluated. Similar remarks apply to DB2, SN2, SNINC2 which specify the stopband. Values of DB1=-.1, SN1=.175, SNINC1=.0175, DB2=-10.0, SN2=.42, SNINC2=.02 are typical. The program next inputs ALPHA, LIMIT, EPSMIN, RHO, ETA, DAPPA, DELTA, and FEPS. FEPS is the tolerance within which our objective function is to be minimized and is typically selected as .01. RAZOR conducts a pattern search (PATSER) around the initial base point by perturbing in turn each of the components of the base point. The actual absolute step sizes used in PATSER are SDEL=DELTA*R(I)*S(I)/100 where R(I) = 100*(HIGH(I)-LOW(I)) is the parameter range of permissible values in the Ith component, and S(I) has values +1 or -1 to establish directionality of the perturbation.

Since dielectric constants are considered in the range 1→25 and thicknesses .02→1 for non-air dielectrics and .1→2 for air dielectrics, we observe that selecting an initial DELTA=.1 yields step sizes of 2.4 for dielectric constants with .008 for non-air thicknesses and .19 for air thicknesses.

EPSLON and DELTA are used as relative measures of step size reductions, with DELTA<EPSLON signifying that a pattern search, PATSER, would be useless at this point. Initially EPSLON=EPSMIN*(ETA**KAPPA)

where	EPSMIN = .001	(a starting value)
	ETA = 2	(a halving factor)
	KAPPA = 3	(max of 3 random moves).

EPSMIN = .001 was selected so that EPSLON = .001 $*2^3$ = .008 thereby rendering the initial DELTA = .1 larger than EPSLON and thus guaranteeing a PATSER the first time through.

ALPHA is a parameter within PATSER which reduces the size of DELTA in the event initial explorations give no improvement in reducing the value of the objective function. A value of .25 gives significant reduction of DELTA, but does not reduce too rapidly to obtain a solution.

When all explorations about the base point have been unsuccessful, RAZOR perturbs each component of the base point by RHO*RANDOM*EPSLON/100 in order to obtain a new provisional base point about which the process can be repeated. RANDOM provides random values between -1 and +1 with RHO selected as 400. EPSLON is then halved by ETA and new explorations are begun.

Since an enormous number of functional evaluations must be performed not only in exploratory moves but in evaluatory criteria, LIMIT (the maximum number of functional values to be computed in the entire optimization program) has been set to a large value, typically on the order of 1000. The objective function U is summarized in Figure 7 and in equation 25. Its actual implementation is performed in two steps. For each fixed sine theta (sine theta = 0 through SN1 in steps of SNINC1) cycle through the range of frequencies FLO through FHI in steps of FINCR constantly determining UMN=CABS(RT) - OFFSET where OFFSET = 10.0 ↑ (.05*DB1) and RT is the complex valued transmission coefficient returned from a call to subroutine RXTX. The negative of the minimum value of these UMN values is kept as the first part of the objective function.

The second part is determined in the following manner. Beginning with a fixed sine theta value of SN2, cycle through the range of frequencies FLO through FHI in steps of FINCR constantly determining UMX-CABS(RT) - OFFSET where OFFSET = 10.0 ↑ (.05*DB2). Continue this process with the next fixed sine theta value incremented by SN1NC2 over its previous value only for as long as the center frequencies CABS(RT) values are declining.

A.3 Program Flow of Principle Programs and Subroutines

To give a more complete description of the optimization procedure, the following paragraphs simultaneously outline program flow and comment on the implementation of the principle programs and subroutines. RAZOR($\emptyset^{o}$, ε_{min}, ρ, η, kappa) is the principal procedure in the optimization process. $\emptyset^{o}$, ε_{min}, ρ, η, kappa are FORMAL parameters through which the initial values are acquired from the calling program. Within the algorithm $\emptyset$, U$\emptyset$ are local variables, κ is the dimensionality of the $\emptyset$ vector, and δ is common (i.e. global) to RAZOR and has been initialized by the main program to a value $\delta > \varepsilon_{min} * \eta^{kappa}$ to ensure bypassing the IF $\delta < \varepsilon$ criterion in PATSER which RAZOR invokes at the outset of its deliberations.

Comment: initialize the local quantity U$\emptyset^{o}$ to reflect the starting value. Set up the initial directions for the explorations. Initialize the starting ε and then invoke a pattern search. If a point is uncovered with a functional value within the FEPS tolerance specified, then terminate the procedure otherwise renew the search (kappa number of times if necessary) with an arbitrary point randomly selected in the vicinity of $\emptyset^{o}$ and with a reduced ε value;

```
UØ°: = U(Ø°); for i:=1 step 1 until κ DO S_i:=1;
ε:=ε_min*η^kappa; PATSER (Ø°, UØ°);
If finish (UØ°) then go to FIN;

for j:=1 step 1 until kappa DO

Begin comment initialize a local variable UØ° to the best
              functional value and a local vector Ø to
              contain the coordinates of a randomly
              selected point in the vicinity of Ø°.  Another
              local variable UØ is initialized to contain
              the functional value at the random point.
              ε and δ are reduced and a pattern search
              is initiated;

     UØ°:=U(Ø°);
     for i:=1 step 1 until κ DO Ø_i:=Ø°_i +ρ *RANDOM*ε;
     ε:=ε/η;   δ:=|Ø-Ø°|√κ;
     UØ:=U(Ø); PATSER (Ø,UØ);

If UØ<UØ°
Then L1: begin comment set UØ° to the returned improved
                       value UØ.  Establish θ as the
                       direction of improvement and Ø°
                       to the returned improved location
                       Ø;
      UØ°:=UØ; θ:=Ø-Ø°; Ø°:=Ø
      End
```

Else

Begin Comment reset UØ to the starting functional value $U\emptyset^{o}$ over which there was no improvement and set θ in the opposite random direction;

$U\emptyset := U\emptyset^{o}$; $\theta := \emptyset^{o} - \emptyset$

End;

Comment set local Ø as the new extrapolated point from $\emptyset^{o}$ in the θ direction and δ equal to the square of the magnitude of θ. Invoke a pattern move;

$\emptyset := \emptyset^{o} + \theta$; $\delta := |\theta|^2$; PATMV $(U\emptyset, \emptyset, \emptyset^{o})$;

Comment if the returned functional value is an improvement then return to L1 for further refinement until none better is found. Then check if the returned refinement is within the FEPS tolerance which causes a termination of the RAZOR optimization. Failing this, the next random point is selected even closer to $\emptyset^{o}$;

If $U\emptyset < U\emptyset^{o}$ then go to L1;
If finish $(U\emptyset^{o})$ then go to fin

End;

Write ("no convergence");

Fin: End

PATSER $(\emptyset^{o}, U\emptyset^{o})$ is the chief searching procedure. $\emptyset^{o}$ and $U\emptyset^{o}$ are formal parameters and Ø,UØ are local variables in the following algorithm.

```
L1: . IF δ<ε then go to fin;
      Comment initialize the local variables Ø,UØ to the
              corresponding values transferred through
              FORMAL parameters Ø°, UØ°.  Then invoke
              EXPLR to perform initial explorations.
              Ø,UØ will be changed hopefully to an
              improved point and its functional value;
      UØ:=UØ°;  Ø:=Ø°;  EXPLR (UØ,Ø);
      If UØ>UØ°
      Then begin comment there is no improvement in any
                         of the explorations.  Reduce
                         size of δ and try again;
        δ:=α*δ;  go to L1
        End;
        Comment an improvement was detected.  Change the
                formal parameters Ø°,UØ° to reflect the
                improved location and its functional
                value.  Establish into θ the general
                direction of improvement.  Set the local
                quantity Ø to contain the new extrapolated
                value and δ to contain the square of the
                magnitude of θ.  Invoke a pattern move
                (PATMV) and return to L2 if there is an
                improvement, otherwise begin anew  by
                returning to L1;
```

L2: $U\emptyset^o := U\emptyset$; $\theta := \emptyset - \emptyset^o$; $\emptyset^o := \emptyset$; $\emptyset := \emptyset^o + \theta$;

$\delta := |\theta|^2$;

PATMV $(U\emptyset, \emptyset, \emptyset^o)$;

If $U\emptyset < U\emptyset^o$ then go to L2 else go to L1;

Fin: End

PATMV $(U\emptyset^o, \emptyset, \emptyset^0)$ where $\emptyset^o$ is the vector describing the best location so far and $\emptyset$ is the extrapolated location around which explorations are to be performed within PATMV, is best described graphically in terms of a two dimensional $\emptyset$. If the explorations depicted below uncover a better point than $\emptyset$, then that point is returned in place of $\emptyset$ and the functional value at the uncovered point is returned to $U\emptyset$. Within the algorithm K is the dimensionality of the $\emptyset$ vector, while δ and the vector θ are common (i.e. global) to PATMV. The functional value of the original extrapolated point $\emptyset$ is computed immediately upon entry into PATMV and is retained in a local variable named UPHI. It is against this local quantity that functional values of exploratory test points (about $\emptyset$) returned by EXPLR are compared to determine if improvement has occurred.

PATMV first performs explorations (using EXPLR) with a new $\delta = \sqrt{\delta / \kappa}$ and returns into $\emptyset$ any of the possible locations indicated and into $U\emptyset$ the corresponding functional value. Note that θ is the direction established earlier in the process and reflects the general direction of improvement from some former $\emptyset^o$ location to the present $\emptyset^o$ location specified upon entry into PATMV.

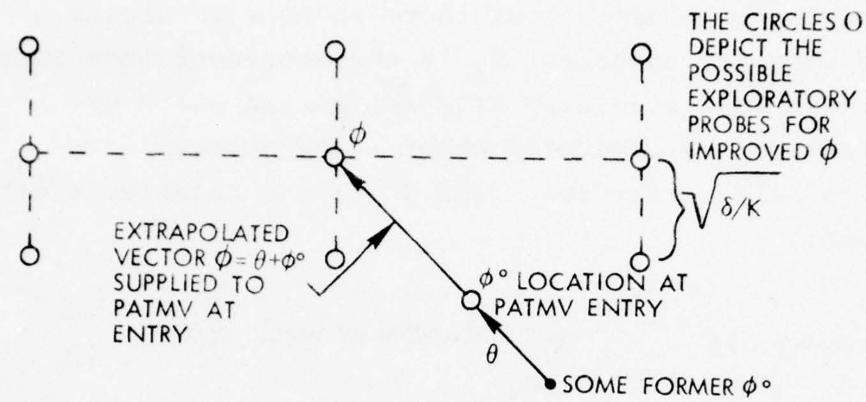

Figure A-1 - Initial Exploration in Subprogram PATMV

If the exploratory moves about $\emptyset$ fail to uncover a better point or in the case there is an improvement but there is no significant change in each component $\emptyset_i$ i.e. for every i $|\emptyset_i - \emptyset_i^o| < 10^{-6} * |\emptyset_i^o|$, then the step size is halved to $1/2\sqrt{\delta/\kappa}$ and explorations are conducted about a new extrapolated location half as far away from $\emptyset^o$ in the θ direction as shown.

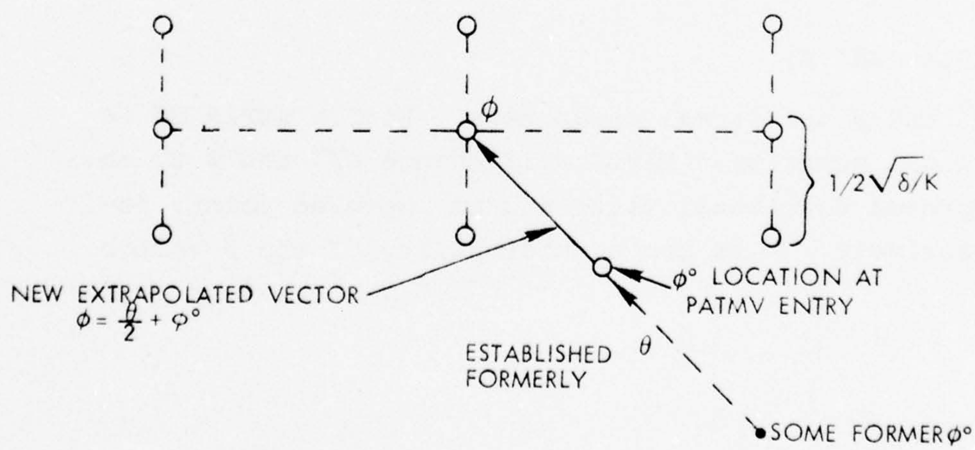

Figure A-2 - Explorations About New Extrapolated Vector

$$\phi = \frac{\theta}{2} + \phi$$

Finally, if there is still no improvement or in the case there is an improvement but there is no significant change in every component $\emptyset_i$ in the aforementioned sense, then the halved step size $1/2\sqrt{\delta/\kappa}$ is used again but explorations are conducted about a new extrapolated location half as far away from $\emptyset^O$ in the negative θ direction as shown.

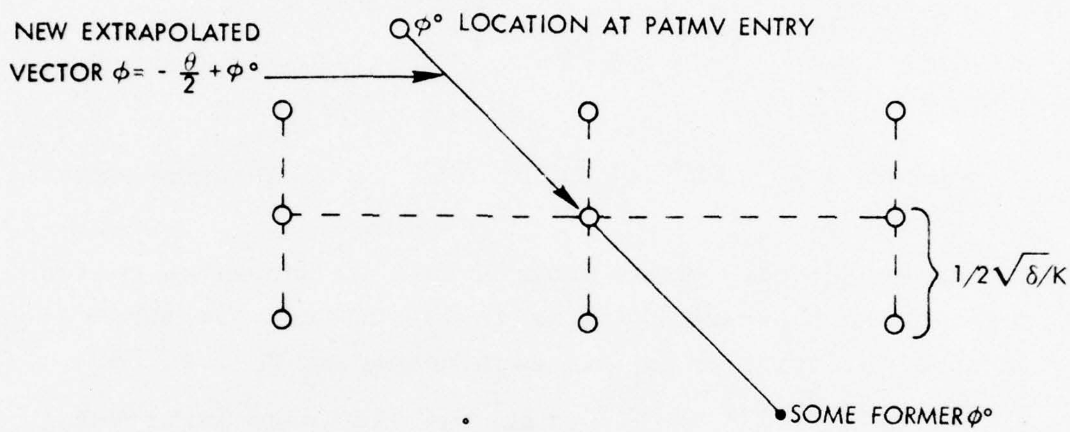

Figure A-3 - Explorations About New Extrapolated Base Point in $-\theta$ Direction

EXPLR $(U\emptyset^O, \emptyset)$

$U\emptyset^O$ and $\emptyset$ are formal parameters. Within EXPLR $U\emptyset$ is a local quantity. EXPLR will change $U\emptyset^O$ and $\emptyset$ to an improved functional value and an improved point, respectively. κ is the dimensionality of the $\emptyset$ vector.

In graphic terms of a two dimensional Ø, EXPLR will return into Ø any of the possible positions indicated, and into $UØ^{O}$ the corresponding functional value.

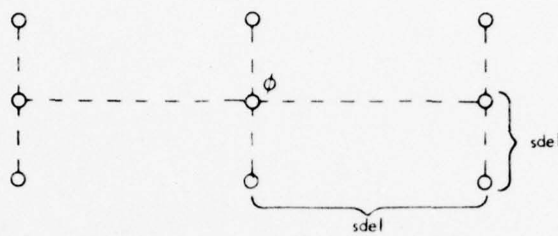

Figure A-4 - Two Dimensional Graphic Representation of EXPLR

The center point is the location of Ø upon entry into EXPLR. In the event that EXPLR is unable to find an improvement in $UØ^{O}$ at any of the locations sdel away from the center point, upon exit from EXPLR, the original functional value $UØ^{O}$ and the original Ø location remain unchanged.

FINISH ($UØ^{O}$) is the logical procedure which furnishes a value of true if the functional value contained in its formal parameter is within the tolerance FEPS initialized by the main calling program.

APPENDIX B

MICROWAVE DIELECTRICS FOR APPLICATION IN STRATIFIED DIELECTRIC SLAB SPATIAL FILTERS

The table given in this appendix summarizes the availability of low loss microwave dielectrics suitable for use in stratified dielectric slab spatial filters. The data presented was obtained over the period of 1 Apr 1976 to 1 Oct 1976, and as such represents an up to date compilation of available data. Where possible, information relative to physical properties is included.

All materials in the table have constant or nearly constant electrical properties from S band to X band. The loss tangent of all materials is less than .002.

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Dielectric	Name	Cost	Available	Density	Bonding	Machinability	Thermal	Volts/Mil Electric Strength	Tensile Strength	Flexibility Strength	Comments
ϵ = 1, 02 → 2, 4 Step. 1	Eccofoam PS		√								Emerson and Cumming
ϵ = 1, 14 → 1, 35	Polyimide Foamable Powder		√	1, 6, 12, 18 lb/in.³			-320°F → +700°F				Skybond Foamable Powders (higher density foams are to exact shape of container without expansion) Monsanto
ϵ = 1, 15	Pittsburgh-Corning Foamed Silica			0, 16							AF Report
ϵ = 1, 23	Corning 1742										
ϵ = 1, 41	Owens-Illinois Integrate Wollastonite			0, 88							AF Report
ϵ = 2, 0	Eccostock R-20 Epoxy Foamed Stock		√	0, 7	OK	OK	-95°F → 350°	350		4, 500	Emerson and Cumming
ϵ = 2, 2	Eccostock MT0003 Thermosat Fluoro-Keterocarbon		√	1, 5	OK	OK	-95°F → 500°	500		12, 000	Emerson and Cumming
ϵ = 2, 0, 2, 2, 2, 4, 2, 55, 2, 7, 2, 8	Stycast Hi Lo K		√	0, 7 → 1, 3	OK	← Assume the Same as Rexolite →				2, 000	Substitute for Rexolite
ϵ = 2, 32	Polyguide 165 High Density Polyolefin Laminate Made without Adhesives		√	0, 93	OK			500	3, 000		Electronized Chemicals Corporation
ϵ = 2, 4	Eccostock CPE Cross-Linked Polyethylene		√	0, 99	OK	OK	-98°F → 350°	500	2, 600	8, 500	Emerson and Cumming
ϵ = 2, 45-2, 55	K-6098 Teflon-Glass [GT, GX, LX]		√	2, 2			-80°F → 500°F		20, 500	13, 500	3M, 55 Fourth Ave., Needham Heights, Mass.
ϵ = 2, 48 Fluorglas 600/2	Impregnated Glass Cloth without Fluroglas, PTFE/Glass		√				-240°C → 260°		20, 000	12, 000	Atlantic Laminates
ϵ = 2, 5	Rulon (Dixon Corp.)		√	2, 2	Good		→ 500°F			7, 500	
ϵ = 2, 52 Fluorglas 600/1	Fluorglas, PTFE/Glass Laminates Made from PTFE		√				-240°C → 260°		19, 000	11, 000	Atlantic Laminates
ϵ = 2, 53 Rexolite 1422	Rexolite, Cross-Linked Styrene Copolymer (1422)		√	1, 05	Use of Rexolite Adhesive	Great to Very Close Tolerance	-60°C → 100°C	500	7, 000	11, 500	Atlantic Laminates, 174 N. Main St., Franklin, N. H.
ϵ = 2, 53	Textolite 11711 (GE) Polyphenylene Oxide (PPO)		√	1, 067		OK	-321°F → 356°F	200	10, 500		Polyphenylene Oxide (PPO) GE

Dielectric	Name	Cost	Available	Density	Bonding	Machinability	Thermal	Volts/Mil Electric Strength	Tensile Strength	Flexibility Strength	Comments
$\epsilon = 2.53$	Stycast 0005 Cross-Linked Polystyrene		√	1.06	OK	OK	-84°F → 275°	500	11,000	17,000	Emerson and Cumming
$\epsilon = 2.54$	Custom Poly C Polystyrene		√	1.05		Easily Machined	-80°F → 230°F	700	8,000	15,000	3M
$\epsilon = 2.55$	Custom Poly TG Teflon/Glass		√				-80°F → 500°F		16,000	13,000	3M
$\epsilon = 2.62$	Custom Poly CR Polystyrene/Glass Reinforced		√			Easily Machined	-80°F → 230°F	700	9,000	12,000	3M
$\epsilon = 2.62$ Rexolite 2200	Rexolite, Cross-Linked Styrene Polymer (2200)		√	1.11	12,517 is recommended		-75°C → 100°C	500	8,700	12,000	Atlantic Laminates
$\epsilon = 3.32$	Corning 7941										
$\epsilon \approx 3.32$	Corning 7942										
$\epsilon = 3.40 \rightarrow 3.52$ (depending on frequency)	Cast Silica 7940 M (Corning)			1.96			100°F → 1800°				Boeing Report
ϵ is approximately 3.5-3.6 (depending on frequency)	Fluorosilit TFE		√	2.2	Good if Etched Properly	Good	3 → 500°F	300	750 → 1200		Polymer Corp., Reading, Pa.
$\epsilon = 3.66$	Corning 7945										
$\epsilon = 3.75$	Corning 7905										
$\epsilon = 3.76$	Corning 7913										
$\epsilon = 3.76$	Corning 7920										
$\epsilon = 3.78$	Corning 7940										
$\epsilon = 3.82$	Corning 7911 96 percent Silica Glass			2.18							AF Report and Von Hippel
$\epsilon = 3.82$	Corning 7900 96 percent Silica Glass			2.18							AF Report and Von Hippel
$\epsilon = 3.84 \rightarrow 3.94$ (depending on frequency)	Fused Silica - 915C (Corning)			2.19			100°F → 1800°				Boeing Report
$\epsilon = 4.0$	Corning 7052 Potash-Lithia-Borosilicate Glass			3.13							AF Report and Von Hippel
$\epsilon = 4.3$	D-4 Cordierite			2.30							Trans-Tech
ϵ varies with frequency 4.40 → 4.54 Boeing Report	Boron Nitride			2.10		OK	50°F → 1800°F	300			Carborundum Co.
$\epsilon = 4.50$	Corning 9409										
$\epsilon = 4.52$	Corning 7740 Borosilicate Glass			2.23							AF Report and Von Hippel

Dielectric	Name	Cost	Available	Density	Bonding	Machinability	Thermal	Volts/Mil Electric Strength	Tensile Strength	Flexibility Strength	Comments
$\epsilon = 5.2 \rightarrow 6.0$ (depending on frequency)	Steatite Alsimag 665 L-533C (BM. American Lava)		√	2.7			25°C → 500°	230	10,000 from Coors Sheet	21,000 from BM Sheet	3M (American Lava) Brush Co. Sheet
$\epsilon = 5.4 \rightarrow 5.8$ (depending on frequency)	Corning 8606 Pyroceram			3.18							AF Report
$\epsilon = 5.55$	Corning 9606 Pyroceram										
$\epsilon = 5.65 \rightarrow 5.85$ (depending on frequency)	Pyroceram 9606 (Corning)			2.59			0°F → 400°				Boeing Report
$\epsilon = 5.68$	Macor, Corning Code 9658 Variable Glass Ceramic		√	2.52		Great					Corning
$\epsilon = 5.8 \rightarrow 6.3$ (depending on frequency)	Forsterite Alsimag 243 L-723C (BM. American Lava)			2.8			25°C → 500°	240	10,000 from Coors Sheet		Brush Co. Sheet
$\epsilon = 6$	Custom LAM 606 Teflon/Glass Ceramic Powder Used		√				-80°F → 500°F		16,000	13,000	3M
$\epsilon = 6.07$	Corning 1723										
$\epsilon = 6.1 \rightarrow 6.3$ (depending on frequency)	99 percent Beryllia (Brush Wellman) (Beryllium Co.)			2.86			25°C → 500°	240 → 760	20,700	34,000	Called Thermalox (995 and 998) Brush Beryllium Sheet
$\epsilon = 6.3$	DS-6 Forsterite			2.89							Trans-Tech
$\epsilon = 6.5$	Supramica 560 Ceramoplastic and Synthetic Mica		√	2.7		Precision Molded	50°F → 250°F	350	4,000	12,000	Mycalex Corp.
$\epsilon = 6.6 \rightarrow 8.2$ (depending on frequency)	Berlox Beryllium Oxide (National Beryllia)			2.76			100°F → 2500°F	300 → 350	22,000	40,000	Berlox K-160, K-150, K-140, K-120 Boeing Report and National Beryllia Sheet
$\epsilon = 6.79$	Corning 9608 Pyroceram										
$\epsilon = 6.8 \rightarrow 8.5$ (depending on frequency)	B-932 Beryllia (Coors Porcelain)			2.87			100°F → 2500°				Coors Porcelain Boeing Report
$\epsilon \approx 6.8$	Corning 9611										
$\epsilon = 6.9$ solid	Supramica 500 Ceramoplastic		√	3.0		Excellent	0°F → 600°F	500	6,000	15,000	Must be Molded No Longer Available as Sheets Mycalex Corp.
$\epsilon = 6.9 \rightarrow 8.4$ (depending on frequency)	BD-98 Beryllia (Coors Porcelain)			2.82			100°F → 2400°				Coors Porcelain Boeing Report

Dielectric	Name	Cost	Available	Density	Bonding	Machinability	Thermal	Volts/Mil Electric Strength	Tensile Strength	Flexibility Strength	Comments
ϵ = 7.12-7.32 (depending on frequency) AF Report and Von Hippel	Mycalex 400 Glass Bonded Mica		√	3.0		OK	-25°F → 600°F	500	6,000	15,000	Mycalex Corp. Figures from Poop Sheet, AF Report, Von Hippel
ϵ = 8.0	S-71 Spinel		√	3.53			25°C → 300°C				Trans-Tech
ϵ = 8.2	S-78 Spinel			3.52			25°C → 300°C				Trans-Tech
ϵ = 8.5	Alsimag Cordierite 576-L5A (3M)			3.4							3M, AF Report
ϵ = 8.79-9.03 (depending on frequency)	Alumina, Coors AI-200 (Coors Porcelain)			3.61							Coors Porcelain, AF Report
ϵ = 8.5	S-98 Spinel			3.51			25°C → 300°C				Trans-Tech
ϵ = 9.0	S-10 Spinel			3.49			25°C → 300°				Trans-Tech
ϵ = 9.32	Supramica 555 Ceramoplastic		√	4.13 AF		Precision Molded					
ϵ = 8.8	Mycalex			3.8 Mycalex			0°F → 600°F	400	4,000	12,000	Mycalex Corp. and AF Report
ϵ = 9.5	DA-9 Alumina		√	3.85							Trans-Tech
ϵ = 9.5 → 11.3 (depending on frequency)	TC-352 Alumina Gladding-McBean			3.78			0°F → 2700°F				Boeing Report
ϵ = 9.6 → 11.3 (depending on frequency)	AD-99.5 Alumina (Coors Porcelain)			3.80	OK (Epoxy Bonding)		0°F → 2700°F	215 → 625	15K → 28K	28K → 45K	Coors Porcelain Boeing Report and Coors Sheet
ϵ = 8.7 → 11.2 (depending on frequency)	AD-99 Alumina (Coors Porcelain)			3.79	OK (Epoxy Bonding)		200°F → 2500°	215 → 600	12K → 48K	25K → 48K	Coors Porcelain Boeing Report and Coors Sheet
ϵ = 9.8	772, 99.5 percent Aluminum Case Alsi Base		√	3.89			→ 1800°F	220		70,000	3M
ϵ = 10.0-11.3 (depending on frequency, See Boeing Report)	GE Lucalox, 99.9 percent, Al_2O_3 Polycrystalline Ceramic		√					1,700			Available as Lucalox, Lucalox-HS, Lucalox-GM GE
ϵ = 10.1	Vistal (98.9 percent Alumina) (Coors Porcelain)			3.98			25°C	230 → 650	15K → 30K	25K → 41K	Coors Porcelain
ϵ = 13	D-13 Magnesium Titanate			3.40							Trans-Tech
ϵ = 16	D-16 Magnesium Titanate			3.60							Trans-Tech
ϵ = 18	MCT-18 Magnesium Calcium Titanate			3.47							Trans-Tech
ϵ = 3 → 15 (Steps of 1)	Stycast, Hi K Loaded Cross-Linked Polystyrene		√	1.4 → 2.6	OK	OK	-95°F → 215°	200		8,000	Substitute for Polytetra Fluoroethylene Thermal Neutron Shield Emerson and Cumming

Dielectric	Name	Cost	Available	Density	Bonding	Machinability	Thermal	Volts/Mil Electric Strength	Tensile Strength	Flexibility Strength	Comments
ϵ = 3 → 25 (Steps of 1)	Stycast Hi K 500-F Loaded Thermoset Hydrocarbon		√	2.2 → 2.9	OK	OK	-95°F → 500°	300		8,000	Emerson and Cumming
ϵ = 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90	Eccoceram Hi K Fired Ceramic		√	3.5	OK	Only with Diamond Tools	-95°F → 1500°F	100-200		8,000	Emerson and Cumming
ϵ = 3-15	Custom Hi K 7071, Cross-Linked Polystyrene Ceramic Powder Filled		√	Varies	Good	Excellent	-80°F → 230°F	225	2,300 → 3,400	6,000	3M
ϵ = 3-20	Custom Hi K 707 Silicone, Ceramic Powder Filled		√	Varies	Good	Excellent	-80°F → 380°F	350	4,000 → 7,000	8,000 → 12,000	Available as Sheet Stock and also as a Castable Compound 3M

APPENDIX C
PROGRAM LISTINGS

In this appendix, program listings are given for all computer programs written in the course of this study. The listings are self-explanatory. Information relative to the optimization programs and subprograms is given in Appendix A.

```
      PROGRAM TEST1(INPUT,TAPE1,OUTPUT,TAPE6=OUTPUT)
C.....THIS IS THE VERY FIRST WORKING OPTIMIZATION PROGRAM
C.....IT IS USED IN CONJUNCTION WITH  RXS  +  RZS3
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *              S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACE,ODD
      REAL LOW
      COMMON /UFCT/ D(13),EPS(14),NS,NSLABS,IP,ODD,FLO,FHI,FINCR,
     *              DB1,SN1,SNINC1,DB2,SN2,SNINC2
      DIMENSION MSG(3),MSG2(2),MSG3(2), PHO(15),DIELCT(10)
      DATA MSG/10HEPSMIN,RHO , 10H,ETA,KAPPA , 7H,DELTA= /
      DATA MSG2/10HFREQ LO,HI , 6H,INCR=/
C.....INPUT NS, THE NUMBER OF NON-AIR DIELECTRICS
C.....NSLABS IS THE TOTAL NUMBER OF AIR % NON-AIR DIELECTRICS
C.....IP IS THE NUMBER OF DIFFERENT NON-AIR DIELECTRICS
C.....K IS THE DIMENSION OF PHO VECTOR =TOTAL NR OF PERTURBATIONS=
1     CALL DISPLA(9HNR SLABS=,1,2)
      READ(1,*) NS
      IF(NS .LE. 0) STOP
      NSLABS=2*NS
      NSLAB1=NSLABS-1
      IP=(NS+1)/2
      K=IP+NSLAB1
C.....INPUT DIELCT(I) I=1 TO IP % INITIALIZE EPS VECTOR
      ENCODE(20,289,MSG3) IP
289   FORMAT(* EPS(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (DIELCT(I),I=1,IP)
      ODD=.TRUE.
      IF(MOD(NS,2) .EQ. 0) ODD=.FALSE.
      DO 78 I=1,IP
      IX=2*I
      EPS(IX-1)=1.0
      EPS(IX)=DIELCT(I)
      IF(ODD .AND. (I.EQ.IP)) GO TO 78
      IX=2*(IP+I)
      EPS(IX-1)=1.0
      IY=NS/2+1-I
      EPS(IX)=DIELCT(IY)
78    CONTINUE
C.....INPUT D(I) I=1 TO NSLAB1
      ENCODE(20,290,MSG3) NSLAB1
290   FORMAT(*   D(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (D(I),I=1,NSLAB1)
C.....INPUT CONSTRAINTS LOW,HIGH,RANGE ON ENTIRE PHO VECTOR
C.....INPUT LOW(I) I=1 TO K
      ENCODE(20,291,MSG3) K
291   FORMAT(* LOW(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (LOW(I),I=1,K)
C.....INPUT HIGH(I) I=1 TO K
      ENCODE(20,292,MSG3) K
292   FORMAT(*HIGH(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (HIGH(I),I=1,K)
      DO 84 I=1,K
84    RANGE(I)=100.0*(HIGH(I)-LOW(I))
C.....INITIALIZE PHO VECTOR TO INPUT DIELECTRICS % THICKNESSES
      DO 79 I=1,IP
```

```
79    PHO(I)=DIELCT(I)
      DO 80 I=1,NSLAB1
      IX=IP+I
80    PHO(IX)=D(I)
C.....INPUT FREQLOW,FREQHI,FREQINCR
      CALL DISPLA(MSG2,2,1)
      READ(1,*) FLO,FHI,FINCR
C.....INPUT DB1...................
      CALL DISPLA(4HDB1=,1,1)
      READ(1,*) DB1
C.....INPUT SIN(THETA1) % SIN(THETA1)INCREMENT
      CALL DISPLA(10HSTH1%INCR=,1,1)
      READ(1,*) SN1,SNINC1
C.....INPUT DB2...................
      CALL DISPLA(4HDB2=,1,1)
      READ(1,*) DB2
C.....INPUT SIN(THETA2) % SIN(THETA2)INCREMENT
      CALL DISPLA(10HSTH2%INCR=,1,1)
      READ(1,*) SN2,SNINC2
C.....INPUT ALPHA % MAX LIMIT OF U FUNCTION EVALUATIONS
      CALL DISPLA(9HALFA,LMT=,1,1)
      READ(1,*) ALPHA,LIMIT
C.....INPUT EPSMIN,RHO,ETA,KAPPA,DELTA
      CALL DISPLA(MSG,3,1)
      READ(1,*) EPSMIN,RHO,ETA,KAPPA,DELTA
C.....DESIRE TRACE OPTION [
81    CALL DISPLA(9HTRACE T/F,1,1)
      READ(1,390) ITRACE
390   FORMAT(A1)
      IF(ITRACE .NE. 1HT) GO TO 82
      TRACE=.TRUE.
      GO TO 83
82    IF(ITRACE .NE. 1HF) GO TO 81
      TRACE=.FALSE.
C.....INPUT FUNCTIONAL EPSILON FEPS
83    CALL DISPLA(8HFCT EPS=,1,1)
      READ(1,*) FEPS
      CALL RAZOR(PHO,EPSMIN,RHO,ETA,KAPPA)
      WRITE(6,391) (PHO(I),I=1,K)
391   FORMAT(5E15.8)
      GO TO 1
      END
      FUNCTION U(NAME,PHO)
      DIMENSION PHO(1)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *               S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACE,ODD,NOT1ST
      REAL LOW
      COMMON /UFCT/ D(13),EPS(14),NS,NSLABS,IP,ODD,FLO,FHI,FINCR,
     *               DB1,SN1,SNINC1,DB2,SN2,SNINC2
      COMPLEX RT
      DATA TWOPI/6.2831853071796/
C.....TRANSFER PERTURBED VALUES *EPS(I) I=1 TO IP* FROM PHO VECTOR
C.....TO APPROPRIATE EPS VECTOR COMPONENTS FOR SUBROUTINE RXTX
      DO 22 I=1,IP
      IX=2*I
      EPS(IX)=PHO(I)
      IF(ODD .AND. (I.EQ.IP)) GO TO 22
      IX=2*(IP+I)
      IY=NS/2+1-I
```

```
      FPS(IX)=PHO(IY)
22    CONTINUE
C.....TRANSFER PERTURBED VALUES *D(I) I=IP+1 TO K* FROM PHO VECTOR
C.....TO D VECTOR *I=1 TO NSLABS-1* FOR SUBROUTINE RXTX
      NN=NSLABS-1
      DO 23 I=1,NN
      IX=I+IP
23    D(I)=PHO(IX)
      NFR=INT( (FHI-FLO)/FINCR+0.5) + 1
      ITHR=INT(SN1/SNINC1+0.5) + 1
      NFCENT=(NFR+1)/2
      OFFSET=10.0**(.05*DB1)
      NOT1ST=.FALSE.
      DO 26 I=1,ITHR
      SKN=(I-1)*SNINC1
      DO 27 J=1,NFR
      TPIL=TWOPI*(FLO+(J-1)*FINCR)
      CALL RXTX(NSLABS,SKN,TPIL,EPS,D,RT)
      UMN=CABS(RT)-OFFSET
      IF(NOT1ST) GO TO 28
      NOT1ST=.TRUE.
      UMIN=UMN
28    IF(UMN .LT. UMIN) UMIN=UMN
27    CONTINUE
26    CONTINUE
      T1=-AMIN1(UMIN,0.0)
C-----------------------------------------------
      UMIN=10000.0
      OFFSET=10.0**(.05*DB2)
      NOT1ST=.FALSE.
      SKN=SN2
100   V=UMIN
      DO 29 J=1,NFR
      TPIL=TWOPI*(FLO+(J-1)*FINCR)
      CALL RXTX(NSLABS,SKN,TPIL,EPS,D,RT)
      IF(J .EQ.NFCENT) UMIN=CABS(RT)
      UMX=CABS(RT)-OFFSET
      IF(NOT1ST) GO TO 30
      NOT1ST=.TRUE.
      UMAX=UMX
30    IF(UMX .GT. UMAX) UMAX=UMX
29    CONTINUE
      SKN=SKN+SNINC2
      IF(UMIN .LT. V) GO TO 100
      T2=AMAX1(UMAX,0.0)
      U=T1+T2
      IF(TRACE) WRITE(6,102) NAME,U,DELTA,EPSLON,(PHO(I),I=1,K)
102   FORMAT(1X,A6,4X,3G20.10/(11X,5G20.10))
      RETURN
      END
      SUBROUTINE DISPLA(MSG,NWDS,LINES)
      DIMENSION MSG(1),M(8)
      DATA NCRLF/ 00010000000000000000B /
      IFLD(I,K,IW)=SHIFT(IW,I+K).AND.SHIFT(MASK(K),K)
      N=MAX0(MIN0(NWDS,6),1)
      DO 100 I=1,N
100   M(I)=MSG(I)
      MSUBN=M(N)
      DO 102 I=1,5
      J=12*(5-I)
```

```
      IF( IFLD(J,12,MSUBN).NE.2R   ) GO TO 104
102   CONTINUE
104   IF(J .LE. 36) GO TO 105
      N=N+1
      M(N)=NCRLF
      GO TO 106
105   J=J+12
      M(N)=OR(AND(MSUBN,MASK(J)),SHIFT(NCRLF,-J))
106   N=N+1
      M(N)=0
      IF(LINES .EQ. 2) WRITE(6,107)
107   FORMAT(1H )
      WRITE(6) (M(I),I=1,N)
      RETURN
      END
••
```

```
      PROGRAM TEST2(INPUT,TAPE1,OUTPUT,TAPE6=OUTPUT,TAPE10)
C.....THIS PROGRAM COMPUTES THE QUARTER WAVE LENGTH DESIGN
C.....IT IS USED IN CONJUNCTION WITH  RXS +  RZ83
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACE,ODD
      REAL LOW
      COMMON /UFCT/ D(13),EPS(14),NS,NSLABS,IP,ODD,FLO,FHI,FINCR,
     *              DB1,SN1,SNINC1,DB2,SN2,SNINC2
      DIMENSION MSG(3),MSG2(2),MSG3(2), PHO(15),DIELCT(10)
      DATA MSG/10HEPSMIN,RHO , 10H,ETA,KAPPA , 7H,DELTA= /
      DATA MSG2/10HFREQ LO,HI , 6H,INCR=/
C.....INPUT NS, THE NUMBER OF NON-AIR DIELECTRICS
C.....NSLABS IS THE TOTAL NUMBER OF AIR % NON-AIR DIELECTRICS
C.....IP IS THE NUMBER OF DIFFERENT NON-AIR DIELECTRICS
C.....K IS THE DIMENSION OF PHO VECTOR =TOTAL NR OF PERTURBATIONS=
1     CALL DISPLA(9HNR SLABS=,1,2)
      READ(1,*) NS
      IF(NS .LE. 0) STOP
      NSLABS=2*NS
      NSLAB1=NSLABS-1
      IP=(NS+1)/2
C.....DETERMINES IF NS IS ODD OR EVEN
C.....SETS K=IP+NSLAB1-2 IF NS IS EVEN
C.....  %  K=IP+NSLAB1-1 IF NS IS ODD
C.....THUS REDUCING THE NUMBER OF PERTURBATION COMPONENTS
C.....ON THE PHO VECTOR AS A RESULT OF THE MIDDLE DIELECTRIC
C.....VARYING AT  LAMBDA/(4*SQRT(EPSILON))
      ODD=.TRUE.
      K=IP+NSLAB1-1
      IF(MOD(NS,2) .EQ. 1) GO TO 42
      ODD=.FALSE.
      K=K-1
C.....INPUT DIELCT(I) I=1 TO IP % INITIALIZE EPS VECTOR
42    ENCODE(20,287,MSG3) IP
289   FORMAT(* EPS(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (DIELCT(I),I=1,IP)
      DO 78 I=1,IP
      IX=2*I
      EPS(IX-1)=1.0
      EPS(IX)=DIELCT(I)
      IF(ODD .AND. (I.EQ.IP)) GO TO 78
      IX=2*(IP+I)
      EPS(IX-1)=1.0
      IY=NS/2+1-I
      EPS(IX)=DIELCT(IY)
78    CONTINUE
C.....INPUT D(I) I=1 TO NSLAB1
      ENCODE(20,290,MSG3) NSLAB1
290   FORMAT(*   D(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (D(I),I=1,NSLAB1)
C.....INPUT CONSTRAINTS LOW,HIGH,RANGE ON ENTIRE PHO VECTOR
C.....INPUT LOW(I) I=1 TO K
      ENCODE(20,291,MSG3) K
291   FORMAT(* LOW(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (LOW(I),I=1,K)
C.....INPUT HIGH(I) I=1 TO K
```

```
      ENCODE(20,292,MSG3) K
292   FORMAT(*HIGH(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (HIGH(I),I=1,K)
      DO 84 I=1,K
84    RANGE(I)=100.0*(HIGH(I)-LOW(I))
C.....INITIALIZE PHO VECTOR TO INPUT DIELECTRICS % THICKNESSES
      DO 79 I=1,IP
79    PHO(I)=DIELCT(I)
      NN1=NSLAB1/2
      NN2=NN1+2
      NN3=NN1+1
      IJ=1
      DO 80 I=1,NSLAB1
      IPIJ=IP+IJ
      IF(ODD) GO TO 801
      IF(I.EQ.NN1 .OR. I.EQ.NN2) GO TO 80
      PHO(IPIJ)=D(I)
      IJ=IJ+1
      GO TO 80
801   IF(I .EQ. NN3) GO TO 80
      PHO(IPIJ)=D(I)
      IJ=IJ+1
80    CONTINUE
C.....INPUT FREQLOW,FREQHI,FREQINCR
      CALL DISPLA(MSG2,2,1)
      READ(1,*) FLO,FHI,FINCR
C.....INPUT DB1....................
      CALL DISPLA(4HDB1=,1,1)
      READ(1,*) DB1
C.....INPUT SIN(THETA1) % SIN(THETA1)INCREMENT
      CALL DISPLA(10HSTH1%INCR=,1,1)
      READ(1,*) SN1,SNINC1
C.....INPUT DB2....................
      CALL DISPLA(4HDB2=,1,1)
      READ(1,*) DB2
C.....INPUT SIN(THETA2) % SIN(THETA2)INCREMENT
      CALL DISPLA(10HSTH2%INCR=,1,1)
      READ(1,*) SN2,SNINC2
C.....INPUT ALPHA % MAX LIMIT OF U FUNCTION EVALUATIONS
      CALL DISPLA(9HALFA,LMT=,1,1)
      READ(1,*) ALPHA,LIMIT
C.....INPUT EPSMIN,RHO,ETA,KAPPA,DELTA
      CALL DISPLA(MSG,3,1)
      READ(1,*) EPSMIN,RHO,ETA,KAPPA,DELTA
C.....DESIRE TRACE OPTION ?
81    CALL DISPLA(9HTRACE T/F,1,1)
      READ(1,390) ITRACE
390   FORMAT(A1)
      IF(ITRACE .NE. 1HT) GO TO 82
      TRACE=.TRUE.
      GO TO 83
82    IF(ITRACE .NE. 1HF) GO TO 81
      TRACE=.FALSE.
C.....INPUT FUNCTIONAL EPSILON FEPS
83    CALL DISPLA(8HFCT EPS=,1,1)
      READ(1,*) FEPS
      CALL RAZOR(PHO,EPSMIN,RHO,ETA,KAPPA)
      WRITE(10,391) (PHO(I),I=1,K)
391   FORMAT(5E15.8)
```

```
      GO TO 1
      END
      FUNCTION U(NAME,PHO)
      DIMENSION PHO(1)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACE,ODD,NOT1ST
      REAL LOW
      COMMON /UFCT/ D(13),EPS(14),NS,NSLABS,IP,ODD,FLO,FHI,FINCR,
     *             DB1,SN1,SNINC1,DB2,SN2,SNINC2
      COMPLEX RT
      DATA TWOPI/6.2831853071796/
C.....TRANSFER PERTURBED VALUES *EPS(I) I=1 TO IP* FROM PHO VECTOR
C.....TO APPROPRIATE EPS VECTOR COMPONENTS FOR SUBROUTINE RXTX
      DO 22 I=1,IP
      IX=2*I
      EPS(IX)=PHO(I)
      IF(ODD .AND. (I.EQ.IP)) GO TO 22
      IX=2*(IP+I)
      IY=NS/2+1-I
      EPS(IX)=PHO(IY)
22    CONTINUE
C.....TRANSFER PERTURBED VALUES *D(I) I=IP+1 TO K* FROM PHO VECTOR
C.....TO D VECTOR *I=1 TO NSLABS-1* FOR SUBROUTINE RXTX
      PHOIP=PHO(IP)
      NN=NSLABS-1
      NN1=NN/2
      NN2=NN1+2
      NN3=NN1+1
      IJ=1
      DO 23 I=1,NN
      IJIP=IJ+IP
      IF(ODD) GO TO 20
      IF(I.EQ.NN1 .OR. I.EQ.NN2) GO TO 19
      D(I)=PHO(IJIP)
      IJ=IJ+1
      GO TO 23
19    D(I)=0.25/SQRT(PHOIP)
      GO TO 23
20    IF(I .EQ. NN3) GO TO 19
      D(I)=PHO(IJIP)
      IJ=IJ+1
23    CONTINUE
      NFR=INT( (FHI-FLO)/FINCR+0.5) + 1
      ITHR=INT(SN1/SNINC1+0.5) + 1
      NFCENT=(NFR+1)/2
      OFFSET=10.0**(.05*DB1)
      NOT1ST=.FALSE.
      DO 26 I=1,ITHR
      SKN=(I-1)*SNINC1
      DO 27 J=1,NFR
      TPIL=TWOPI*(FLO+(J-1)*FINCR)
      CALL RXTX(NSLABS,SKN,TPIL,EPS,D,RT)
      UMN=CABS(RT)-OFFSET
      IF(NOT1ST) GO TO 28
      NOT1ST=.TRUE.
      UMIN=UMN
28    IF(UMN .LT. UMIN) UMIN=UMN
27    CONTINUE
26    CONTINUE
```

```
      T1=-AMIN1(UMIN,0.0)
C-----------------------------------------------------------
      UMIN=10000.0
      OFFSET=10.0**(.05*DB2)
      NOT1ST=.FALSE.
      SKN=SN2
100   V=UMIN
      DO 29 J=1,NFR
      TPIL=TWOPI*(FLO+(J-1)*FINCR)
    . CALL RXTX(NSLABS,SKN,TPIL,EPS,D,RT)
      IF(J .EQ.NFCENT) UMIN=CABS(RT)
      UMX=CABS(RT)-OFFSET
      IF(NOT1ST) GO TO 30
      NOT1ST=.TRUE.
      UMAX=UMX
30    IF(UMX .GT. UMAX) UMAX=UMX
29    CONTINUE
      SKN=SKN+SNINC2
      IF(UMIN .LT. V) GO TO 100
      T2=AMAX1(UMAX,0.0)
      U=T1+T2
      IF(TRACE) WRITE(6,102) NAME,U,DELTA,EPSLON,(PHO(I),I=1,K)
102   FORMAT(1X,A6,4X,3G20.10/(11X,5G20.10))
      RETURN
      END
      SUBROUTINE DISPLA(MSG,NWDS,LINES)
      DIMENSION MSG(1),M(8)
      DATA NCRLF/ 0001000000000000000B /
      IFLD(I,K,IW)=SHIFT(IW,I+K).AND.SHIFT(MASK(K),K)
      N=MAX0(MIN0(NWDS,6),1)
      DO 100 I=1,N
100   M(I)=MSG(I)
      MSUBN=M(N)
      DO 102 I=1,5
      J=12*(5-I)
      IF( IFLD(J,12,MSUBN).NE.2R  ) GO TO 104
102   CONTINUE
104   IF(J .LE. 36) GO TO 105
      N=N+1
      M(N)=NCRLF
      GO TO 106
105   J=J+12
      M(N)=OR(AND(MSUBN,MASK(J)),SHIFT(NCRLF,-J))
106   N=N+1
      M(N)=0
      IF(LINES .EQ. 2) WRITE(6,107)
107   FORMAT(1H )
      WRITE(6) (M(I),I=1,N)
      RETURN
      END

**
```

```
      PROGRAM TEST3(INPUT,TAPE1,OUTPUT,TAPE6=OUTPUT,TAPE10)
C.....THIS PROGRAM IS ESSENTIALLY TEST1 EXCEPT THAT IT
C.....INCORPORATES A TABLE SEARCH FOR PHYSICALLY REALIZABLE
C.....DIELECTRIC MATERIALS.  IT IS USED IN CONJUNCTION WITH
C.....RXS  +  RZS4(WHICH DOES A TABLE SEARCH IN SUBR. EXPLR)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACF,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACF,ODD
      REAL LOW
      COMMON /UFCT/ D(13),EPS(14),NS,NSLABS,IP,ODD,FLO,FHI,FINCR,
     *              DB1,SN1,SNINC1,DB2,SN2,SNINC2
      DIMENSION MSG(3),MSG2(2),MSG3(2), PHO(15),DIELCT(10)
      DATA MSG/10HEPSMIN,RHO , 10H,ETA,KAPPA , 7H,DELTA= /
      DATA MSG2/10HFREQ LO,HI , 6H,INCR=/
C.....INPUT NS, THE NUMBER OF NON-AIR DIELECTRICS
C.....NSLABS IS THE TOTAL NUMBER OF AIR % NON-AIR DIELECTRICS
C.....IP IS THE NUMBER OF DIFFERENT NON-AIR DIELECTRICS
C.....K IS THE DIMENSION OF PHO VECTOR .TOTAL NR OF PERTURBATIONS=
1     CALL DISPLA(9HNR SLABS=,1,2)
      READ(1,*) NS
      IF(NS .LE. 0) STOP
      NSLABS=2*NS
      NSLAB1=NSLABS-1
      IP=(NS+1)/2
      K=IP+NSLAB1
C.....INPUT DIELCT(I) I=1 TO IP % INITIALIZE EPS VECTOR
      ENCODE(20,289,MSG3) IP
289   FORMAT(* EPS(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (DIELCT(I),I=1,IP)
      ODD=.TRUE.
      IF(MOD(NS,2) .EQ. 0) ODD=.FALSE.
      DO 78 I=1,IP
      IX=2*I
      EPS(IX-1)=1.02
      EPS(IX)=DIELCT(I)
      IF(ODD .AND. (I.EQ.IP)) GO TO 78
      IX=2*(IP+I)
      EPS(IX-1)=1.02
      IY=NS/2+1-I
      EPS(IX)=DIELCT(IY)
78    CONTINUE
C.....INPUT D(I) I=1 TO NSLAB1
      ENCODE(20,290,MSG3) NSLAB1
290   FORMAT(*    D(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (D(I),I=1,NSLAB1)
C.....INPUT CONSTRAINTS LOW,HIGH,RANGE ON ENTIRE PHO VECTOR
C.....INPUT LOW(I) I=1 TO K
      ENCODE(20,291,MSG3) K
291   FORMAT(* LOW(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (LOW(I),I=1,K)
C.....INPUT HIGH(I) I=1 TO K
      ENCODE(20,292,MSG3) K
292   FORMAT(*HIGH(1 TO *,I2,*)=*)
      CALL DISPLA(MSG3,2,1)
      READ(1,*) (HIGH(I),I=1,K)
      DO 84 I=1,K
84    RANGE(I)=100.0*(HIGH(I)-LOW(I))
```

```
C.....INITIALIZE PHO VECTOR TO INPUT DIELECTRICS % THICKNESSES
      DO 79 I=1,IP
79    PHO(I)=DIELCT(I)
      DO 80 I=1,NSLAB1
      IX=IP+I
80    PHO(IX)=D(I)
C.....INPUT FREQLOW,FREQHI,FREQINCR
      CALL DISPLA(MSG2,2,1)
      READ(1,*) FLO,FHI,FINCR
C.....INPUT DB1....................
      CALL DISPLA(4HDB1=,1,1)
      READ(1,*) DB1
C.....INPUT SIN(THETA1) % SIN(THETA1)INCREMENT
      CALL DISPLA(10HSTH1%INCR=,1,1)
      READ(1,*) SN1,SNINC1
C.....INPUT DB2....................
      CALL DISPLA(4HDB2=,1,1)
      READ(1,*) DB2
C.....INPUT SIN(THETA2) % SIN(THETA2)INCREMENT
      CALL DISPLA(10HSTH2%INCR=,1,1)
      READ(1,*) SN2,SNINC2
C.....INPUT ALPHA % MAX LIMIT OF U FUNCTION EVALUATIONS
      CALL DISPLA(9HALFA,LMT=,1,1)
      READ(1,*) ALPHA,LIMIT
C.....INPUT EPSMIN,RHO,ETA,KAPPA,DELTA
      CALL DISPLA(MSG,3,1)
      READ(1,*) EPSMIN,RHO,ETA,KAPPA,DELTA
C.....DESIRE TRACE OPTION ?
81    CALL DISPLA(9HTRACE T/F,1,1)
      READ(1,390) ITRACE
390   FORMAT(A1)
      IF(ITRACE .NE. 1HT) GO TO 82
      TRACE=.TRUE.
      GO TO 83
82    IF(ITRACE .NE. 1HF) GO TO 81
      TRACE=.FALSE.
C.....INPUT FUNCTIONAL EPSILON FEPS
83    CALL DISPLA(8HFCT EPS=,1,1)
      READ(1,*) FEPS
      CALL RAZOR(PHO,EPSMIN,RHO,ETA,KAPPA)
      WRITE(10,391) (PHO(I),I=1,K)
391   FORMAT(5E15.8)
      GO TO 1
      END
      FUNCTION U(NAME,PHO)
      DIMENSION PHO(1)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *               S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACE,ODD,NOT1ST
      REAL LOW
      COMMON /UFCT/ D(13),EPS(14),NS,NSLABS,IP,ODD,FLO,FHI,FINCR,
     *               DB1,SN1,SNINC1,DB2,SN2,SNINC2
      COMPLEX RT
      DATA TWOPI/6.2831853071796/
C.....TRANSFER PERTURBED VALUES *EPS(I) I=1 TO IP* FROM PHO VECTOR
C.....TO APPROPRIATE EPS VECTOR COMPONENTS FOR SUBROUTINE RXTX
      DO 22 I=1,IP
      IX=2*I
      EPS(IX)=PHO(I)
      IF(ODD .AND. (I.EQ.IP)) GO TO 22
```

```
      IX=2*(IP+I)
      IY=NS/2+1-I
      EPS(IX)=PHO(IY)
22    CONTINUE
C.....TRANSFER PERTURBED VALUES #D(I) I=IP+1 TO K# FROM PHO VECTOR
C.....TO D VECTOR #I=1 TO NSLABS-1# FOR SUBROUTINE RXTX
      NN=NSLABS-1
      DO 23 I=1,NN
      IX=I+IP
23    D(I)=PHO(IX)
      NFR=INT( (FHI-FLO)/FINCR+0.5) + 1
      ITHR=INT(SN1/SNINC1+0.5) + 1
      NFCENT=(NFR+1)/2
      OFFSET=10.0**(.05*DB1)
      NOT1ST=.FALSE.
      DO 26 I=1,ITHR
      SKN=(I-1)*SNINC1
      DO 27 J=1,NFR
      TPIL=TWOPI*(FLO+(J-1)*FINCR)
      CALL RXTX(NSLABS,SKN,TPIL,EPS,D,RT)
      UMN=CABS(RT)-OFFSET
      IF(NOT1ST) GO TO 28
      NOT1ST=.TRUE.
      UMIN=UMN
28    IF(UMN .LT. UMIN) UMIN=UMN
27    CONTINUE
26    CONTINUE
      T1=-AMIN1(UMIN,0.0)
C-----------------------------------------------
      UMIN=10000.0
      OFFSET=10.0**(.05*DB2)
      NOT1ST=.FALSE.
      SKN=SN2
100   V=UMIN
      DO 29 J=1,NFR
      TPIL=TWOPI*(FLO+(J-1)*FINCR)
      CALL RXTX(NSLABS,SKN,TPIL,EPS,D,RT)
      IF(J .EQ.NFCENT) UMIN=CABS(RT)
      UMX=CABS(RT)-OFFSET
      IF(NOT1ST) GO TO 30
      NOT1ST=.TRUE.
      UMAX=UMX
30    IF(UMX .GT. UMAX) UMAX=UMX
29    CONTINUE
      SKN=SKN+SNINC2
      IF(UMIN .LT. V) GO TO 100
      T2=AMAX1(UMAX,0.0)
      U=T1+T2
      IF(TRACE) WRITE(6,102) NAME,U,DELTA,EPSLON,(PHO(I),I=1,K)
102   FORMAT(1X,A6,4X,3G20.10/(11X,5G20.10))
      RETURN
      END
      SUBROUTINE DISPLA(MSG,NWDS,LINES)
      DIMENSION MSG(1),M(8)
      DATA NCRLF/ 00010000000000000000B /
      IFLD(I,K,IW)=SHIFT(IW,I+K).AND.SHIFT(MASK(K),K)
      N=MAX0(MIN0(NWDS,6),1)
      DO 100 I=1,N
100   M(I)=MSG(I)
      MSUBN=M(N)
```

```
      DO 102 I=1,5
      J=12*(5-I)
      IF( IFLD(J,12,MSUBN).NE.2H  ) GO TO 104
102   CONTINUE
104   IF(J .LE. 36) GO TO 105
      N=N+1
      M(N)=NCRLF
      GO TO 106
105   J=J+12
      M(N)=OR(AND(MSUBN,MASK(J)),SHIFT(NCRLF,-J))
106   N=N+1
      M(N)=0
      IF(LINES .EQ. 2) WRITE(6,107)
107   FORMAT(1H )
      WRITE(6) (M(I),I=1,N)
      RETURN
      END
**
```

```
C.....THIS SUB-PROGRAM IS CALLED RXS
C.....IT IS USED IN CONJUNCTION WITH EITHER  TEST1/TEST2/TEST3/
      SUBROUTINE RXTX(NSLAB,SKN,TPIL,EPS,D,RT)
      COMPLEX RT,U,J,GLRT,TY,S(2,2),A(2,2),AD(14,2,2)
      DIMENSION EPS(1),D(1),Y0(14),AJ(14,2,2)
      REAL KAPPA(14)
      EQUIVALENCE (S11,S(1,1)) , (S21,S(2,1)) , (RLTY,TY)
      DATA J/(0.,1.)/
C
C.....COMPUTE KAPPA\S AND Y0\S *REAL*
C
      SKN2=SKN*SKN
      DO 100 ND=1,NSLAB
      KAPPA(ND)=SQRT(EPS(ND)-SKN2)
100   Y0(ND)=EPS(ND)/KAPPA(ND)
C
C.....CONSTRUCT JUNCTION WAVE TRANSMISSION MATRICES, AJ, *REAL*
C
      NSLAB1=NSLAB-1
      DO 110 ND=1,NSLAB1
      RLTY=1.0/(Y0(ND)+Y0(ND+1))
      S11=(Y0(ND)-Y0(ND+1))*RLTY
      S21=2.0*Y0(ND)*RLTY
      RLTY=Y0(ND+1)/Y0(ND)
      AJ(ND,1,1)=1.0/S21
      AJ(ND,1,2)=S11/S21
      AJ(ND,2,1)=AJ(ND,1,2)
      AJ(ND,2,2)=(RLTY*S21*S21+S11*S11)/S21
C
C.....CONSTRUCT LINE LENGTH WAVE TRANSMISSION MATRICES, AD, *COMPLEX*
C
      AD(ND,1,1)=CEXP(J*KAPPA(ND+1)*TPIL*D(ND))
      AD(ND,2,2)=1./AD(ND,1,1)
      AD(ND,1,2)=(0.,0.)
110   AD(ND,2,1)=(0.,0.)
C
C.....FORM TOTAL WAVE TRANSMISSION MATRIX, A, *COMPLEX*
C
      DO 130 ND=1,2
      DO 130 MD=1,2
      A(ND,MD)=(0.,0.)
      IF (ND.EQ.MD) A(ND,MD)=(1.,0.)
130   CONTINUE
C
      DO 180 ND=1,NSLAB1
      ND1=NSLAB-ND
      DO 160 ID=1,2
      DO 160 KD=1,2
      TY=(0.,0.)
      DO 150 LD=1,2
      U=(0.,0.)
      DO 140 MD=1,2
140   U=U+AD(ND1,LD,MD)*A(MD,KD)
150   TY=TY+U*AJ(ND1,ID,LD)
160   S(ID,KD)=TY
      DO 170 ID=1,2
      DO 170 KD=1,2
170   A(ID,KD)=S(ID,KD)
180   CONTINUE
      GLRT=(Y0(NSLAB)-Y0(1))/(Y0(NSLAB)+Y0(1))
```

```
      TY=A(1,1)+GLRT*A(1,2)
C.....RETURNS TRANSMISSION COEFFICIENT *COMPLEX*
      RT=(1.+GLRT)/TY
      RETURN
      END
**
```

```
C.....THIS SUB-PROGRAM IS CALLED  RZ83
C.....IT IS USED IN CONJUNCTION WITH EITHER  TEST1/TEST2/
      SUBROUTINE RAZOR(PHO,EPSMIN,RHO,ETA,KAPPA)
      DIMENSION PHI(15),PHO(15)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL FINISH,TRACE
      REAL LOW
      CALL SECOND(TIME)
      N=1
      N1=1
      N2=0
      N3=0
      N4=0
      IC=0
C.....EVALUATE FUNCTION AT STARTING POINT
      UPHO=U(6HRAZOR1,PHO)
      IF(TRACE)  WRITE(6,1) UPHO,(PHO(I),I=1,K)
1     FORMAT(1H0,4X,6HUPHO =,G20.10,15X,5HPHO =,3G20.10/(11X,5G20.10))
C.....FINISH CRITERIA SATISFIED ?
      IF(FINISH(UPHO)) GO TO 14
      DO 2 I = 1,K
2     S(I)=1.0
      EPSLON=EPSMIN*(ETA**KAPPA)
C.....CONDUCT PATTERN SEARCH
      IF(TRACE) WRITE(6,100)
100   FORMAT(7H PATSR1)
      CALL PATSER(PHO,UPHO)
C.....FINISH CRITERIA SATISFIED ?
      IF(FINISH(UPHO)) GO TO 14
      DO 10 J=1,KAPPA
      N4=N-N4
      UPHO=U(6HRAZOR2,PHO)
      IF(TRACE)  WRITE(6,3) N4,UPHO,(PHO(I),I=1,K)
3     FORMAT(4H N =,I5,16X,6HUPHO =,G20.10/6X,5HPHO =,3G20.10/
     *        (11X,5G20.10))
      N4=N
      IF(N.GT.LIMIT) GO TO 12
C.....OBTAIN NEW STARTING POINT AND EXPLORATORY PARAMETERS
      DELTA=0.0
      DO 4 I=1,K
      RANDOM=-1.0+2.0*RANF(0.0)
      PHI(I)=BOUND(I,PHO(I)+RHO*RANDOM*EPSLON/100.0)
      T=(PHI(I)-PHO(I))/RANGE(I)*100.0
4     DELTA=DELTA+T*T
      DELTA=SQRT(DELTA/K)
C.....EVALUATE FUNCTION AND CONDUCT PATTERN SEARCH
      UPHI=U(6HRAZOR3,PHI)
      N=N+1
      N1=N1+1
      IF(TRACE)  WRITE(6,5) UPHI,(PHI(I),I=1,K)
5     FORMAT(1H0,4X,6HUPHI =,G20.10,15X,5HPHI =,3G20.10/
     *        (11X,5G20.10))
      EPSLON=EPSLON/ETA
      IF(TRACE) WRITE(6,101)
101   FORMAT(7H PATSR2)
      CALL PATSER(PHI,UPHI)
C.....OUTCOME AN IMPROVEMENT ?
      IF(UPHI.LT.UPHO) GO TO 7
      IF(N.GT.LIMIT) GO TO 12
```

```
C.....PROJECT NEW POINT
      DELTA=0.0
      DO 6 I=1,K
      T=PHO(I)-PHI(I)
      T1=T/RANGE(I)*100.0
      THETA(I)=T
      PHI(I)=BOUND(I,PHO(I)+T)
6     DELTA=DELTA+T1*T1
      UPHI=UPHO
C.....CONDUCT PATTERN MOVE
      IF(TRACE) WRITE(6,102)
102   FORMAT(7H PATMV1)
      CALL PATMV(UPHI,PHI,PHO)
C.....OUTCOME AN IMPROVEMENT (
      IF(UPHI.GE.UPHO) GO TO 9
C.....RETAIN BEST POINT AND FUNCTION VALUE
7     UPHO=UPHI
C.....PROJECT NEW POINT
      DELTA=0.
      DO 8 I=1,K
      T=PHI(I)-PHO(I)
      T1=T/RANGE(I)*100.0
      THETA(I)=T
      PHO(I)=PHI(I)
      PHI(I)=BOUND(I,PHO(I)+T)
8     DELTA=DELTA+T1*T1
      IF(N.GT.LIMIT) GO TO 12
C.....CONDUCT PATTERN MOVE
      IF(TRACE) WRITE(6,103)
103   FORMAT(7H PATMV2)
      CALL PATMV(UPHI,PHI,PHO)
C.....OUTCOME AN IMPROVEMENT (
      IF(UPHI.LT.UPHO) GO TO 7
C.....FINISH CRITERIA SATISFIED (
9     IF(FINISH(UPHO)) GO TO 14
10    CONTINUE
      CALL SECOND(TIME1)
      TIME=TIME1-TIME
      WRITE(6,11) N,TIME
11    FORMAT(*0NO CONCLUSION BY RAZOR AFTER*,I4,* FUNCTION EVALUATIONS*,
     *       *  AND*,F7.2,*SECONDS*)
      GO TO 16
12    CALL SECOND(TIME1)
      TIME=TIME1-TIME
      WRITE(6,13) TIME
13    FORMAT(54H0LIMIT ON FUNCTION EVALUATIONS EXCEEDED BY RAZOR AFTER,
     *       F7.2,8H SECONDS)
      GO TO 16
14    CALL SECOND(TIME1)
      TIME=TIME1-TIME
      WRITE(6,15) TIME,N
15    FORMAT(33H0CONVERGENCE OBTAINED BY RAZOR IN,F7.2,
     *       14H SECONDS AFTER,I5,21 H FUNCTION EVALUATIONS)
16    N4=N-N4
      WRITE(6,17) N1,N2,N3,N4,UPHO,(PHO(I),I=1,K)
17    FORMAT(37H THE FUNCTION EVALUATION BREAKDOWN IS/I10,
     *       9H BY RAZOR/I10,14H BY PATMV, AND/I10,9H BY EXPLR/
     *       24H0FINAL PARAMETER VALUES,4H N =,I5,3X,
     *       6HUPHO =,G15.7,5X,5HPHO =,G15.7/(13X,6G15.7))
      RETURN
```

```
      END
      LOGICAL FUNCTION FINISH(UPHO)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACE
      REAL LOW
      FINISH=.FALSE.
      IF(UPHO.LT.FEPS) FINISH=.TRUE.
      IF(TRACE) WRITE(6,100)
100   FORMAT(7H FINISH)
      RETURN
      END
      SUBROUTINE PATSER(PHO,UPHO)
      DIMENSION  PHI(15),PHO(1)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL FINISH,TRACE
      REAL LOW
1     IF(N .GT. LIMIT) RETURN
C.....EXPLORATORY INCREMENT TOO SMALL ?
      IF(DELTA.LT.EPSLON) RETURN
      IF(FINISH(UPHO)) RETURN
      UPHI=UPHO
      DO 2 I=1,K
2     PHI(I)=PHO(I)
C.....CONDUCT EXPLORATION AROUND BASE POINT
      CALL EXPLR(UPHI,PHI)
      IF(TRACE) WRITE(6,100)
100   FORMAT(7H PATSER)
C.....OUTCOME AN IMPROVEMENT ?
      IF(UPHI.LT.UPHO) GO TO 3
C.....REDUCE EXPLORATORY INCREMENT
7     DELTA=ALPHA*DELTA
      GO TO 1
C.....RETAIN BEST POINT AND FUNCTION VALUE
C.....PROJECT NEW POINT
3     DELTA=0.0
      UPHO=UPHI
      DO 4 I=1,K
      T1=PHI(I)-PHO(I)
      T=T1/RANGE(I)*100.0
      THETA(I)=T1
      PHO(I)=PHI(I)
      PHI(I)=BOUND(I,PHO(I)+T1)
4     DELTA=DELTA+T*T
      IF(FINISH(UPHO)) RETURN
      IF(N.GT.LIMIT) RETURN
C.....CONDUCT PATTERN MOVE
      CALL PATMV(UPHI,PHI,PHO)
      IF(TRACE) WRITE(6,100)
C.....OUTCOME AN IMPROVEMENT ?
      IF(UPHI-UPHO)3,7,7
      END
      FUNCTION BOUND(I,EXPR)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      REAL LOW
      BOUND=AMAX1(AMIN1(HIGH(I),EXPR),LOW(I))
      RETURN
      END
```

```
      SUBROUTINE EXPLR(UPHO,PHI)
      DIMENSION  PHI(1)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *              S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACE
      REAL LOW
      DO 4 I=1,K
      SDEL=DELTA/100.0*S(I)*RANGE(I)
C.....INCREMENT PARAMETER
      PHISAV=PHI(I)
      PHI(I)=AMAX1(AMIN1(HIGH(I),PHISAV+SDEL),LOW(I))
C.....EVALUATE FUNCTION
      UPHI=U(6HEXPLR1,PHI)
      N=N+1
      N3=N3+1
C.....OUTCOME AN IMPROVEMENT (
      IF(UPHI.LT.UPHO) GO TO 2
      IF(N.GT.LIMIT) GO TO 1
C.....INCREMENT PARAMETER IN OPPOSITE DIRECTION
      S(I)=-S(I)
      PHI(I)=AMAX1(AMIN1(HIGH(I),PHISAV-SDEL),LOW(I))
C.....EVALUATE FUNCTION
      UPHI=U(6HEXPLR2,PHI)
      N=N+1
      N3=N3+1
C.....OUTCOME AN IMPROVEMENT (
      IF(UPHI.LT.UPHO) GO TO 2
C.....RESET PARAMETER
1     PHI(I)=PHISAV
      GO TO 3
C.....RETAIN BEST FUNCTION VALUE
2     UPHO=UPHI
3     IF(N.GT.LIMIT) RETURN
4     CONTINUE
      RETURN
      END
      SUBROUTINE PATMV(UPHO,PHI,PHO)
      DIMENSION PHI(1),PHO(1)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *              S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACE
      REAL LOW
      M=1
C.....OBTAIN EXPLORATORY INCREMENT
      DELTA=SQRT(DELTA/K)
C.....EXPLORATORY INCREMENT TOO SMALL (
1     IF(DELTA.LT.EPSLON) RETURN
C.....EVALUATE FUNCTION
2     UPHI=U(5HPATMV,PHI)
      N=N+1
      N2=N2+1
      IF(N.GT.LIMIT) RETURN
C.....CONDUCT EXPLORATION
      CALL EXPLR(UPHI,PHI)
C.....OUTCOME AN IMPROVEMENT (
      IF(UPHI.GE.UPHO) GO TO 4
C.....PARAMETER CHANGE SIGNIFICANT (
      DO 3 I=1,K
      IF(ABS(PHI(I)-PHO(I)).GT.1.E-6*ABS(PHO(I))) GO TO 10
3     CONTINUE
```

```
4     IF(N.GT.LIMIT) RETURN
      GO TO (5,7,9),M
C.....REDUCE EXPLORATORY INCREMENT
5     DELTA=0.5*DELTA
      M=2
C.....DEFINE PROJECTED POINT NEARER BASE POINT
      DO 6 I=1,K
6     PHI(I)=BOUND(I,PHO(I)+.5*THETA(I))
      GO TO 1
7     M=3
C.....DEFINE PROJECTED POINT IN OPPOSITE DIRECTION
      DO 8 I=1,K
      S(I)=-S(I)
8     PHI(I)=BOUND(I,PHO(I)-.5*THETA(I))
      GO TO 2
9     RETURN
C.....RETAIN BEST FUNCTION VALUE
10    UPHO=UPHI
      RETURN
      END
••
```

```
C.....THIS SUB-PROGRAM IS CALLED RZS4
C.....IT IS USED WITH TESTS TO OPTIMIZE WITH
C.....PHYSICALLY REALIZABLE DIELECTRIC MATERIALS.
C.....REFER TO SUBROUTINE EXPLR FOR THE TABLE SEARCH.
      SUBROUTINE RAZOR(PHO,EPSMIN,RHO,ETA,KAPPA)
      DIMENSION PHI(15),PHO(15)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL FINISH,TRACE
      REAL LOW
      CALL SECOND(TIME)
      N=1
      N1=1
      N2=0
      N3=0
      N4=0
      IC=0
C.....EVALUATE FUNCTION AT STARTING POINT
      UPHO=U(6HRAZOR1,PHO)
      IF(TRACE)  WRITE(6,1) UPHO,(PHO(I),I=1,K)
1     FORMAT(1H0,4X,6HUPHO =,G20.10,15X,5HPHO =,3G20.10/(11X,5G20.10))
C.....FINISH CRITERIA SATISFIED ?
      IF(FINISH(UPHO)) GO TO 14
      DO 2 I = 1,K
2     S(I)=1.0
      EPSLON=EPSMIN*(ETA**KAPPA)
C.....CONDUCT PATTERN SEARCH
      IF(TRACE) WRITE(6,100)
100   FORMAT(7H PATSR1)
      CALL PATSER(PHO,UPHO)
C.....FINISH CRITERIA SATISFIED ?
      IF(FINISH(UPHO)) GO TO 14
      DO 10 J=1,KAPPA
      N4=N-N4
      UPHO=U(6HRAZOR2,PHO)
      IF(TRACE)  WRITE(6,3) N4,UPHO,(PHO(I),I=1,K)
3     FORMAT(4H N =,I5,16X,6HUPHO =,G20.10/6X,5HPHO =,3G20.10/
     *       (11X,5G20.10))
      N4=N
      IF(N.GT.LIMIT) GO TO 12
C.....OBTAIN NEW STARTING POINT AND EXPLORATORY PARAMETERS
      DELTA=0.0
      DO 4 I=1,K
      RANDOM=-1.0+2.0*RANF(0.0)
      PHI(I)=BOUND(I,PHO(I)+RHO*RANDOM*EPSLON/100.0)
      T=(PHI(I)-PHO(I))/RANGE(I)*100.0
4     DELTA=DELTA+T*T
      DELTA=SQRT(DELTA/K)
C.....EVALUATE FUNCTION AND CONDUCT PATTERN SEARCH
      UPHI=U(6HRAZOR3,PHI)
      N=N+1
      N1=N1+1
      IF(TRACE)  WRITE(6,5) UPHI,(PHI(I),I=1,K)
5     FORMAT(1H0,4X,6HUPHI =,G20.10,15X,5HPHI =,3G20.10/
     *       (11X,5G20.10))
      EPSLON=EPSLON/ETA
      IF(TRACE) WRITE(6,101)
101   FORMAT(7H PATSR2)
      CALL PATSER(PHI,UPHI)
C.....OUTCOME AN IMPROVEMENT ?
```

```
      IF(UPHI.LT.UPHO) GO TO 7
      IF(N.GT.LIMIT) GO TO 12
C.....PROJECT NEW POINT
      DELTA=0.0
      DO 6 I=1,K
      T=PHO(I)-PHI(I)
      T1=T/RANGE(I)*100.0
      THETA(I)=T
      PHI(I)=BOUND(I,PHO(I)+T)
6     DELTA=DELTA+T1*T1
      UPHI=UPHO
C.....CONDUCT PATTERN MOVE
      IF(TRACE) WRITE(6,102)
102   FORMAT(7H PATMV1)
      CALL PATMV(UPHI,PHI,PHO)
C.....OUTCOME AN IMPROVEMENT ?
      IF(UPHI.GE.UPHO) GO TO 9
C.....RETAIN BEST POINT AND FUNCTION VALUE
7     UPHO=UPHI
C.....PROJECT NEW POINT
      DELTA=0.
      DO 8 I=1,K
      T=PHI(I)-PHO(I)
      T1=T/RANGE(I)*100.0
      THETA(I)=T
      PHO(I)=PHI(I)
      PHI(I)=BOUND(I,PHO(I)+T)
8     DELTA=DELTA+T1*T1
      IF(N.GT.LIMIT) GO TO 12
C.....CONDUCT PATTERN MOVE
      IF(TRACE) WRITE(6,103)
103   FORMAT(7H PATMV2)
      CALL PATMV(UPHI,PHI,PHO)
C.....OUTCOME AN IMPROVEMENT ?
      IF(UPHI.LT.UPHO) GO TO 7
C.....FINISH CRITERIA SATISFIED ?
9     IF(FINISH(UPHO)) GO TO 14
10    CONTINUE
      CALL SECOND(TIME1)
      TIME=TIME1-TIME
      WRITE(6,11) N,TIME
11    FORMAT(*0NO CONCLUSION BY RAZOR AFTER*,I4,* FUNCTION EVALUATIONS*,
     *       *  AND*,F7.2,*SECONDS*)
      GO TO 16
12    CALL SECOND(TIME1)
      TIME=TIME1-TIME
      WRITE(6,13) TIME
13    FORMAT(54H0LIMIT ON FUNCTION EVALUATIONS EXCEEDED BY RAZOR AFTER,
     *       F7.2,8H SECONDS)
      GO TO 16
14    CALL SECOND(TIME1)
      TIME=TIME1-TIME
      WRITE(6,15) TIME,N
15    FORMAT(33H0CONVERGENCE OBTAINED BY RAZOR IN,F7.2,
     *       14H SECONDS AFTER,I5,21 H FUNCTION EVALUATIONS)
16    N4=N-N4
      WRITE(6,17) N1,N2,N3,N4,UPHO,(PHO(I),I=1,K)
17    FORMAT(37H THE FUNCTION EVALUATION BREAKDOWN IS/I10,
     *       9H BY RAZOR/I10,14H BY PATMV, AND/I10,9H BY EXPLR/
     *       24H0FINAL PARAMETER VALUES,4H N =,I5,3X,
```

```
      *        6HUPHO =,G15.7,5X,5HPHO =,G15.7/(13X,6G15.7))
      RETURN
      END
      LOGICAL FUNCTION FINISH(UPHO)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACE
      REAL LOW
      FINISH=.FALSE.
      IF(UPHO.LT.FEPS) FINISH=.TRUE.
      IF(TRACE) WRITE(6,100)
100   FORMAT(7H FINISH)
      RETURN
      END
      SUBROUTINE PATSER(PHO,UPHO)
      DIMENSION  PHI(15),PHO(1)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL FINISH,TRACE
      REAL LOW
1     IF(N .GT. LIMIT) RETURN
C.....EXPLORATORY INCREMENT TOO SMALL (
      IF(DELTA.LT.EPSLON) RETURN
      IF(FINISH(UPHO)) RETURN
      UPHI=UPHO
      DO 2 I=1,K
2     PHI(I)=PHO(I)
C.....CONDUCT EXPLORATION AROUND BASE POINT
      CALL EXPLR(UPHI,PHI)
      IF(TRACE) WRITE(6,100)
100   FORMAT(7H PATSER)
C.....OUTCOME AN IMPROVEMENT (
      IF(UPHI.LT.UPHO) GO TO 3
C.....REDUCE EXPLORATORY INCREMENT
7     DELTA=ALPHA*DELTA
      GO TO 1
C.....RETAIN BEST POINT AND FUNCTION VALUE
C.....PROJECT NEW POINT
3     DELTA=0.0
      UPHO=UPHI
      DO 4 I=1,K
      T1=PHI(I)-PHO(I)
      T=T1/RANGE(I)*100.0
      THETA(I)=T1
      PHO(I)=PHI(I)
      PHI(I)=BOUND(I,PHO(I)+T1)
4     DELTA=DELTA+T*T
      IF(FINISH(UPHO)) RETURN
      IF(N.GT.LIMIT) RETURN
C.....CONDUCT PATTERN MOVE
      CALL PATMV(UPHI,PHI,PHO)
      IF(TRACE) WRITE(6,100)
C.....OUTCOME AN IMPROVEMENT (
      IF(UPHI-UPHO)3,7,7
      END
      FUNCTION BOUND(I,EXPR)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      REAL LOW
      BOUND=AMAX1(AMIN1(HIGH(I),EXPR),LOW(I))
```

```
      RETURN
      END
      SUBROUTINE EXPLR(UPHO,PHI)
      DIMENSION  PHI(1)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACE
      REAL LOW
      COMMON /UFCT/ D(13),EPS(14),NS,NSLABS,IP
      DIMENSION TABL(92)
      DATA TABL /1.02,1.03,1.05,1.1,1.14,1.15,1.2,1.23,
     *           1.3,1.4,1.41,1.5,1.6,1.7,1.8,1.9,
     *    2.0,2.1,2.2,2.3,2.32,2.4,2.45,2.48,2.5,2.52,
     *    2.53,2.54,2.55,2.62,2.7,2.8,
     *    3.0,3.32,3.4,3.5,3.66,3.75,3.76,3.78,3.82,3.84,
     *    4.0,4.3,4.4,4.5,4.52,   5.0,5.2,5.4,5.55,5.65,5.68,
     *    5.8,6.0,6.07,6.1,6.3,6.5,6.6,6.79,6.8,6.9,
     *    7.0,7.12,  8.0,8.2,8.5,8.79,8.8,  9.0,9.5,9.6,
     *    9.7,9.8,  10.0,10.1,  11.0,  12.0,  13.0,  14.0,
     *    15.0,  16.0,  17.0,  18.0,  19.0,  20.0,  21.0,
     *    22.0,  23.0,  24.0,  25.0    /
      DATA NR/92/
      DO 4 I=1,K
      SDEL=DELTA/100.0*S(I)*RANGE(I)
C.....INCREMENT PARAMETER
      PHISAV=PHI(I)
      PHI(I)=AMAX1(AMIN1(HIGH(I),PHISAV+SDEL),LOW(I))
C.....FOR I .LE. IP *PHI COMPONENTS ARE DIELECTRICS*
C.....SEARCH TABL FOR THE CLOSEST DIELECTRIC CONSTANT
C.....AND REASSIGN THAT VALUE INSTEAD OF THE COMPUTED VALUE
      IF(I .GT. IP) GO TO 90
      PHII=0.01*AINT(100.0*PHI(I)+0.5)
      DSTMIN=999.0
      DO 88 L=1,NR
      TABLL=TABL(L)
      IF(PHII .EQ. TABLL) GO TO 90
      DIST=ABS(PHII-TABLL)
      IF(DIST .GE. DSTMIN) GO TO 88
      DSTMIN=DIST
      LOC=L
88    CONTINUE
      PHI(I)=TABL(LOC)
C.....EVALUATE FUNCTION
90    UPHI=U(6HEXPLR1,PHI)
      N=N+1
      N3=N3+1
C.....OUTCOME AN IMPROVEMENT (
      IF(UPHI.LT.UPHO) GO TO 2
      IF(N.GT.LIMIT) GO TO 1
C.....INCREMENT PARAMETER IN OPPOSITE DIRECTION
      S(I)=-S(I)
      PHI(I)=AMAX1(AMIN1(HIGH(I),PHISAV-SDEL),LOW(I))
C.....FOR I .LE. IP *PHI COMPONENTS ARE DIELECTRICS*
C.....SEARCH TABL FOR THE CLOSEST DIELECTRIC CONSTANT
C.....AND REASSIGN THAT VALUE INSTEAD OF THE COMPUTED VALUE
      IF(I .GT. IP) GO TO 100
      PHII=0.01*AINT(100.0*PHI(I)+0.5)
      DSTMIN=999.0
      DO 99 L=1,NR
      TABLL=TABL(L)
```

```
      IF(PHII .EQ. TABLL) GO TO 100
      DIST=ABS(PHII-TABLL)
      IF(DIST .GE. DSTMIN) GO TO 99
      DSTMIN=DIST
      LOC=L
99    CONTINUE
      PHI(I)=TABL(LOC)
C.....EVALUATE FUNCTION
100   UPHI=U(6HEXPLR2,PHI)
      N=N+1
      N3=N3+1
C.....OUTCOME AN IMPROVEMENT (
      IF(UPHI.LT.UPHO) GO TO 2
C.....RESET PARAMETER
1     PHI(I)=PHISAV
      GO TO 3
C.....RETAIN BEST FUNCTION VALUE
2     UPHO=UPHI
3     IF(N.GT.LIMIT) RETURN
4     CONTINUE
      RETURN
      END
      SUBROUTINE PATMV(UPHO,PHI,PHO)
      DIMENSION PHI(1),PHO(1)
      COMMON /RZR/ K,DELTA,ALPHA,LIMIT,N,N2,N3,EPSLON,THETA(15),
     *             S(15),FEPS,TRACE,LOW(15),HIGH(15),RANGE(15)
      LOGICAL TRACE
      REAL LOW
      M=1
C.....OBTAIN EXPLORATORY INCREMENT
      DELTA=SQRT(DELTA/K)
C.....EXPLORATORY INCREMENT TOO SMALL (
1     IF(DELTA.LT.EPSLON) RETURN
C.....EVALUATE FUNCTION
2     UPHI=U(5HPATMV,PHI)
      N=N+1
      N2=N2+1
      IF(N.GT.LIMIT) RETURN
C.....CONDUCT EXPLORATION
      CALL EXPLR(UPHI,PHI)
C.....OUTCOME AN IMPROVEMENT (
      IF(UPHI.GE.UPHO) GO TO 4
C.....PARAMETER CHANGE SIGNIFICANT (
      DO 3 I=1,K
      IF(ABS(PHI(I)-PHO(I)).GT.1.E-6*ABS(PHO(I))) GO TO 10
3     CONTINUE
4     IF(N.GT.LIMIT) RETURN
      GO TO (5,7,9),M
C.....REDUCE EXPLORATORY INCREMENT
5     DELTA=0.5*DELTA
      M=2
C.....DEFINE PROJECTED POINT NEARER BASE POINT
      DO 6 I=1,K
6     PHI(I)=BOUND(I,PHO(I)+.5*THETA(I))
      GO TO 1
7     M=3
C.....DEFINE PROJECTED POINT IN OPPOSITE DIRECTION
      DO 8 I=1,K
      S(I)=-S(I)
8     PHI(I)=BOUND(I,PHO(I)-.5*THETA(I))
```

```
      GO TO 2
9     RETURN
C.....RETAIN BEST FUNCTION VALUE
10    UPHO=UPHI
      RETURN
      END
**
```

```
      PROGRAM FILTER3(INPUT,OUTPUT,TAPE1=INPUT,TAPE6=OUTPUT,TAPE4)
C.....THIS IS THE ORIGINAL WORKING PLOTTING PROGRAM
      DIMENSION T(103),ST(103),D(21),EPS(22),DIELCT(6),FREQ(6),
     *          SAVE(6,101)
      COMPLEX Z
      LOGICAL ODD,SKIPIT
      DATA ST /100*0.0 , .999 , 0.0 , .20 /
      DATA  T /101*0.0 , -50.0 , 10.0 /
      DATA TWOPI /6.2831853071796/
      CALL PLOTF(30,4)
      DO 100 I=1,100
100   ST(I)=0.01*(I-1)
C.....INPUT NS, THE NUMBER OF NON-AIR DIELECTRICS
C.....NSLABS IS THE TOTAL NUMBER OF AIR % NON-AIR DIELECTRICS
C.....IP IS THE NUMBER OF DIFFERENT NON-AIR DIELECTRICS
110   PRINT *,'  '
      PRINT *,'NR SLABS=',
      READ(1,*) NS
      IF(NS .LE. 0) GO TO 140
      NSLABS=2*NS
      NSLAB1=NSLABS-1
      IP=(NS+1)/2
C.....INPUT DIELCT(I) I=1 TO IP % INITIALIZE EPS VECTOR
      PRINT *,'EPS(1 TO ',IP,')=',
      READ(1,*) (DIELCT(I),I=1,IP)
      ODD=.TRUE.
      IF(MOD(NS,2) .EQ. 0) ODD=.FALSE.
      DO 78 I=1,IP
      IX=2*I
      EPS(IX-1)=1.0
      EPS(IX)=DIELCT(I)
      IF(ODD .AND. (I.EQ.IP)) GO TO 78
      IX=2*(IP+I)
      EPS(IX-1)=1.0
      IY=NS/2+1-I
      EPS(IX)=DIELCT(IY)
78    CONTINUE
C.....INPUT D(I) I=1 TO NSLAB1
      PRINT *,'D(1 TO ',NSLAB1,')=',
      READ(1,*) (D(I),I=1,NSLAB1)
C.....INPUT  TE OR TM MODE..................
112   PRINT *,'MODE=TE/TM%=',
      READ(1,390) INMODE
390   FORMAT(A2)
      MODE=2HTM
      IF(INMODE .EQ. MODE) GO TO 113
      MODE=2HTE
      IF(INMODE .EQ. MODE) GO TO 113
      GO TO 112
C.....INPUT SIN(THETA1) SIN(THETA2) DB1 DB2
113   PRINT *,'STH1,STH2,DB1,DB2=',
      READ(1,*) STH1,STH2,DB1,DB2
C.....INPUT FREQ LOW,HIGH,INCR
      PRINT *,'FREQ LOW,HIGH,INCR=',
      READ(1,*) FLO,FHI,FINCR
      NFR=INT( (FHI-FLO)/FINCR + 0.5) + 1
C.....DETERMINE IF DATA PRINTING DESIRED
114   PRINT *,'WANT PRINTING OF DATA -Y/N%=',
      READ(1,390) INTRCE
      SKIPIT=.TRUE.
```

```
      IF(INTRCE .EQ. 1HN) GO TO 115
      SKIPIT=.FALSE.
      IF(INTRCE .EQ. 1HY) GO TO 115
      GO TO 114
115   CALL AXIS(1.5,3.5,10H  SINO***=,-10,5.,0.,0.,.2)
      CALL AXIS(1.5,3.5,29HTRANSMISSION COEFFICIENT (DB),29,5.,90.,-50.
     *          ,10.0)
      CALL PLOT(1.5,3.5,-3)
      L=1
      DO 130 I=1,NFR
      F=FLO+(I-1)*FINCR
      TPIL=TWOPI*F
      FREQ(L)=F
      L=L+1
      DO 120 J=1,101
      CALL RXTX(NSLABS,ST(J),TPIL,MODE,EPS,D,Z)
      TJ=CABS(Z)**2
      TJ=10.*ALOG10(TJ)
      T(J)=AMAX1(TJ,-50.0)
      SAVE(I,J)=T(J)
120   CONTINUE
      CALL LINE(ST,T,101,1,5,I-1)
130   CONTINUE
C.....TRACE OUT SAVED DATA................
      WRITE(6,394) (SAVE(K,1),K=1,NFR)
394   FORMAT(1X,6(F7.3,3X))
      IF(SKIPIT) GO TO 300
      DO 200 J=1,101
      WRITE(6,393) ST(J),(SAVE(K,J),K=1,NFR)
393   FORMAT(1X,F5.3,2X,6(F7.3,3X))
200   CONTINUE
300   S=5.*STH1
      CALL PLOT(S,0.0,3)
      CALL PLOT(S,5.5,2)
      CALL SYMBOL(999.,5.6,.07,4HSTH1,0.,4)
      S=5.*STH2
      CALL PLOT(S,0.0,3)
      CALL PLOT(S,5.5,2)
      CALL SYMBOL(999.,5.6,.07,4HSTH2,0.,4)
      S=5.+0.1*DB1
      CALL PLOT(0.,S,3)
      CALL PLOT(5.,S,2)
      CALL SYMBOL(5.1,999.,.07,3HDB1,0.,3)
      S=5.+0.1*DB2
      CALL PLOT(0.,S,3)
      CALL PLOT(5.,S,2)
      CALL SYMBOL(5.1,999.,.07,3HDB2,0.,3)
      CALL SYMBOL(1.,-1.5,.1,6HLEGEND,0.,6)
      L=0
      Y=-1.5
      DO 135 I=1,5
      Y=Y-.25
      DO 135 J=1,2
      L=L+1
      X=.5+2.5*(J-1)
      IF(L .GT. NFR) GO TO 136
      CALL SYMBOL(X,Y,.1,L-1,0.,-1)
      CALL SYMBOL(X+.2,Y,.1,7HFREQ = ,0.,7)
      CALL NUMBER(999.,999.,.1,FREQ(L),0.,2)
135   CONTINUE
```

```
136   CALL PLOT(7.,-3.5,-3)
      GO TO 110
140   CALL PLOT(0.,0.,999)
      ENDFILE 4
      STOP
C
      END
      SUBROUTINE RXTX(NSLAB,SKN,TPIL,MODE,EPS,D,RT)
      COMPLEX RT,U,J,GLRT,TY,S(2,2),A(2,2),AD(21,2,2)
      DIMENSION EPS(1),D(1),Y0(21),AJ(21,2,2)
      REAL KAPPA(21)
      EQUIVALENCE (S11,S(1,1)) , (S21,S(2,1)) , (RLTY,TY)
      DATA J/(0.,1.)/
C
C.....COMPUTE KAPPA\S AND Y0\S @REAL≠
C
      SKN2=SKN*SKN
      DO 100 ND=1,NSLAB
      KAPPA(ND)=SQRT(EPS(ND)-SKN2)
      Y0(ND)=KAPPA(ND)
      IF(MODE .EQ. 2HTM) Y0(ND)=EPS(ND)/KAPPA(ND)
100   CONTINUE
C
C.....CONSTRUCT JUNCTION WAVE TRANSMISSION MATRICES, AJ, @REAL≠
C
      NSLAB1=NSLAB-1
      DO 110 ND=1,NSLAB1
      RLTY=1.0/(Y0(ND)+Y0(ND+1))
      S11=(Y0(ND)-Y0(ND+1))*RLTY
      S21=2.0*Y0(ND)*RLTY
      RLTY=Y0(ND+1)/Y0(ND)
      AJ(ND,1,1)=1.0/S21
      AJ(ND,1,2)=S11/S21
      AJ(ND,2,1)=AJ(ND,1,2)
      AJ(ND,2,2)=(RLTY*S21*S21+S11*S11)/S21
C
C.....CONSTRUCT LINE LENGTH WAVE TRANSMISSION MATRICES, AD, @COMPLEX≠
C
      AD(ND,1,1)=CEXP(J*KAPPA(ND+1)*TPIL*D(ND))
      AD(ND,2,2)=1./AD(ND,1,1)
      AD(ND,1,2)=(0.,0.)
110   AD(ND,2,1)=(0.,0.)
C
C.....FORM TOTAL WAVE TRANSMISSION MATRIX, A, @COMPLEX≠
C
      DO 130 ND=1,2
      DO 130 MD=1,2
      A(ND,MD)=(0.,0.)
      IF (ND.EQ.MD) A(ND,MD)=(1.,0.)
130   CONTINUE
C
      DO 180 ND=1,NSLAB1
      ND1=NSLAB-ND
      DO 160 ID=1,2
      DO 160 KD=1,2
      TY=(0.,0.)
      DO 150 LD=1,2
      U=(0.,0.)
      DO 140 MD=1,2
140   U=U+AD(ND1,LD,MD)*A(MD,KD)
```

AD-A037 960 RAYTHEON CO BEDFORD MASS MISSILE SYSTEMS DIV F/G 9/5
SYNTHESIS OF PLANE STRATIFIED DIELECTRIC SLAB SPATIAL FILTERS U--ETC(U)
DEC 76 J H POZGAY, S ZAMOSCIANYK, L R LEWIS F19628-76-C-0189

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```
150     TY=TY+U*AJ(ND1,ID,LD)
160     S(ID,KD)=TY
        DO 170 ID=1,2
        DO 170 KD=1,2
170     A(ID,KD)=S(ID,KD)
180     CONTINUE
        GLRT=(YO(NSLAB)-YO(1))/(YO(NSLAB)+YO(1))
        TY=A(1,1)+GLRT*A(1,2)
C.....RETURNS TRANSMISSION COEFFICIENT *COMPLEX*
        RT=(1.+GLRT)/TY
        RETURN
        END
**
```

```
      PROGRAM FILTR4(INPUT,OUTPUT,TAPE1=INPUT,TAPE6=OUTPUT,TAPE4)
C.....MODIFIED FILTERS PROGRAM TO WORK ON 6 SLAB CASE
C.....WITH SET STH1,STH2,FLO,FHI,FINCR,DB1,DB2
C.....ONLY DIELECTRIC + THICKNESSES ARE INPUT
C.....THESE INPUT VALUES ARE PLOTTED ON THE GRAPH.
C.....NOTE8  ALL AIR DIELECTRICS HAVE BEEN ASSIGNED EPS=1.02
C.....           TO CONFORM WITH A PHYSICAL FOAM APPROXIMATION TO AIR.
      DIMENSION T(103),ST(103),D(21),EPS(22),DIELCT(6),FREQ(6),
     *             SAVE(6,101)
      COMPLEX Z
      LOGICAL ODD
      DATA ST /100*0.0 ,'.999 , 0.0 , .20 /
      DATA  T /101*0.0 , -50.0 , 10.0 /
      DATA TWOPI /6.2831853071796/
      CALL PLOTF(30,4)
      DO 100 I=1,100
100   ST(I)=0.01*(I-1)
      STH1=.174
      STH2=.42
      DB1=-1.0
      DB2=-10.0
      FLO=.98
      FHI=1.02
      FINCR=.02
      NFR=INT( (FHI-FLO)/FINCR + 0.5) + 1
      MODE=2HTM
C.....INPUT NS, THE NUMBER OF NON-AIR DIELECTRICS
C.....NSLABS IS THE TOTAL NUMBER OF AIR % NON-AIR DIELECTRICS
C.....IP IS THE NUMBER OF DIFFERENT NON-AIR DIELECTRICS
      NS=6
      NSLABS=2*NS
      NSLAB1=NSLABS-1
      IP=(NS+1)/2
C.....INPUT DIELCT(I) I=1 TO IP % INITIALIZE EPS VECTOR
110   PRINT *,'EPS(1 TO ',IP,')=',
      READ(1,*) (DIELCT(I),I=1,IP)
      IF(DIELCT(1) .LT. 0.0) GO TO 140
      ODD=.TRUE.
      IF(MOD(NS,2) .EQ. 0) ODD=.FALSE.
      DO 78 I=1,IP
      IX=2*I
      EPS(IX-1)=1.0
      EPS(IX)=DIELCT(I)
      IF(ODD .AND. (I.EQ.IP)) GO TO 78
      IX=2*(IP+I)
      EPS(IX-1)=1.0
      IY=NS/2+1-I
      EPS(IX)=DIELCT(IY)
78    CONTINUE
C.....INPUT D(I) I=1 TO NSLAB1
      PRINT *,'D(1 TO ',NSLAB1,')=',
      READ(1,*) (D(I),I=1,NSLAB1)
      CALL AXIS(1.5,3.5,10HSINE THETA,-10,5.,0.,0.,.2)
      CALL AXIS(1.5,3.5,29HTRANSMISSION COEFFICIENT (DB),29,5.,90.,-50.,
     *          .10,0)
      CALL PLOT(1.5,3.5,-3)
      L=1
      DO 130 I=1,NFR
      F=FLO+(I-1)*FINCR
      TPIL=TWOPI*F
```

```
      FREQ(L)=F
      L=L+1
      DO 120 J=1,101
      CALL RXTX(NSLABS,ST(J),TPIL,MODE,EPS,D,Z)
      TJ=CABS(Z)**2
      TJ=10.*ALOG10(TJ)
      T(J)=AMAX1(TJ,-50.0)
      SAVE(I,J)=T(J)
120   CONTINUE
      CALL LINE(ST,T,101,1,5,I-1)
130   CONTINUE
C.....TRACE OUT SAVED DATA..............
      WRITE(6,394) (SAVE(K,1),K=1,NFR)
394   FORMAT(1X,6(F7.3,3X))
      S=5.*STH1
      CALL PLOT(S,0.0,3)
      CALL PLOT(S,5.5,2)
      CALL SYMBOL(999.,5.6,.07,4HSTH1,0.,4)
      S=5.*STH2
      CALL PLOT(S,0.0,3)
      CALL PLOT(S,5.5,2)
      CALL SYMBOL(999.,5.6,.07,4HSTH2,0.,4)
      S=5.+0.1*DB1
      CALL PLOT(0.,S,3)
      CALL PLOT(5.,S,2)
      CALL SYMBOL(5.1,999.,.07,3HDB1,0.,3)
      S=5.+0.1*DB2
      CALL PLOT(0.,S,3)
      CALL PLOT(5.,S,2)
      CALL SYMBOL(5.1,999.,.07,3HDB2,0.,3)
      CALL SYMBOL(1.,-.75,.1,6HLEGEND,0.,6)
      L=0
      Y=-0.75
      DO 135 I=1,5
      Y=Y-.25
      DO 135 J=1,2
      L=L+1
      X=.5+2.5*(J-1)
      IF(L .GT. NFR) GO TO 136
      CALL SYMBOL(X,Y+.05,.1,L-1,0.,-1)
      CALL SYMBOL(X+.2,Y,.1,7HFREQ = ,0.,7)
      CALL NUMBER(999.,999.,.1,FREQ(L),0.,2)
135   CONTINUE
136   CALL SYMBOL(0.0,-1.75,.1,12HDIELECTRICS=,0.,12)
      DO 200 K=1,3
      CALL SYMBOL(999.0,999.0,.1,2H  ,0.,2)
200   CALL NUMBER(999.0,999.0,.1,DIELCT(K),0.,2)
      CALL SYMBOL(0.0,-2.0,.1,12HTHICKNESSES=,0.,12)
      CALL WHERE(X0,Y0,FACTR)
C.....SINCE WHERE HAS BEEN CALLED AFTER A CALL TO SYMBOL
C.....THE COORDINATES RETURNED TO X0,Y0 ARE THOSE OF THE
C.....LAST PART OF THE SYMBOL DRAWN.
C.....HENCE, THEY REQUIRE A SLIGHT ADJUSTMENT TO LOCATE
C.....THE COORDINATES OF THE BEGINNING OF THE NEXT SYMBOL.
C.....THE NEXT LINE ADJUSTS FOR THE  =  SYMBOL WHICH WAS
C.....THE LAST DRAWN BEFORE THE CALL TO WHERE(X0,Y0,FACTR)
      Y0=Y0-.05
      L=0
      DO 202 K=1,6
      X=X0
```

```
      Y=Y0-0.25*(K-1)
      DO 201 KK=1,4
      L=L+1
      IF(L .GT. NSLAB1) GO TO 139
      CALL SYMBOL(X,Y,.1,2H  ,0.,2)
      CALL NUMBER(999.0,999.0,.1,D(L),0.,3)
      X=999.0
      Y=999.0
201   CONTINUE
202   CONTINUE
139   CALL PLOT(7.,-3.5,-3)
      GO TO 110
140   CALL PLOT(0.,0.,999)
      ENDFILE 4
      STOP
C
      END
      SUBROUTINE RXTX(NSLAB,SKN,TPIL,MODE,EPS,D,RT)
      COMPLEX RT,U,J,GLRT,TY,S(2,2),A(2,2),AD(21,2,2)
      DIMENSION EPS(1),D(1),Y0(21),AJ(21,2,2)
      REAL KAPPA(21)
      EQUIVALENCE (S11,S(1,1)) , (S21,S(2,1)) , (RLTY,TY)
      DATA J/(0.,1.)/
C
C.....COMPUTE KAPPA\S AND Y0\S *REAL*
C
      SKN2=SKN*SKN
      DO 100 ND=1,NSLAB
      KAPPA(ND)=SQRT(EPS(ND)-SKN2)
      Y0(ND)=KAPPA(ND)
      IF(MODE .EQ. 2HTM) Y0(ND)=EPS(ND)/KAPPA(ND)
100   CONTINUE
C
C.....CONSTRUCT JUNCTION WAVE TRANSMISSION MATRICES, AJ. *REAL*
C
      NSLAB1=NSLAB-1
      DO 110 ND=1,NSLAB1
      RLTY=1.0/(Y0(ND)+Y0(ND+1))
      S11=(Y0(ND)-Y0(ND+1))*RLTY
      S21=2.0*Y0(ND)*RLTY
      RLTY=Y0(ND+1)/Y0(ND)
      AJ(ND,1,1)=1.0/S21
      AJ(ND,1,2)=S11/S21
      AJ(ND,2,1)=AJ(ND,1,2)
      AJ(ND,2,2)=(RLTY*S21*S21+S11*S11)/S21
C
C.....CONSTRUCT LINE LENGTH WAVE TRANSMISSION MATRICES, AD. *COMPLEX*
C
      AD(ND,1,1)=CEXP(J*KAPPA(ND+1)*TPIL*D(ND))
      AD(ND,2,2)=1./AD(ND,1,1)
      AD(ND,1,2)=(0.,0.)
110   AD(ND,2,1)=(0.,0.)
C
C.....FORM TOTAL WAVE TRANSMISSION MATRIX, A. *COMPLEX*
C
      DO 130 ND=1,2
      DO 130 MD=1,2
      A(ND,MD)=(0.,0.)
      IF (ND.EQ.MD) A(ND,MD)=(1.,0.)
130   CONTINUE
```

```
C
      DO 180 ND=1,NSLAB1
      ND1=NSLAB-ND
      DO 160 ID=1,2
      DO 160 KD=1,2
      TY=(0.,0.)
      DO 150 LD=1,2
      U=(0.,0.)
      DO 140 MD=1,2
140   U=U+AD(ND1,LD,MD)*A(MD,KD)
150   TY=TY+U*AJ(ND1,ID,LD)
160   S(ID,KD)=TY
      DO 170 ID=1,2
      DO 170 KD=1,2
170   A(ID,KD)=S(ID,KD)
180   CONTINUE
      GLRT=(YO(NSLAB)-YO(1))/(YO(NSLAB)+YO(1))
      TY=A(1,1)+GLRT*A(1,2)
C.....RETURNS TRANSMISSION COEFFICIENT *COMPLEX*
      RT=(1.+GLRT)/TY
      RETURN
      END
**
```

```
      PROGRAM CONTOR (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION EPS(22),D(21),U0(51),V0(51)
100   READ (5,800) NSLABS
      IF (EOF(5).NE.0) CALL EXIT
      NSLAB=NSLABS+1
      READ (5,810) (EPS(I),I=1,NSLAB)
      EPS(1)=1.
      READ (5,810) (D(I),I=1,NSLABS)
      DO 110 I=1,50
      U0(I)=(I-1)*0.02+1.E-05
      V0(I)=(I-1)*0.02+1.E-05
110   CONTINUE
      CALL CROSS (U0,V0,50,50,NSLAB,EPS,D)
      GO TO 100
C
800   FORMAT (16I5)
810   FORMAT (8F10.0)
      END
      SUBROUTINE CROSS (U0,V0,NU,NV,NSLAB,EPS,D)
      DIMENSION U0(1),V0(1),EPS(1),D(1),INOM(51,51),ICRS(51,51)
      COMPLEX TTM,TTE
      DATA TPIL/6.283185308/
      DO 110 IU=1,NU
      U=U0(IU)
      S1=1./(1.-U**2)
      DO 100 IV=1,NV
      V=V0(IV)
      INOM(IU,IV)=100000
      ICRS(IU,IV)=100000
      IF (U**2+V**2.GE.1.0) GO TO 100
      W=SQRT(1.-U**2-V**2)
      S2=S1/(1.-W**2)
      STH=SQRT(1.-W**2)
      CALL RXTX (NSLAB,STH,TPIL,2HTM,EPS,D,TTM)
      CALL RXTX (NSLAB,STH,TPIL,2HTE,EPS,D,TTE)
      C1=U*V*W*S2
      C2=V*V*S2
      C3=S2*(U*W)**2
      T=CABS(C2*TTM+C3*TTE)
      IF (T.LT.1.E-10) T=1.E-10
      T=-200.*ALOG10(T)
      T=AMIN1(T,999.)
      INOM(IU,IV)=T
      T=CABS(C1*(TTM-TTE))
      IF (T.LT.1.E-10) T=1.E-10
      T=-200.*ALOG10(T)
      T=AMIN1(T,999.)
      ICRS(IU,IV)=T
100   CONTINUE
110   CONTINUE
      WRITE (6,900)
      NIU=MIN0(25,NU)
      DO 120 IV=1,NV
      WRITE (6,910) (INOM(IU,IV),IU=1,NIU)
120   CONTINUE
      NIU=MIN0(51,NU)
      WRITE (6,900)
      DO 130 IV=1,NV
      WRITE (6,910) (INOM(IU,IV),IU=26,NIU)
130   CONTINUE
```

```
      WRITE (6,920)
      NIU=MINO(25,NU)
      DO 140 IV=1,NV
      WRITE (6,910) (ICRS(IU,IV),IU=1,NIU)
140   CONTINUE
      WRITE (6,920)
      NIU=MINO(51,NU)
      DO 150 IV=1,NV
      WRITE (6,910) (ICRS(IU,IV),IU=26,NIU)
150   CONTINUE
      RETURN
C
900   FORMAT (1H1,10X,7HNOMINAL,/)
910   FORMAT (1X,26I4)
920   FORMAT (1H1,10X,5HCROSS,/)
      END
      SUBROUTINE RXTX(NSLAB,SKN,TPTL,MODE,EPS,D,RT)
      COMPLEX RT,U,J,GLRT,TY,S(2,2),A(2,2),AD(21,2,2)
      DIMENSION EPS(1),D(1),YO(21),AJ(21,2,2)
      REAL KAPPA(21)
      EQUIVALENCE (S11,S(1,1)) , (S21,S(2,1)) , (RLTY,TY)
      DATA J/(0.,1.)/
C
C.....COMPUTE KAPPA\S AND YO\S *REAL*
C
      SKN2=SKN*SKN
      DO 100 ND=1,NSLAB
      KAPPA(ND)=SQRT(EPS(ND)-SKN2)
      YO(ND)=KAPPA(ND)
      IF(MODE .EQ. 2HTM) YO(ND)=EPS(ND)/KAPPA(ND)
100   CONTINUE
C
C.....CONSTRUCT JUNCTION WAVE TRANSMISSION MATRICES, AJ. *REAL*
C
      NSLAB1=NSLAB-1
      DO 110 ND=1,NSLAB1
      RLTY=1.0/(YO(ND)+YO(ND+1))
      S11=(YO(ND)-YO(ND+1))*RLTY
      S21=2.0*YO(ND)*RLTY
      RLTY=YO(ND+1)/YO(ND)
      AJ(ND,1,1)=1.0/S21
      AJ(ND,1,2)=S11/S21
      AJ(ND,2,1)=AJ(ND,1,2)
      AJ(ND,2,2)=(RLTY*S21*S21+S11*S11)/S21
C
C.....CONSTRUCT LINE LENGTH WAVE TRANSMISSION MATRICES, AD, *COMPLEX*
C
      AD(ND,1,1)=CEXP(J*KAPPA(ND+1)*TPTL*D(ND))
      AD(ND,2,2)=1./AD(ND,1,1)
      AD(ND,1,2)=(0.,0.)
110   AD(ND,2,1)=(0.,0.)
C
C.....FORM TOTAL WAVE TRANSMISSION MATRIX, A, *COMPLEX*
C
      DO 130 ND=1,2
      DO 130 MD=1,2
      A(ND,MD)=(0.,0.)
      IF (ND.EQ.MD) A(ND,MD)=(1.,0.)
130   CONTINUE
C
```

```
      DO 180 ND=1,NSLAB1
      ND1=NSLAB-ND
      DO 160 ID=1,2
      DO 160 KD=1,2
      TY=(0.,0.)
      DO 150 LD=1,2
      U=(0.,0.)
      DO 140 MD=1,2
  140 U=U+AD(ND1,LD,MD)*A(MD,KD)
  150 TY=TY+U*AJ(ND1,ID,LD)
  160 S(ID,KD)=TY
      DO 170 ID=1,2
      DO 170 KD=1,2
  170 A(ID,KD)=S(ID,KD)
  180 CONTINUE
      GLRT=(YO(NSLAB)-YO(1))/(YO(NSLAB)+YO(1))
      TY=A(1,1)+GLRT*A(1,2)
C.....RETURNS TRANSMISSION COEFFICIENT ≠COMPLEX≠
      RT=(1.+GLRT)/TY
      RETURN
      END
••
```

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