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A circuit model for two-path cutoff waveguide dielectric resonator filters

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THESIS

A CIRCUIT MODEL FOR TWO-PATH
CUTOFF WAVEGUIDE
DIELECTRIC RESONATOR FILTERS

by

Gregory A. Miller

March 1992

Thesis Advisor: Jeffrey B. Knorr

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Also, a method for designing this type of filter is proposed. It makes use of commercially available CAD software. An example of the design process is given, along with experimental data obtained from a filter manufactured according to the design.

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A Circuit Model for Two-Path
Cutoff Waveguide
Dielectric Resonator Filters

by

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ABSTRACT

This thesis describes the development of a CAD circuit model for two-path cutoff waveguide dielectric resonator filters. The model was verified using published data of known designs in X-band waveguide. Results from the model agree very well with experimental data.

Also, a method for designing this type of filter is proposed. It makes use of commercially available CAD software. An example of the design procedure is given, along with experimental data obtained from a filter manufactured according to the design.

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I. INTRODUCTION

A. BACKGROUND

A two-path cutoff waveguide dielectric resonator filter is a new type of evanescent-mode waveguide bandpass filter consisting of dielectric resonators incorporated in two parallel cutoff waveguide paths. The two paths are realized by a complete *E*-plane bifurcation of a standard size rectangular waveguide. The resonators are realized using dielectric blocks of low permittivity within the cutoff sections. This type of filter was first proposed by Shigesawa, *et al.*, in 1986 [Ref. 1] and modified by the same authors in 1989 [Ref. 2]. However, evanescent-mode waveguide dielectric resonator filters using low permittivity dielectric material were first proposed much earlier.

The basic idea behind these structures is that a bandpass filter can be constructed from a series of resonators. Each resonator can be pictured as a short section of transmission line terminated at both ends with a large discontinuity. The frequency of resonance depends on the length of the transmission line and the discontinuity elements. The resonators in the subject filters are the dielectric blocks in the below cutoff sections. The dielectric drops the cutoff frequency to well below the desired passband frequencies, hence making a short propagating section. The discontinuities are the below cutoff air-filled sections which behave like large inductive susceptances.

B. OBJECTIVES

The objective of this thesis is to describe a CAD compatible equivalent circuit model for two-path cutoff waveguide dielectric resonator filters. The model is verified by comparing its frequency response to published experimental data obtained from proven designs.

The secondary objective is to describe a design method using the model and the resident optimizers available in the microwave circuit CAD software package *Touchstone* available from *EEsof*. Design by optimizers is faster and more reliable than the design methods described in previous work.

II. PREVIOUS DESIGNS

A. ONE-PATH FILTERS

A typical early design of evanescent-mode waveguide dielectric resonator filters using dielectrics with low relative permittivity is given by Shih and Gray [Ref. 3]. The proposed structure was then a section of below cutoff rectangular waveguide loaded with dielectric resonators such that short blocks of dielectric material completely filled the cross section of the waveguide. This was coupled to the external circuit (a larger rectangular waveguide) via a double-step waveguide junction. The devices that were built used WR-42 as the larger waveguide and WR-22 as the smaller guide. A typical configuration is shown in Fig. 1.

This design has several drawbacks. The fist being the double step junction between different sizes of waveguide. A junction like this is not easy to manufacture, susceptible to stress failure, and is difficult to reproduce with reasonable tolerances. Also, positioning the dielectric blocks within the smaller section accurately is almost impossible. Not all the drawbacks are mechanical in nature, however. The cutoff characteristics of the device allow higher frequencies to couple into the structure just slightly more efficiently than the lower frequencies. This

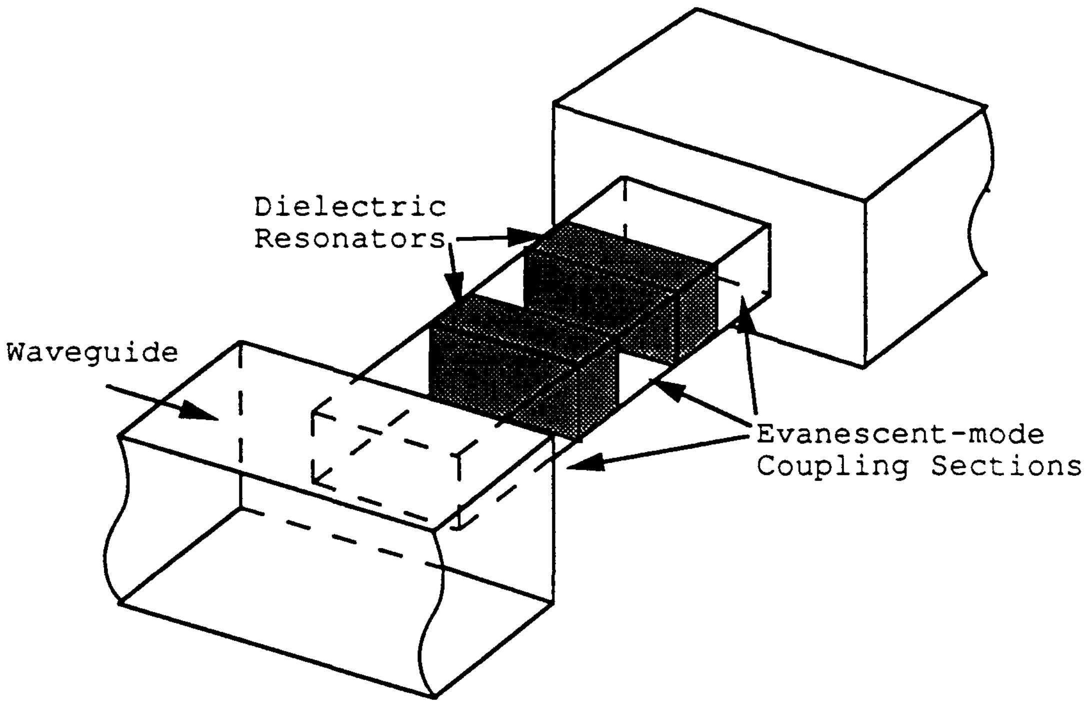

Figure 1. Evanescent-mode waveguide dielectric resonator filter

leads to asymmetric stopband characteristics. That is, the upper skirt of the passband is less steep than the lower skirt. This is often an undesirable phenomenon.

B. TWO-PATH FILTERS

A better structure was proposed [Ref. 1] which eliminated most of the disadvantages of the first designs. It was a two path structure made by bifurcating a rectangular waveguide with a thin metal strip. This structure is shown in Fig. 2. The inherent advantages of this design include ease of manufacture and good reproduceability. Also, the resonant frequencies of either

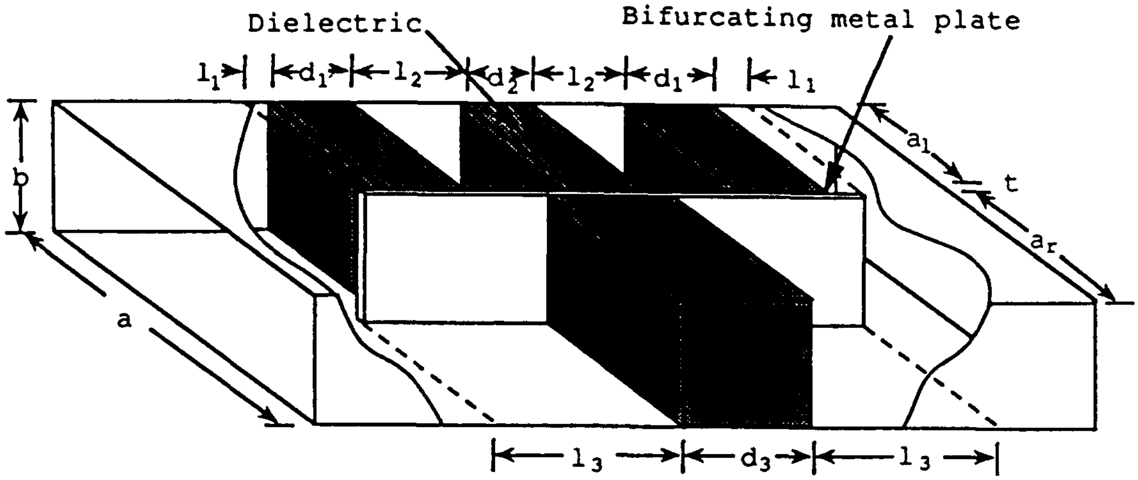

Figure 2. Two-path cutoff waveguide dielectric resonator filter

side of the bifurcated waveguide can be different from each other. The passband around the center frequency is set by the main path and is largely unaffected by the subsidiary path because the wave through that side is heavily attenuated by the cutoff nature of the bifurcated section around the passband frequencies. The resonant frequency of the subsidiary path can be higher than the passband set by the main path. The wave passing through that side at the subsidiary resonant frequency can be made equal in magnitude to that passing through the main path but 180° out of phase, hence the vector sum of both waves at that frequency is zero. This creates an attenuation pole which provides a steep skirt on the high frequency side of the passband. The chief advantage of this scheme is that the main path can be designed to meet a passband requirement, the subsidiary path can be designed to meet a stopband requirement, and each path can be designed independently.

C. DESIGN PROCEDURES

The two-path structure described requires both a generalized scattering matrix technique and a less exact method using impedance converters. The structure is considered to be a direct-coupled cavity filter and is designed with a procedure based on that used by Levy [Ref. 4].

Because the subsidiary path has a negligible effect on the passband, it is replaced by a hypothetical infinitely long homogeneous below cutoff section in the design of the main path. The below cutoff sections in the main path are replaced by impedance inverters whose parameters, K and Φ, can be calculated from the T-equivalent circuit of a below cutoff section of waveguide of the appropriate length as shown in Fig. 3. The desired passband response then

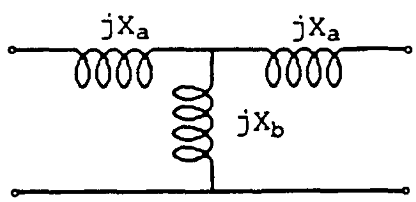

Figure 3. Symmetric T-equivalent circuit

determines the impedance inverters' parameters which determine X_a and X_b of the T-equivalent circuit which in turn give the necessary length of the below cutoff section.

The stopband response, however, requires the use of full wave, multimode analysis. All sections in the bifurcated waveguide are replaced by their generalized scattering matrices which take into account several higher-order modes as well as the fundamental mode. This is shown in Fig. 4.

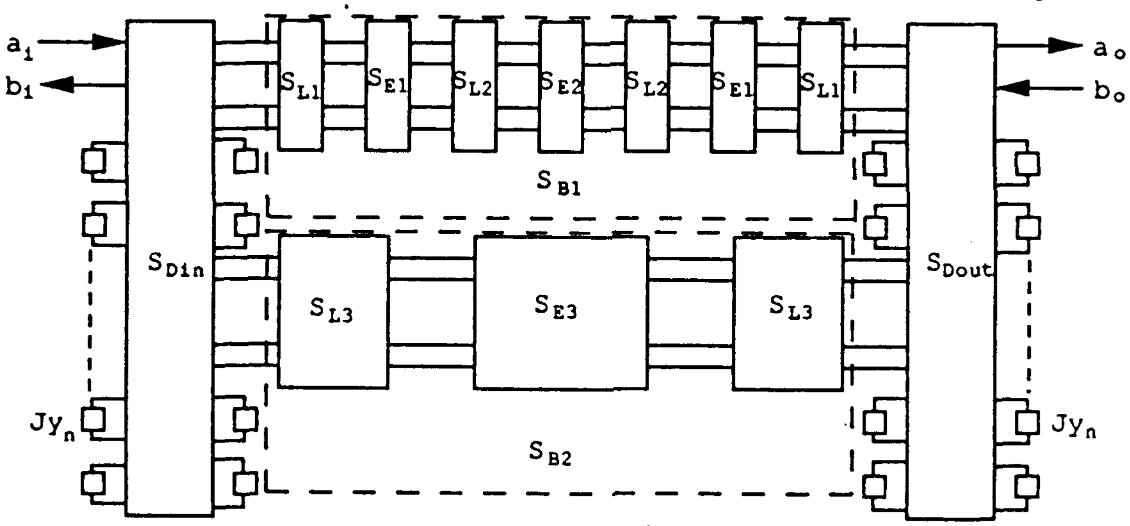

Figure 4. An equivalent circuit with generalized scattering matrices

The matrix element S_{21} of the overall scattering matrix of the entire network can then be determined. It is a function of the main path, which has already been specified, and the length and ϵ_r of the dielectric block in the subsidiary path. A CAD method was developed [Ref. 1] to determine the length of the dielectric block given the desired minimum loss in the stopband, the value of ϵ_r, and the main path design.

The most apparent drawback of this method is that the *T*-equivalent circuits modeling the first and last below cutoff sections are not symmetric, as assumed. The discontinuity caused by the edge of the bifurcating metal plate results in an equivalent circuit shown in Fig. 5. The shunt reactance

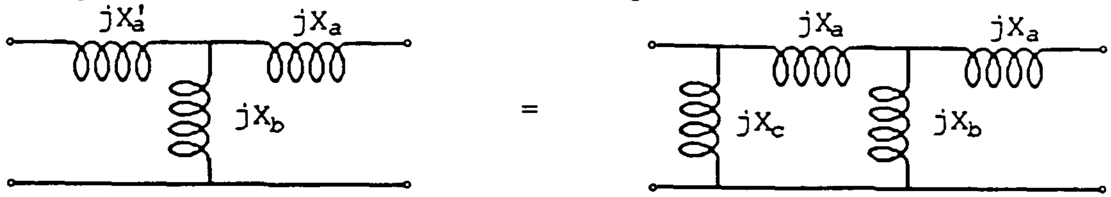

Figure 5. Asymmetric *T*-equivalent circuit

element X_c must be canceled by another shunt reactance element $-X_c$. This additional element is realized by a capacitive window designed to provide the correct reactance at the passband center frequency, f_o. Windows are placed half a guided wavelength (at f_o) from both the input and output discontinuity planes. Without the windows, passband ripple would greatly exceed design requirements.

III. EQUIVALENT CIRCUIT MODEL

A. BASIC MODEL

The filter can be realized in the most rudimentary sense as a series of short rectangular waveguide sections with different values of relative permittivity. The height of each section in the model is the same as the height of the physical waveguide. The width of each section in the model is the same as the bifurcated section (the two sides are not

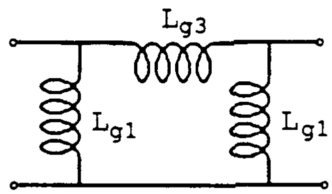

Figure 6. Inductive Π-equivalent circuit of below-cutoff section

necessarily identical). The below-cutoff sections may be replaced by their inductive Π-equivalent circuits as shown in Fig 6. The inductance values are given [Ref. 5] by

$$L_{g1}=L_{g2}=(X_o/2\pi f)\coth(\alpha T/2) \qquad (1)$$

$$L_{g3}=(X_o/2\pi f)\sinh(\alpha T), \qquad (2)$$

where

$$X_o = 120\pi(2b/a)\sqrt{(f_c/f)^2 - 1}, \tag{3}$$

$$\alpha = (2\pi/\lambda)\sqrt{(f_c/f)^2 - 1}, \tag{4}$$

b, a, T are the height, width, and length of the below-cutoff section, and f_c is its cutoff frequency. These circuit elements are thus frequency-dependent. However, they can be computed analytically in a straightforward fashion. A disadvantage to using them is their frequency-dependence, which makes calculations necessary at each frequency point, which in turn makes simulation a slow and inefficient process. The thickness of the bifurcating metal strip is of little importance at this point. The lead section of one half λ_g at f_0 is an air-filled length of standard rectangular waveguide.

The reactance elements realized by symmetric capacitive windows are incorporated in the model as frequency-dependent capacitors. The value of these elements is given [Ref. 6: pp. 314-315] by

$$\frac{B_c}{Y_o} = \frac{4b}{\lambda_g}\ln(\csc(\frac{\pi d}{2b})), \tag{5}$$

where B_c is the susceptance, Y_0 is the characteristic admittance, b is the height of the rectangular waveguide, and d is the size of the window as shown in Fig. 7. In the

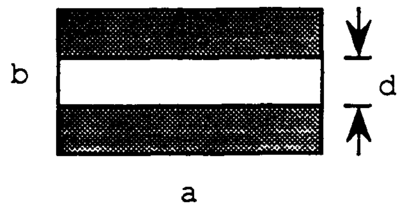

Figure 7. Capacitive window

computer model, the normalized susceptance must be converted to a value of capacitance by dividing it by $2\pi f Z_0$ where the characteristic impedance is frequency-dependent .

The discontinuity of the thin bifurcating metal plate is the most challenging part of the model. It is also very critical. Previous studies of a thin metal septum in waveguide [Ref. 5] suggest that the discontinuity is most simply modeled by a single, frequency-dependent inductor. For better accuracy, it can be modeled using a fixed inductor in parallel with a fixed capacitor.

When all the pieces are finally brought together, the entire model appears as shown in Fig. 8.

B. A SPECIFIC EXAMPLE

The first device to be modeled was a filter described by Shigesawa *et al*. [Ref. 2]. This particular device was chosen because the design specifications and parameters were given along with experimental results. The filter design specifications are given in Table 1, the filter parameters are given in Table 2, and the measured insertion loss is shown in Fig. 9. The residual insertion loss of about 0.5

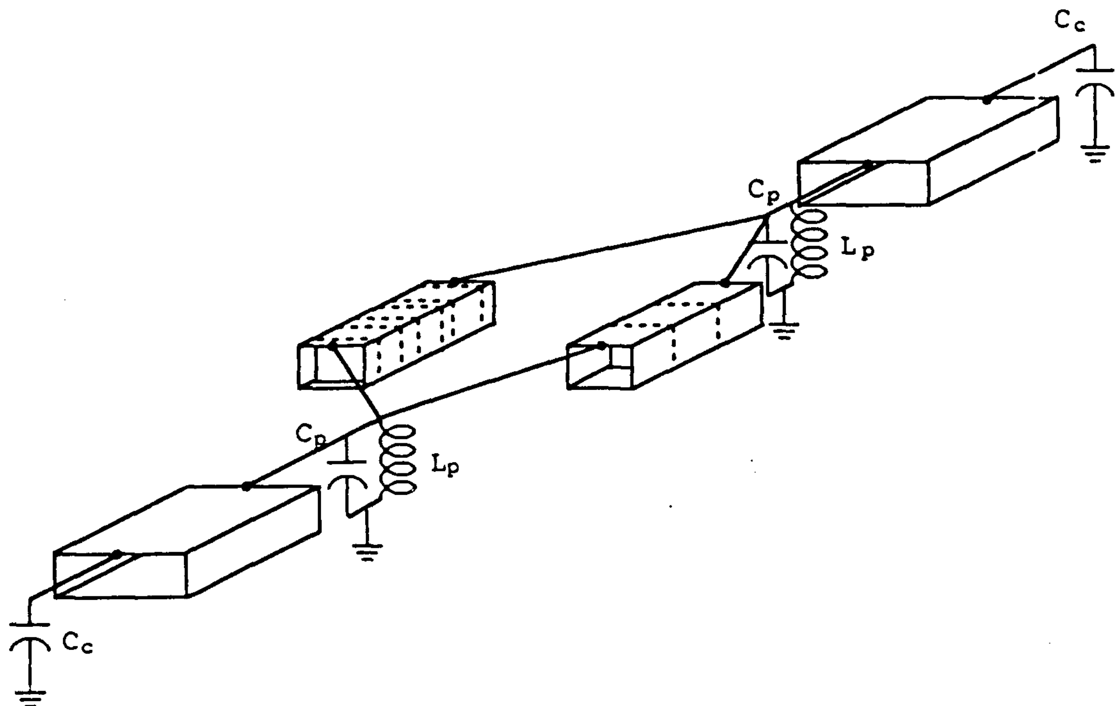

Figure 8. Basic circuit model of the two-path filter

dB in the passband is attributed to gaps between the dielectric blocks and the waveguide walls.

TABLE 1. DESIGN SPECIFICATIONS

Passband response	3-poles, 0.1 dB Chebyshev
Center frequency	f_o = 9.5 GHz
Bandwidth	Δf = 0.3 GHz
Fixed attenuation pole or stopband edge	$f_{\infty 1}$ or f_{s1} = 11.0 GHz
Minimum insertion loss in the stopband	L_{min} = 50 dB

TABLE 2. DESIGN PARAMETERS

Parameter	Length (cm)
a_l	1.18
a_r	1.09
l_1	0.69
l_2	1.33
l_3	2.01
d_1	0.40
d_2	0.40
d_3	1.22
ϵ_r	3.78

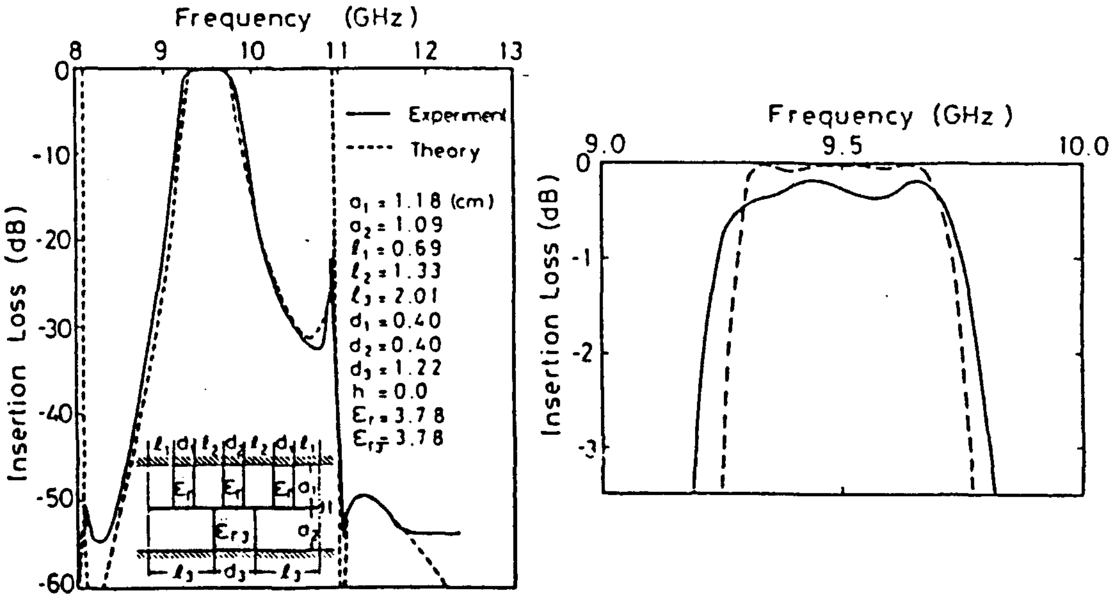

Figure 9. Measured response of the filter

The *Touchstone* circuit file incorporating the model is included as Appendix A. The model is the same as that shown in Fig. 8, with the parameters set to the values given in Table 2. Input and output ports are terminated in a matched load (RWGT). The capacitive windows are modeled as described previously (Eq. 5). The one-half guided wavelength at f_0 is incorporated not as a fixed length, but as a function of f_0 itself. This does not significantly affect the time of a frequency sweep as the calculation is done only once.

The results of sweeping this model are shown in Fig. 10. and Fig. 11. A comparison of these figures to Fig. 9 indicates the gross features of the experimental frequency response are simulated well by the model. These include the resonance at 8.1 GHz and the attenuation pole at 11.0 GHz.

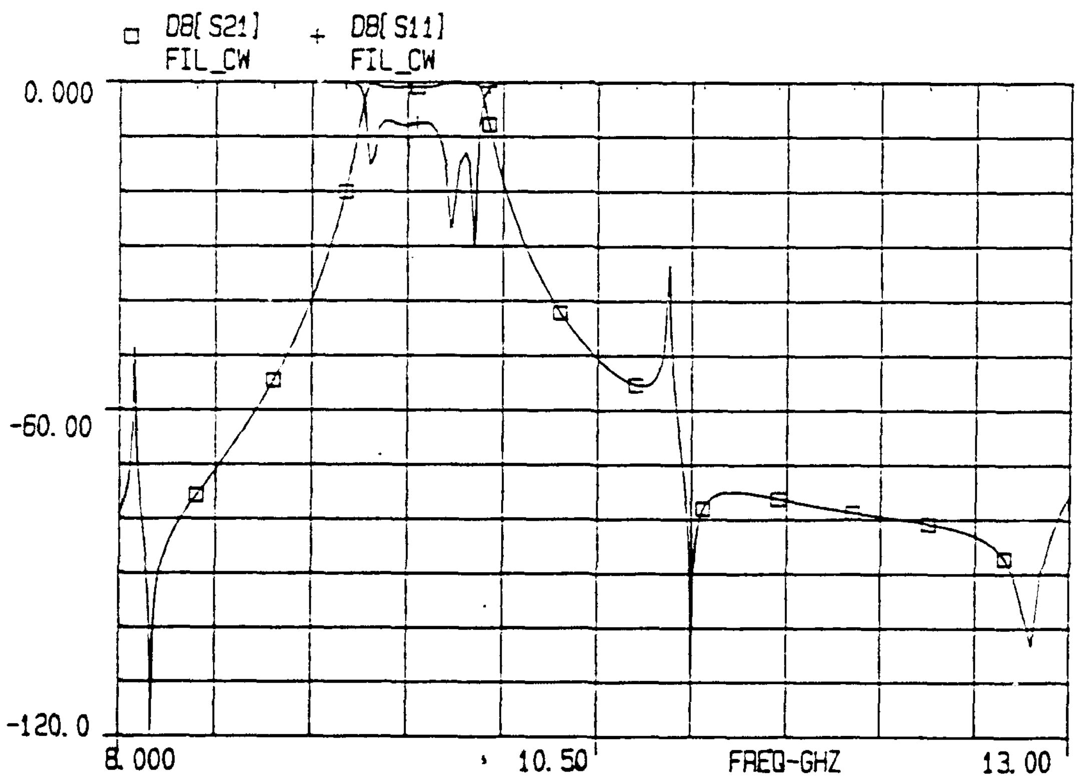

Figure 10. Frequency response of the basic model

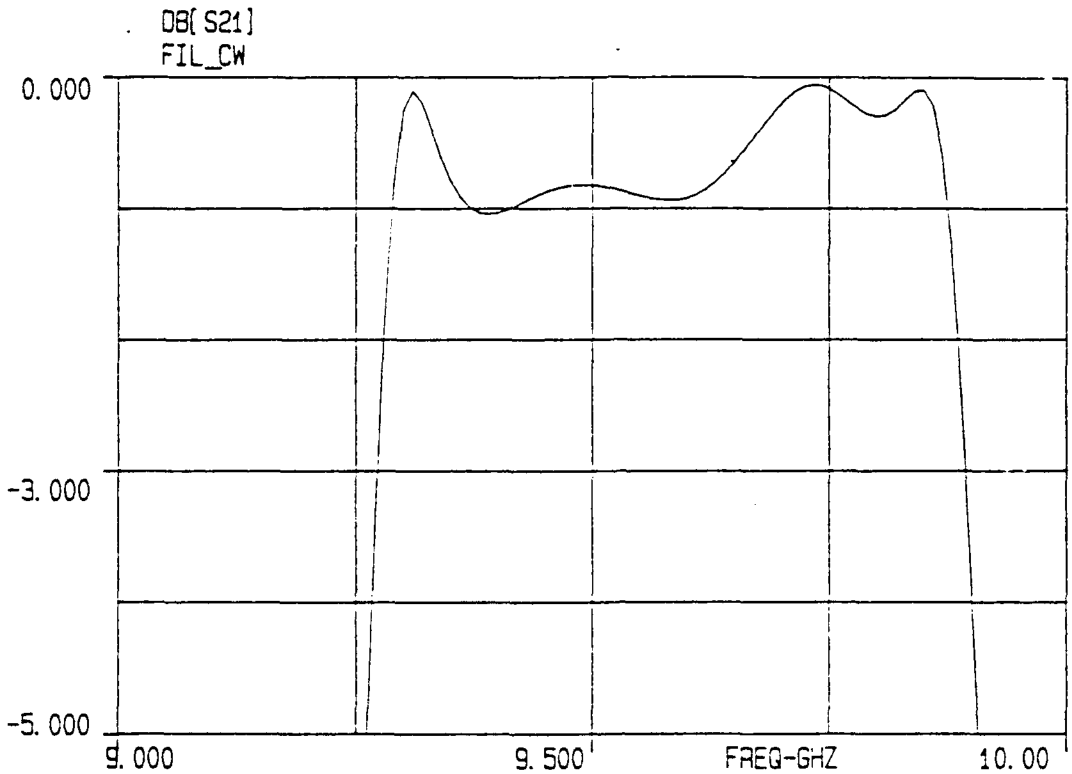

Figure 11. Frequency response of the basic model

However, the exact characteristics of the passband are less than satisfactory.

C. IMPROVEMENT TO *E*-PLANE DISCONTINUITY MODEL

Analysis of Fig. 11 indicates that the passband ripple is 1.1 dB when a ripple of 0.5 dB was expected. Although the performance specifications called for a 0.1 dB ripple, the goal was to match the performance of the physical device, so the model's performance must be compared to the experimental results.

It was determined that the best modification to the model was to change the discontinuity elements from a single parallel inductor and capacitor to a pair of parallel inductors and capacitors. That is, a different inductor and capacitor value would be associated with the main path and the subsidiary path. This modification can be seen in Fig. 12. The reasoning behind this configuration is that the presence of the dielectric block in the below cutoff section has an affect on the discontinuity element values. Instead of being 14.0 nH in parallel with 0.003 pF as in the case of

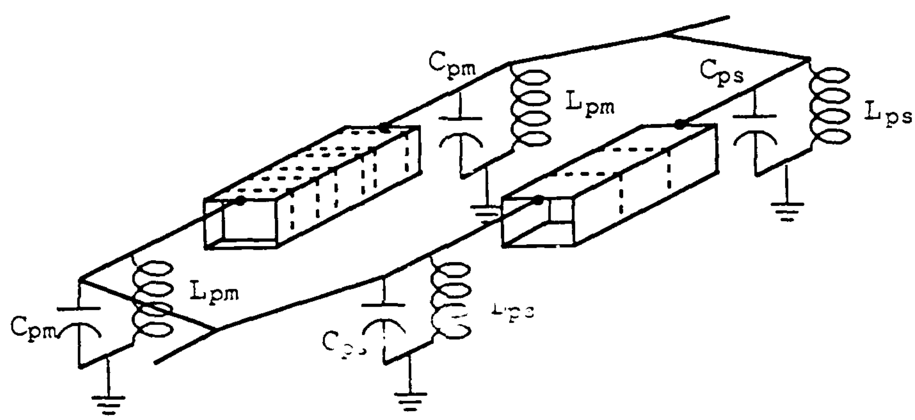

Figure 12. Modification to the model

a long section of air-filled bifurcated waveguide, they would be different.

1. Investigation of bifurcated waveguide with a dielectric block

The problem, of course, was to determine the values of the new elements. To this end, a long section of bifurcated waveguide with a small dielectric block was constructed in the lab as shown in Fig. 13. The scattering parameter S_{11}

was measured at every 500 MHz from 8.0 GHz to 12.0 GHz. Also, several sweeps were made. Each time, the distance, *L*, from the discontinuity plane and the leading edge of the

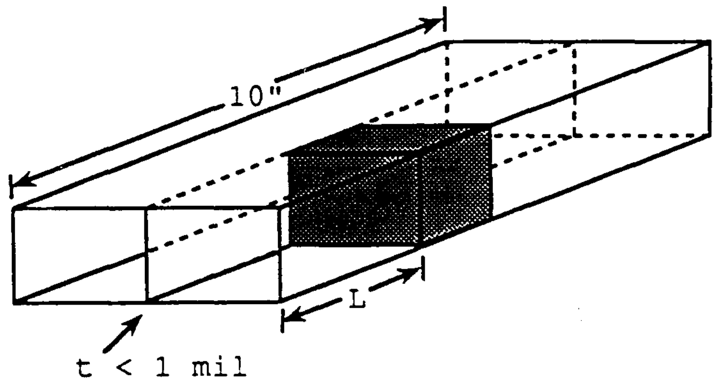

Figure 13. Bifurcated WG with dielectric block

dielectric block was increased. The lengths used were 100, 150, 200, 250, and 300 mils. The data was collected at each point via a slotted line and a VSWR meter. It consisted of the distance between a null with a short and a null with the bifurcated waveguide. It also included the difference in magnitude between adjacent VSWR minima and maxima. The final results of this experiment, represented as angle and magnitude of S_{11} at each frequency, are included as Appendix B.

2. Matching the experimental data

To determine the discontinuity element values, the experimental set up was modeled in a *Touchstone* file included as Appendix C. This file incorporates the discontinuity elements as a different pair of parallel inductors and capacitors like that shown in Fig. 12 above. The elements associated with the section with no dielectric block were given the proven values of 14.0 nH and 0.003 pF. The optimizers available in *Touchstone* were used to determine the values associated with the dielectric-loaded section which resulted in the best agreement between experimental data and that produced by the model. The results are shown in Table 3.

TABLE 3. DISCONTINUITY ELEMENT VALUES

L (mils)	L_{pm} (nH)	C_{pm} (pF)
300	15.21	0.001
250	16.55	0.00025
200	18.60	0.00019

Unfortunately, *Touchstone* exhibits some anomalous behavior when very short rectangular waveguide sections are used. That is, at $L\approx 190$ mils, the frequency response was no longer as well behaved or predictable as it was with longer sections. This means that discontinuity element values for L = 150 mils and L = 100 mils were not found.

D. FINAL MODEL

Once the proper discontinuity elements had been found, they were incorporated in the model. The *Touchstone* circuit file incorporating this modification is included as Appendix D. It is still based on the design reported in Ref. 2.

The frequency response of this model is shown in Fig. 14 and Fig. 15. Although the ripple in the passband is 0.8 dB, it is far better than that given by any other configuration. Also, the position of the attenuation pole at 11.0 GHz as well as the lower-order mode subsidiary path resonance at 8.1 GHz are positioned exactly as reported by Shigesawa *et al.*

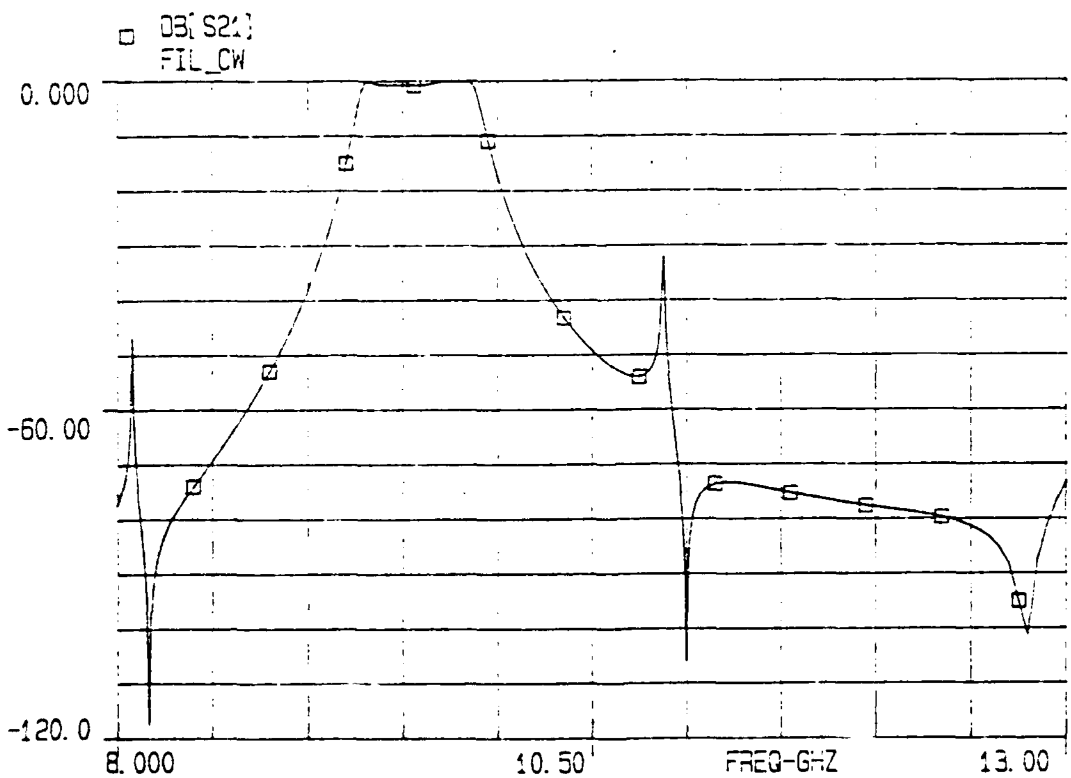

Figure 14. Frequency response of the final model

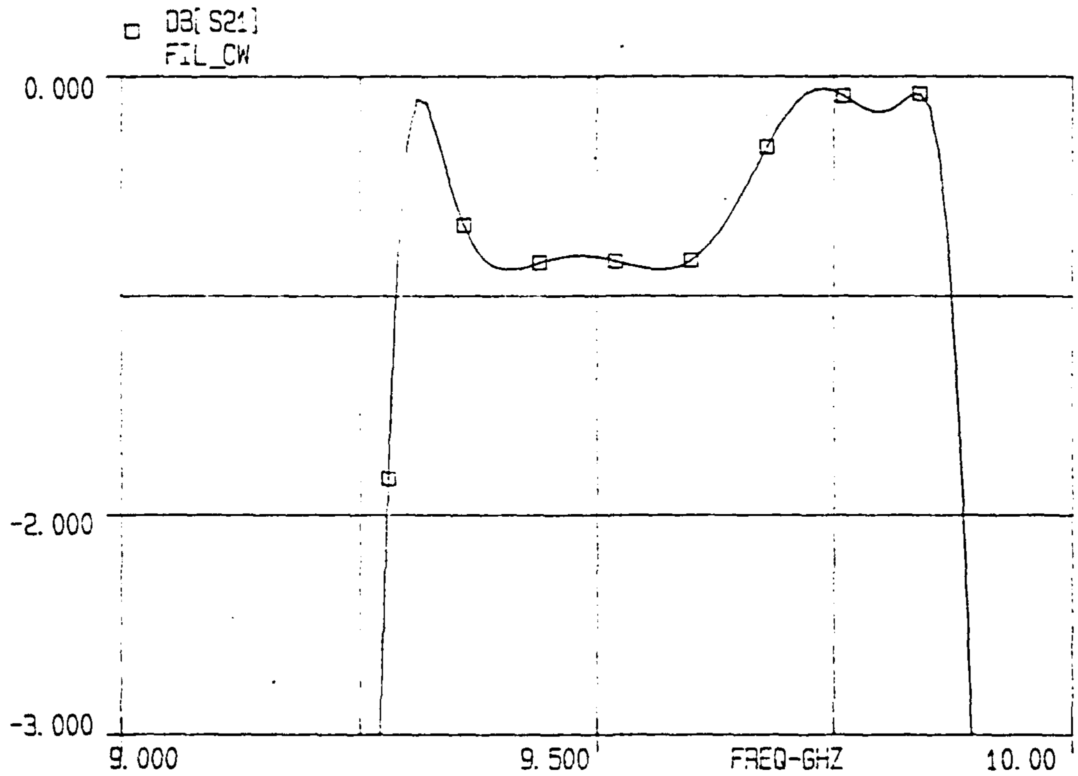

Figure 15. Frequency response of the final model

IV. A DESIGN PROCEDURE

A. SELECTING THE OPTIMIZER

The optimizer resident in *Touchstone* uses one of three search procedures in conjunction with one of four cost functions [Ref. 7]. Choosing the correct search procedure and the correct cost function to be minimized are vital to obtaining a reasonable design in a short period of time.

It was decided to start the search using the Random Search procedure in which new values for the user-specified parameters are selected by a random number generator. Although a random search may appear inefficient, it is faster than the Gradient Search which chooses values according to the gradient of the cost function (it always moves in the direction of decreasing cost). Once the Random Search produces parameter values nearing a solution as indicated by a slowly decreasing cost function, the Gradient Search was used to further refine the design. Thus, the best solution is found in the shortest time. The third search method, Quasi-Newton, was not used because a single iteration required a much longer time than was deemed reasonable.

Selecting the appropriate cost function was less difficult. The Minimax Cost Function leads to a solution in which the point of maximum error is minimized. That is, it leads to an equal ripple solution. This would appear to be the ideal selection as the design will ultimately resemble a Chebyshev response. However, Minimax (as well as the Least P^{th} cost function) are very limited in the number of frequency points allowed, which makes them unusable for such a complicated problem. The third cost function, known as Worst-case, is used to negate the error function, thereby allowing one to find the worst instead of the best solution. Although useful for a worst case analysis of a circuit, it is inappropriate for a design procedure. The last cost function is the Least Squares Cost Function. In it, the squared error between actual response and desired response at each frequency is minimized. This cost function was chosen because of its simplicity and the fact that the other cost functions had been eliminated.

B. DESIGN PROCEDURE

The actual values of the individual elements of the device will be found by the optimizer (Random then Gradient search procedures using the Least Squares error function). Many parameters will have to be selected for the optimizer to function correctly. That is, almost the entire circuit file must be set up leaving only a few parameters to be found. First, the size of the waveguide to be used including the dimensions of the main and subsidiary path must be chosen. Of course, the value of the dielectric's relative permittivity, ϵ_r, must be chosen based on available materials. Because the values of the discontinuity elements depend on the distance between the first dielectric block and the edge of the bifurcating metal septum, the value of l_1 (in Fig. 2) must be fixed along with the associated discontinuity elements. Once the circuit file has been created with the appropriate values, the optimizer will find the values of d_1, d_2, d_3, l_2, l_3, and d (the size of the capacitive window).

The entire filter cannot be designed at once. Separation of the main and subsidiary paths is necessary. The main path which determines the passband characteristics must be designed first and then the subsidiary path must be determined. First, the subsidiary path is replaced by a long section of below-cutoff waveguide. The length depends on the size of the guide. For example, 7 cm is long enough for standard WR-90. The discontinuity elements associated with the subsidiary path must remain in place. Given a reasonable goal, such as FIL_CW DB[S21] > -0.1 in the OPT block of the circuit file, the optimizer will find the best values of l_2, d_1, d_2, and d. Once these numbers are set, the subsidiary path will be replaced. To ensure the subsidiary path will be the same length as the main path, the lines

```
L_TOT=2*(L1+L2+D1)+D2
L3=(L_TOT-D3)/2
```

must be included in the EQN block. Thus, d_3, the length of the dielectric block in the subsidiary path, can be varied alone while keeping the total length of the subsidiary path equal to that of the main path. The subsidiary path is designed only to provide an attenuation pole on the high frequency side of the passband. Because the location of a pole cannot be specified explicitly in the OPT block, the TUNE command will be used to vary d_3 manually until the pole of the entire model (both main and subsidiary paths at this point) appears at the desired position. Although such a "trial and error" method lacks elegance, it is an efficient way to fix the location of the attenuation pole, and clearly illustrates the power of computer-aided design.

Separation of the two paths *for design purposes* is allowed [Ref. 2] because the subsidiary path has a negligible effect on the passband response. A *Touchstone* circuit file exploring this assumption is included as Appendix E. The model parameters are the same as those already given (Table 2). The results of separating the two paths in this file are shown in Fig. 16 and Fig. 17. Comparison of Figs. 14 and 16 reveals that the separation of the two paths is valid. The passband remains essentially unchanged. The high frequency attenuation pole is realized from the outputs of the paths being equal in magnitude (-62 dB) and 180° out of phase (a phase angle of -35° for the

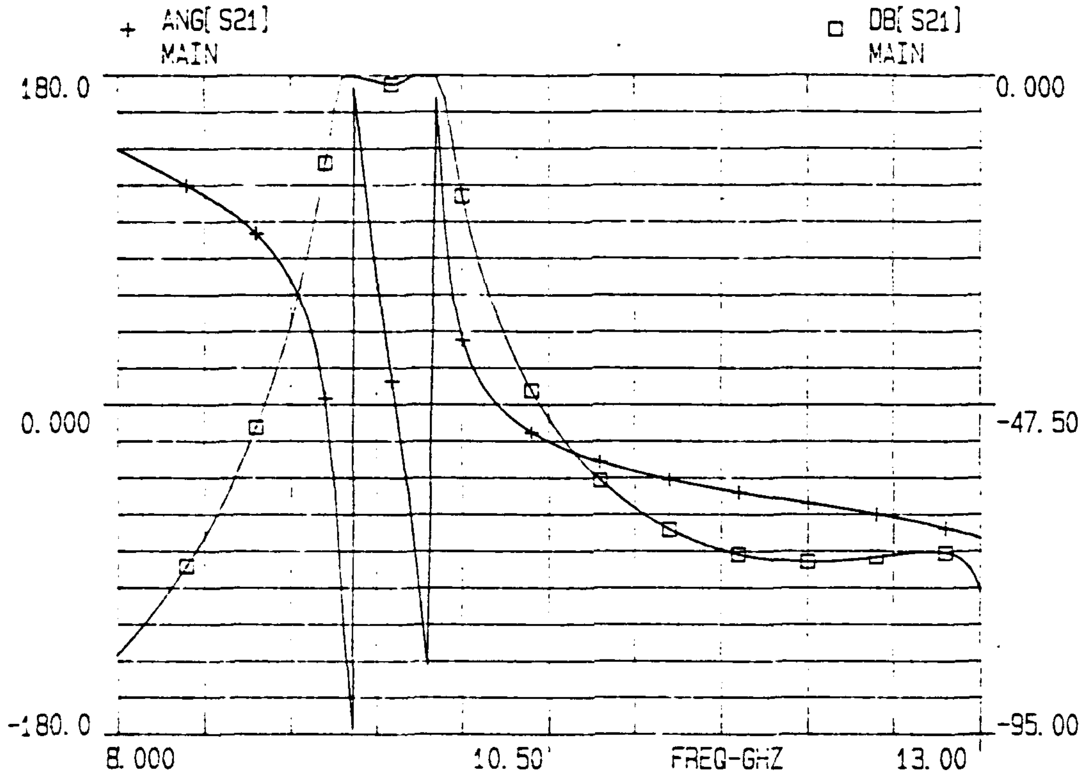

Figure 16. Frequency response of main path

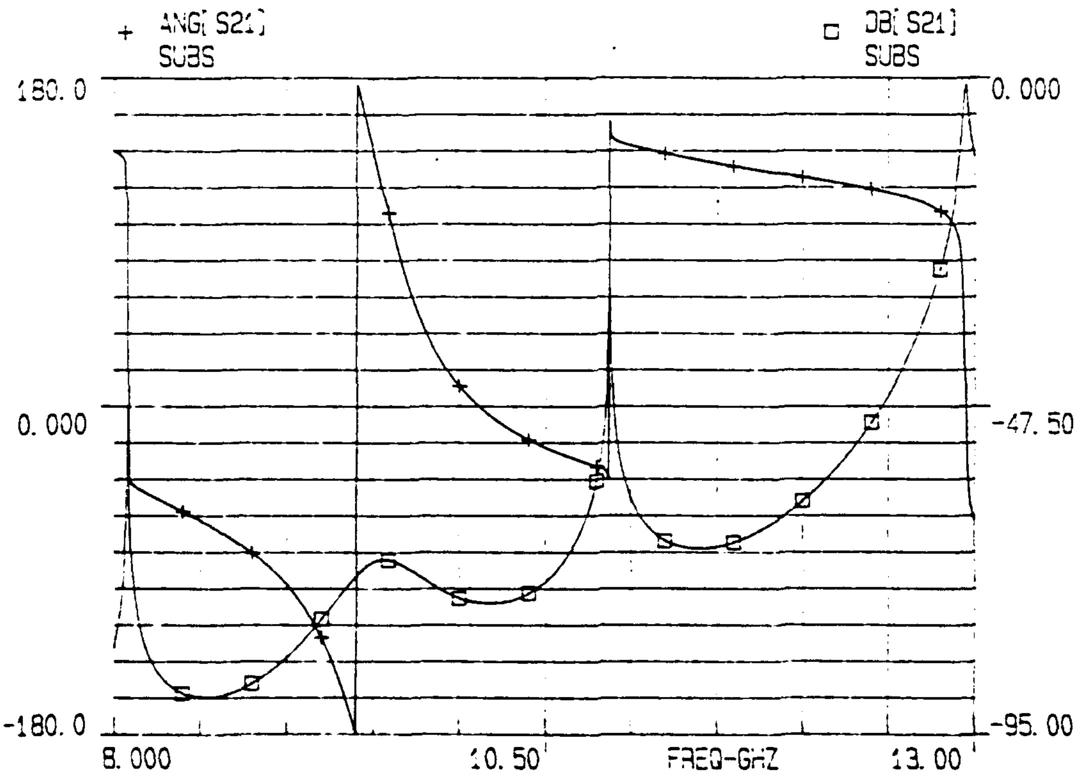

Figure 17. Frequency response of subsidiary path

main path and 145° for the subsidiary path), as discussed earlier.

Initial values for d_1 and d_2 are set by the desired center frequency of the passband. The TE_{mnp} resonant frequency, f_r, of a perfect rectangular cavity is given by the equation [Ref. 6: pp. 430-439]:

$$f_r=\frac{c}{\sqrt{\mu_r\epsilon_r}}\sqrt{(\frac{m}{2a})^2+(\frac{n}{2b})^2+(\frac{p}{2d})^2}, \tag{6}$$

where a, b, and d are the dimensions of the rectangular cavity. Solving for d in the TE_{10p} mode results in

$$d=\frac{p}{2\sqrt{\frac{f_r^2\mu_r\epsilon_r}{c^2}-(\frac{1}{2a})^2}}. \tag{7}$$

The variable d gives the value of d_1 or d_2. Since this equation applies to a perfect cavity, the resonant frequency, f_r, must be set well above the desired frequency. Experience indicates a value 1.8 times greater than that desired will be appropriate. In order for this assumption to remain valid, the coupling into the cavity must be similar to that for which the above rule of thumb was formed. Therefore the initial value of l_2 will be set. The initial value for d_3 can be found using the same equation. In all cases, the TE_{101} mode as well as the TE_{102} mode should be considered.

C. A DESIGN EXAMPLE

Using the procedure described above, a design example was pursued. The design specifications are given in Table 4. Because the dielectric material to be used had a

TABLE 4. DESIGN SPECIFICATIONS

Passband response	3 poles, 0.1 dB Chebyshev
Center frequency	f_0 = 10.5 GHz
Bandwidth	Δf = 0.3 GHz
Fixed attenuation pole or stopband edge	$f_{\infty 1}$ or f_{s1} = 12.0 GHz
Minimum insertion loss in the stopband	L_{min} = 35 dB

relative permittivity of 2.54, the center frequency could not be lower than 8.5 GHz because the bifurcated section filled with the dielectric material had a cutoff frequency of 8.23 GHz. The rest of the design specifications are similar to those found in Ref. 2.

The fixed values are summarized in Table 5. To ease fabrication, a standard WR-90 waveguide was split in equal halves, so both the main path and the subsidiary path would be the same width. Also, as mentioned above, the only useable dielectric material available was Poly-C with ϵ_r = 2.54. The value of l_1 was set at 300 mils (0.762 cm) because the discontinuity elements associated with that

TABLE 5. FIXED DESIGN PARAMETERS

Parameter	Value
a_l	1.143 cm
a_r	1.143 cm
ϵ_r	2.54
l_1	0.762 cm (300 mils)
L_{pm}	15.21 nH
C_{pm}	0.001 pF

length matched the experimental data gathered earlier slightly better than the other possible choices.

The initial and final values of the optimized parameters are given in Table 6. The *Touchstone* circuit file

TABLE 6. OPTIMIZED PARAMETERS

Parameter	Initial value (cm)	Final value (cm)
l_2	1.00	1.50883
d_1	0.60	0.63037
d_2	0.60	0.60423
d	0.1016	0.14934
d_3	1.22	1.740
l_3	N/A	2.333

incorporating this design is included as Appendix F. The optimization of the main path was accomplished with the statements

```
RANGE 10.35 10.65
FIL_CW DB[S21] > -0.1
```

in the OPT block of the file. The frequency response of the final design is shown in Fig. 18 and Fig. 19. Although the design specifications called for a passband ripple of 0.1 dB, a ripple of 0.2 dB was deemed acceptable in part because the difference between 0.1 dB and 0.2 dB is a difference of less than 2.2 %. The response of the main path alone is shown in Fig. 20 to illustrate the effectiveness of the subsidiary path in increasing the steepness of the upper frequency skirt of the passband.

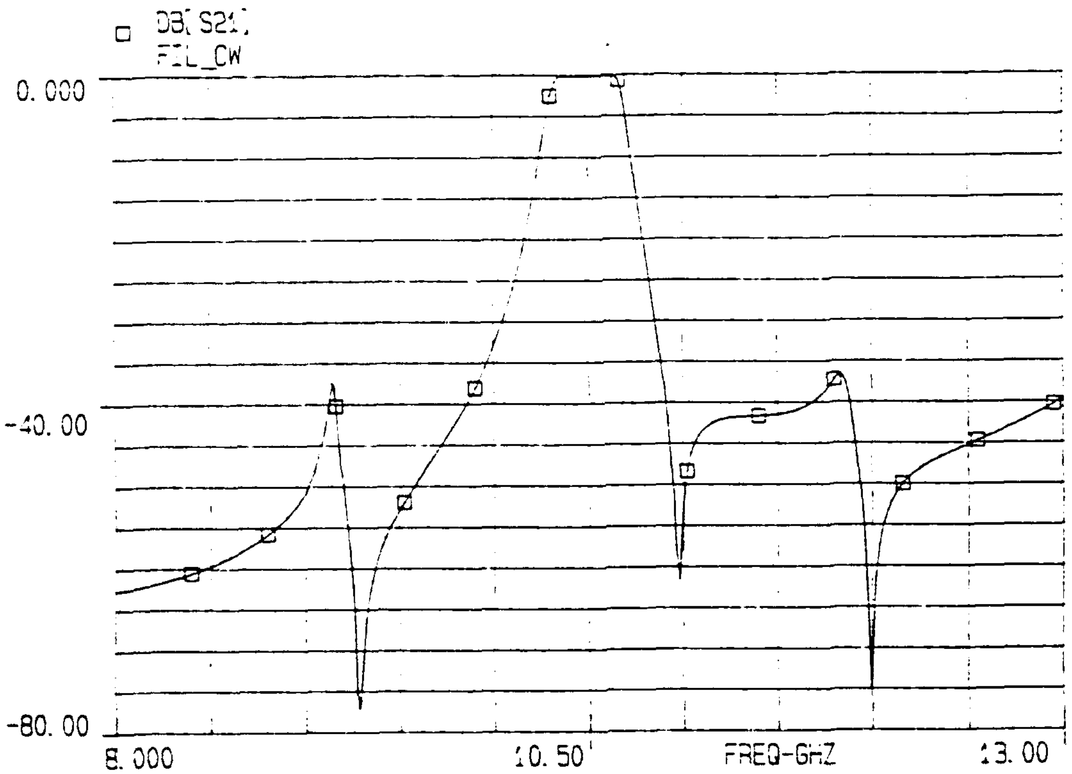

Figure 18. Frequency response of the designed model

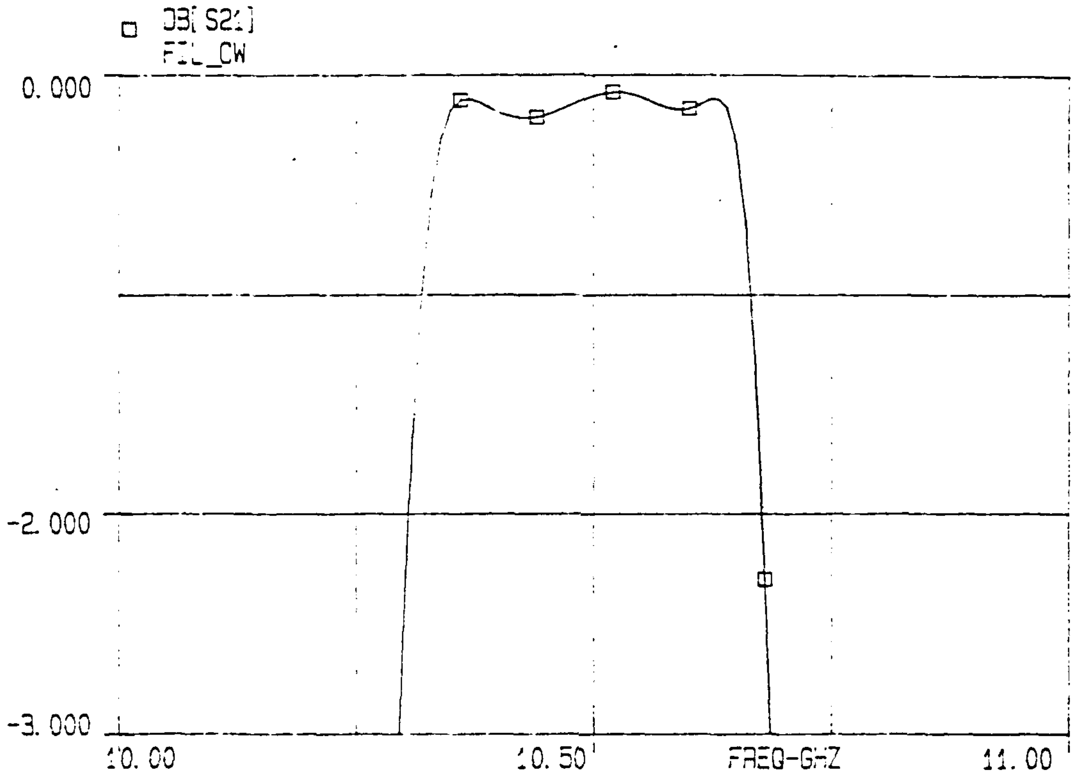

Figure 19. Frequency response of the designed model

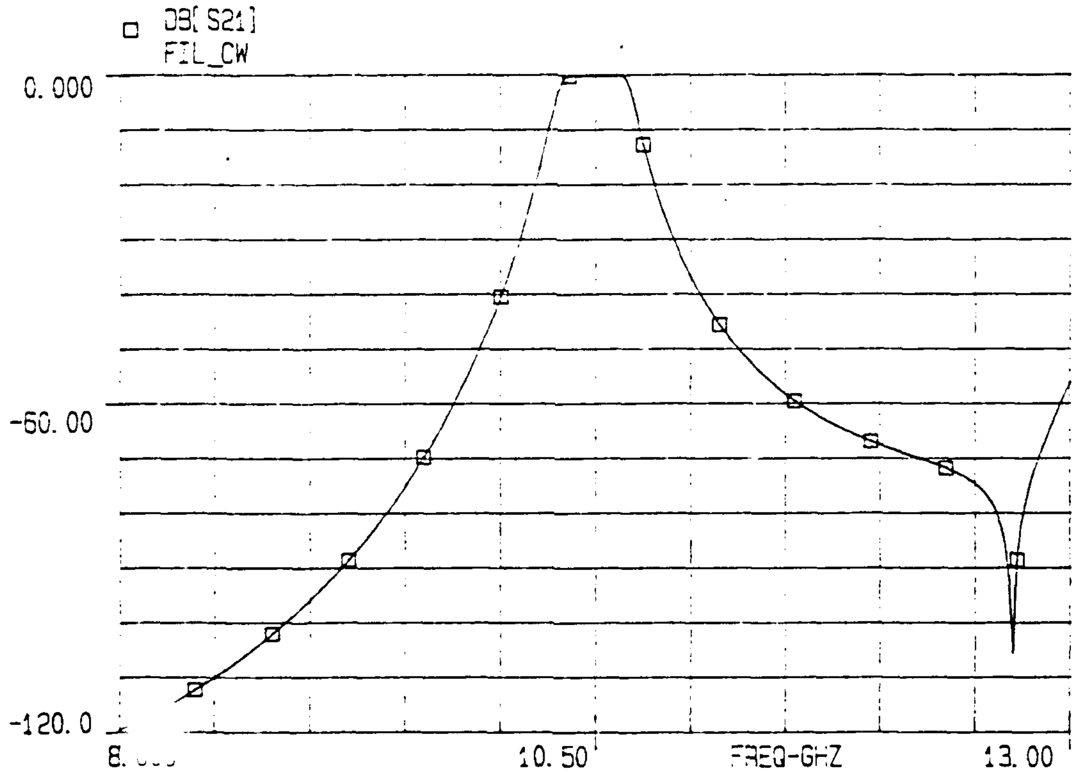

Figure 20. Frequency response of the main path

D. EXPERIMENTAL PERFORMANCE OF DESIGNED FILTER

The above filter was fabricated in accordance with the above specified parameters. Photographs of the filter are shown in Fig. 21 and Fig. 22. The filter itself was manufactured from aluminum barstock with internal dimensions equivalent to those of standard WR-90 rectangular waveguide. The capacitive windows were cut from a copper sheet 0.05 cm thick. The bifurcating metal septum was cut from copper foil 0.005 cm thick. Because of limitations in the machining process, some measurements were different from those specified. Table 7 summarizes the actual measured dimensions.

TABLE 7. PARAMETERS OF MANUFACTURED FILTER

Parameter	Length (cm)
d_1	0.630
d_2	0.600
d_3	1.740
L_c	1.835
d	0.1491
l_1	0.762
l_2	1.509
l_3	2.330

The frequency response of the filter was measured using an HP 8756A Scalar Network Analyzer. The "through"

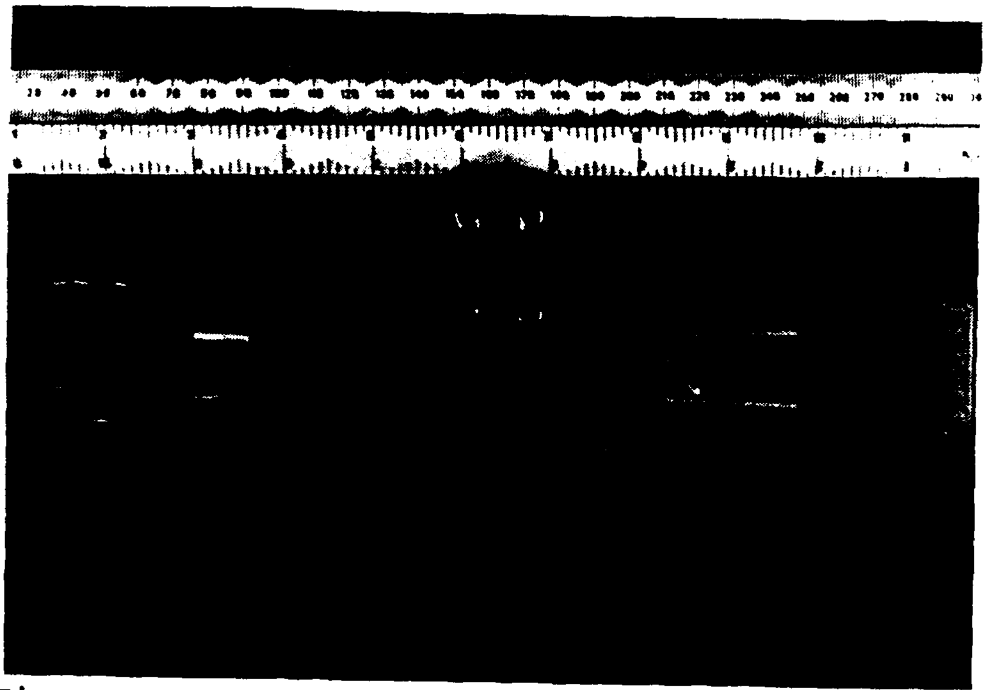

Figure 21. Photograph of disassembled filter

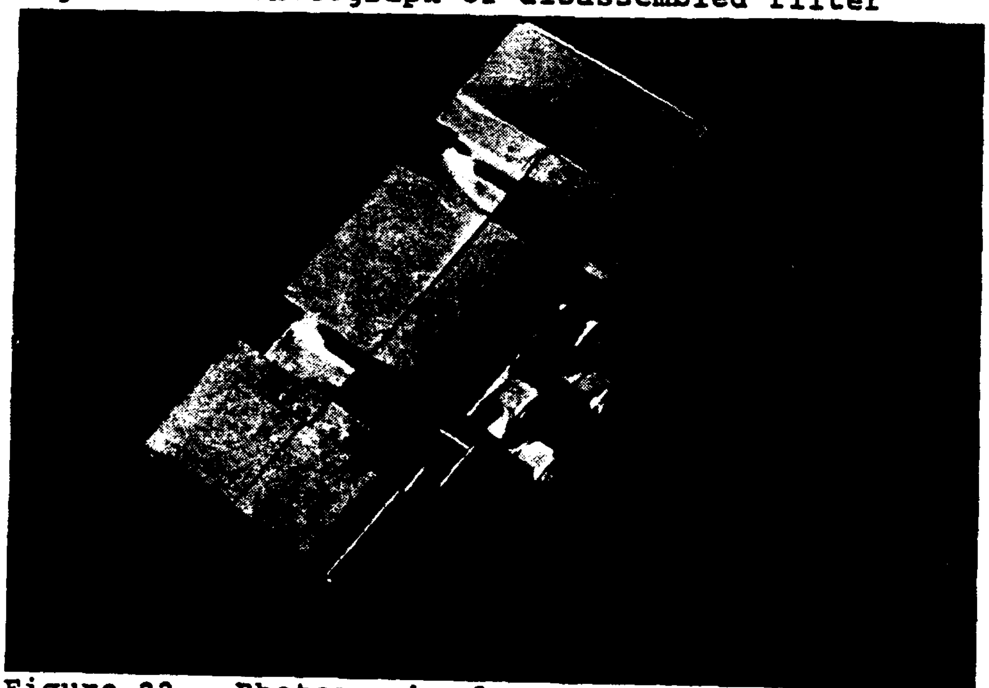

Figure 22. Photograph of assembled filter

calibration was accomplished by placing the filter assembled without the dielectric blocks and without the metal septum between the test ports. This was done to remove losses due to the various connectors and adapters from the final results. The frequency response of the filter is shown in Fig. 23 and Fig. 24. The response is very similar to that predicted by the model. The response of the model incorporating the actual measurements is shown in Fig. 25 and Fig. 26. One can see that the gross features of the filter's frequency response were predicted by the model. These include the resonance at about 9.2 GHz and the position and magnitude of the first ripple of the passband. The discrepancies between tne model response and the actual response are due to transmission loss, gaps between the waveguide walls and the dielectric blocks, misalignment of the capacitive windows, misalignment between adjacent waveguide sections, misalignment of the two halves of the split sections, and problems with the metal septum which include bends of the septum within the body of the filter, overlap and non-vertical alignment at either end leading to a severe folding of the septum itself.

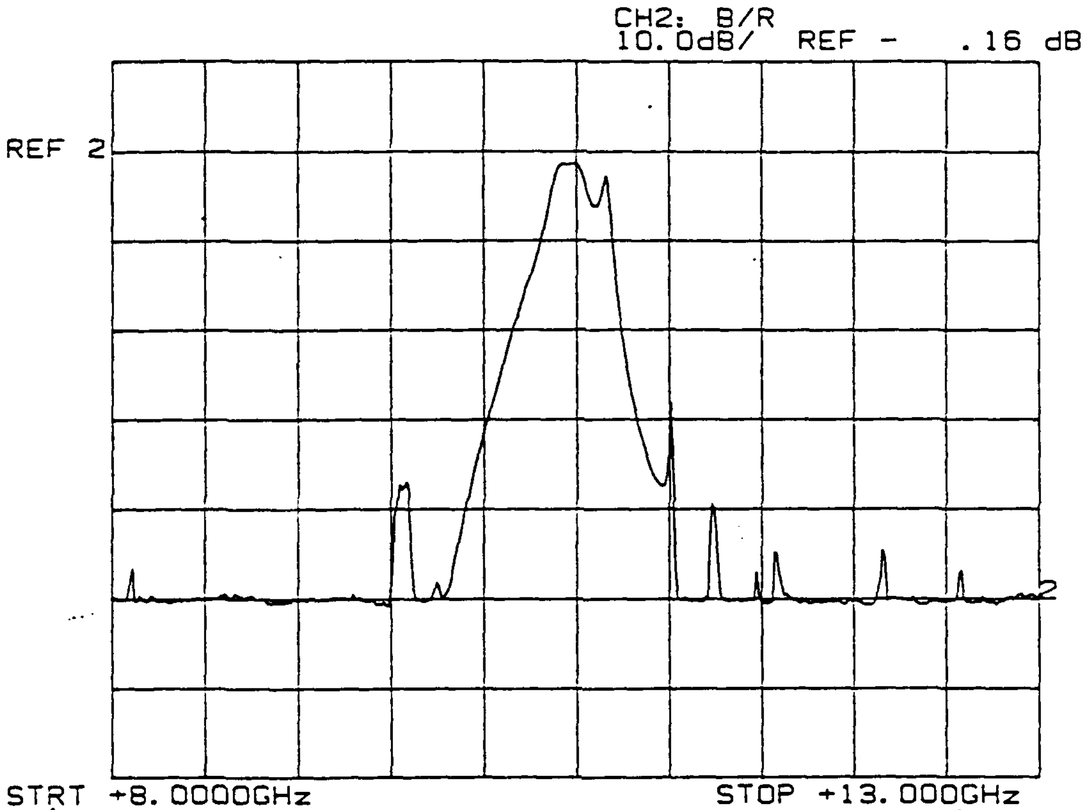

Figure 23. Frequency response of manufactured filter

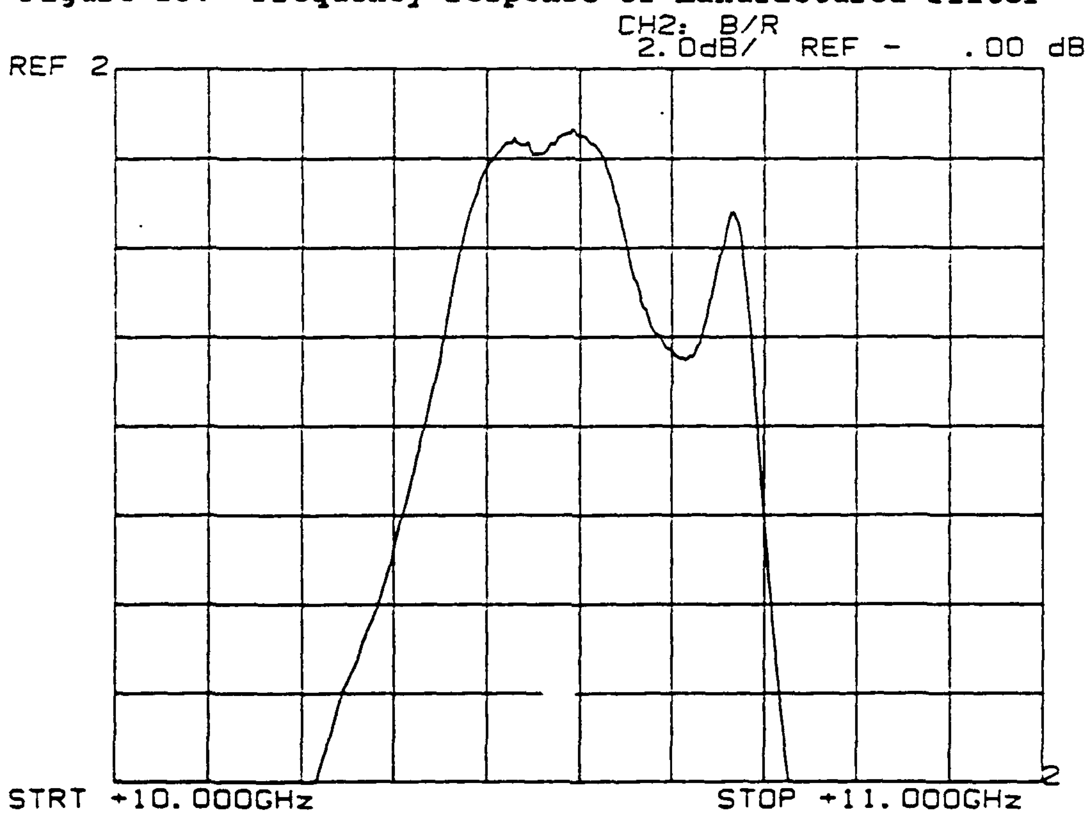

Figure 24. Frequency response of manufactured filter

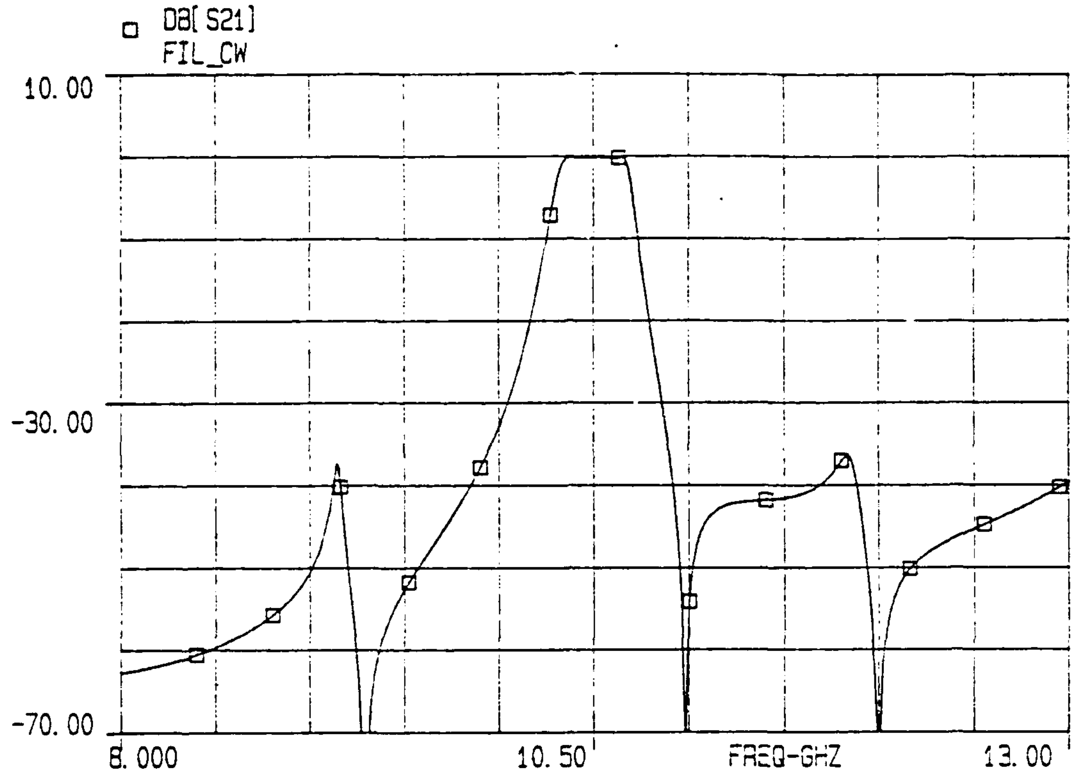

Figure 25. Frequency response of model as manufactured

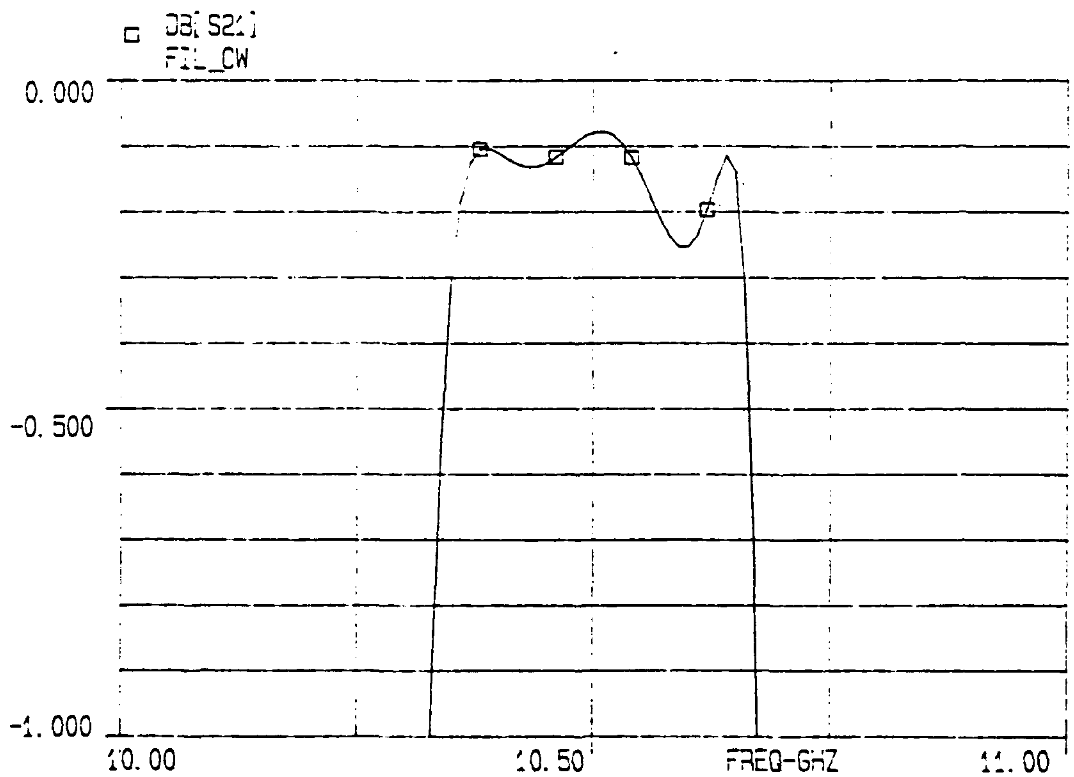

Figure 26. Frequency response of model as manufactured

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis has shown that a two-path cutoff waveguide dielectric resonator filter can be accurately modeled by a simple equivalent circuit using available library elements in a commercial CAD system. Such a model was developed and its performance was shown to match that of an actual device very closely. The positions of the attenuation poles were placed exactly, and the passband ripple was matched to within 0.3 dB.

The circuit model was then used to successfully design this type of filter to prescribed performance criteria using optimizer algorithms. This design approach proved faster and more accurate than design procedures used previously.

B. RECOMMENDATIONS FOR FURTHER STUDY

The effect of the dielectric blocks on the discontinuity element values requires more study in order to develop a complete list matching the distance between the edge of the metal septum and the first dielectric block with the appropriate discontinuity element values. Strategies other than adding discrete elements should also be thoroughly investigated.

The ultimate goal should be to further automate the design process, allowing a user with little or no experience with these filters to effectively design a filter to meet any specifications.

APPENDIX A. BASIC MODEL *TOUCHSTONE* CIRCUIT FILE

```
! FILE:     Two-Path Dielectric Resonator Filter (TPDRF)
! USER:     LT Gregory Miller
! DATE:     24 SEP 91
! REVISED:  3 OCT 91
! CIRCUIT:  Two-path cutoff waveguide dielecrtic resonator
!      filter

! COMMENT:  This file is a trial of some different WG/dielectric
!      combinations.  It is based on a design in Ref.2
!
!      It simulates both halves of a split WG, with a parallel
!      inductor and capacitor to model the losses due to the
!      dicontinuity between the standard WG and the split
!      section.
!
!      It also incorporates the capacitive window absent from
!      previous programs.  It is implemented as a
!      frequency-dependent capacitor.  The frequency dependence
!      is represented as an equation  relating Bc/Yo to
!      capacitive window geometry found in Ref. 6.


DIM
  FREQ GHZ
  RES OH
  IND NH
  CAP PF
  LNG CM
  TIME PS
  COND /OH
  ANG RAD


VAR
   Ag=2.286 ! WR-90 WG
   Al=1.18  ! Left and right halves are not symmetric
   Ar=1.09
   B=1.016

   ER=3.78  ! Dielectric constant used by Shigesawa, et al.

   L1=0.69  ! Length of 1st & last air-filled section, main path
   L2=1.33  ! Length of 2nd & 3rd air-filled section, main path
   L3=2.01  ! Length of 1st & last air-filled section, subs path
   D1=0.40  ! Length of 1st & last er-filled section, main path
   D2=0.40  ! Length of middle er-filled section, main path
   D3=1.22  ! Length of er-filled section, subsidiary path
```

```
   Cp=0.006 ! Value of parallel capacitor (pF)
   Lp=7.0   ! Value of parallel inductor (nH)
   d=0.1138 ! Size of capacitive window (cm)


EQN
! Equations for FREQ-dependent element (capacitive window)
   PI=3.1415927
   Fc=6.562                      ! Cutoff frequency
   Fo=9.5                        ! Center frequency
   lam=30/FREQ                   ! Wavelength in cm if FREQ in GHz
   Gfac=(1-(Fc/FREQ)**2)**0.5    ! Guide factor
   lamg=lam/Gfac                 ! Guided wavelength
   Zo=(120*PI*2*B/Ag)/Gfac       ! Characteristic impedance
   Bc_Yo=(4*B/lamg)*LN(1/SIN(PI*d/(2*b)))! Normalized susceptance
   Cc=1000*Bc_Yo/(Zo*2*PI*FREQ) ! FREQ-dependent capacitance
   Gfaco=(1-(Fc/Fo)**2)**0.5     ! Guide factor at Fo
   Lc=0.5*(30/Fo)/Gfaco          ! Half a guided wavelength at Fo


CKT
! Define each block
   RWG 1 2 A^Al B^B L^L1 ER=1 RHO=1
   DEF2P 1 2 LWG1

   RWG 1 2 A^Al B^B L^D1 ER^ER RHO=1
   DEF2P 1 2 LWGD1

   RWG 1 2 A^Al B^B L^L2 ER=1 RHO=1
   DEF2P 1 2 LWG2

   RWG 1 2 A^Al B^B L^D2 ER^ER RHO=1
   DEF2P 1 2 LWGD2

   RWG 1 2 A^Ar B^B L^L3 ER=1 RHO=1
   DEF2P 1 2 RWG1

   RWG 1 2 A^Ar B^B L^D3 ER^ER RHO=1
   DEF2P 1 2 RWGD

! Connect the elements, and define them as LEFT and RIGHT halves.
   LWG1 1 2
   LWGD1 2 3
   LWG2 3 4
   LWGD2 4 5
   LWG2 6 5
   LWGD1 7 6
   LWG1 8 7
   DEF2P 1 8 LEFT

   RWG1 1 2
   RWGD 2 3
```

```
   RWG1 4 3
   DEF2P 1 4 RIGHT

! Connect them together with a parallel inductor and capacitor at
! both ends and define it as a two-path bandpass filter (TPBPF).
   PLC 1 0 L^Lp C^Cp
   LEFT 1 2
   RIGHT 1 2
   PLC 2 0 L^Lp C^Cp
   DEF2P 1 2 TPBPF

! Connect a capacitive window at the proper length and define
! this as the LEAD section.
   CAP 1 0 C^Cc
   RWG 1 2 A^Ag B^B L^Lc ER=1 RHO=1
   DEF2P 1 2 LEAD

! This is a filter with capacitive windows (FIL_CW).
   LEAD 1 2
   TPBPF 2 3
   LEAD 4 3
   DEF2P 1 4 FIL_CW

! Set up termination of matched load.
   RWGT 1 A^Ag B^B ER=1 RHO=1
   DEF1P 1 WEDGE


TERM
   FIL_CW WEDGE WEDGE


PROC


OUT
   FIL_CW  DB[S21]  GR1  ! Insertion loss
!   FIL_CW  DB[S11]  GR1  ! Return loss


FREQ
   SWEEP 8 13 0.05
   SWEEP 8.0 8.3 0.01
   SWEEP 10.75 11.1 0.01
   SWEEP 9.2 9.9 0.02


GRID
   RANGE 8 13 0.5
!   RANGE  9.0 10.0 0.25
!   GR1 -3 0 1
```

APPENDIX B. *TOUCHSTONE* DATA FILES

A. L = 100 mils

```
! FILE:  Bifurcated WG w/ dielectric 100 mils from edge
!   (BIFWG100)
! USER:  LT Gregory Miller
! DATE:  14 NOV 91
! REVISED: 19 NOV 91

# GHZ S MA R 50

! SCATTERING PARAMETERS:

! FREQ    /S11/    <S11
  8.0     0.984    149.2
  8.5     0.982    140.2
  9.0     0.976    117.4
  9.5     0.967    166.8
  10.0    0.958    142.0
  10.5    0.948    134.1
  11.0    0.937    122.1
  11.5    0.923    115.8
  12.0    0.910     97.2
```

B. L = 150 mils

```
! FILE:  Bifurcated WG w/ dielectric 150 mils from edge
!   (BIFWG150)
! USER:  LT Gregory Miller
! DATE:  14 NOV 91
! REVISED: 19 NOV 91

# GHZ S MA R 50

! SCATTERING PARAMETERS:

! FREQ    /S11/    <S11
  8.0     0.986    149.6
  8.5     0.985    142.4
  9.0     0.982    124.3
  9.5     0.975    149.8
  10.0    0.969    135.9
  10.5    0.962    126.9
  11.0    0.955    119.3
  11.5    0.947    112.8
  12.0    0.939     94.8
```

C. L = 200 mils

```
! FILE:  Bifurcated WG w/ dielectric 200 mils from edge
!    (BIFWG200)
! USER:  LT Gregory Miller
! DATE:  14 NOV 91
! REVISED:  19 NOV 91

# GHZ S MA R 50

! SCATTERING PARAMETERS:

! FREQ     /S11/     <S11
  8.0      0.984     150.0
  8.5      0.984     142.8
  9.0      0.982     130.2
  9.5      0.979     148.7
  10.0     0.975     131.1
  10.5     0.968     126.2
  11.0     0.960     117.8
  11.5     0.952     110.5
  12.0     0.944      96.4
```

D. L = 250 mils

```
! FILE:  Bifurcated WG w/ dielectric 250 mils from edge
!    (BIFWG250)
! USER:  LT Gregory Miller
! DATE:  14 NOV 91
! REVISED:  19 NOV 91

# GHZ S MA R 50

! SCATTERING PARAMETERS:

! FREQ     /S11/     <S11
  8.0      0.983     149.6
  8.5      0.982     143.7
  9.0      0.979     134.7
  9.5      0.976     141.5
  10.0     0.971     129.9
  10.5     0.967     122.3
  11.0     0.963     116.4
  11.5     0.959     108.2
  12.0     0.955      96.4
```

E. L = 300 mils

```
! FILE:  Bifurcated WG w/ dielectric 300 mils from edge
!    (BIFWG300)
! USER:  LT Gregory Miller
! DATE:  14 NOV 91
! REVISED:  19 NOV 91
```

```
# GHZ S MA R 50

! SCATTERING PARAMETERS:

! FREQ     /S11/     <S11
  8.0      0.985     140.1
  8.5      0.983     143.7
  9.0      0.979     136.6
  9.5      0.973     137.1
  10.0     0.968     132.9
  10.5     0.963     122.9
  11.0     0.958     115.0
  11.5     0.953     109.7
  12.0     0.948      96.4
```

APPENDIX C. DISCONTINUITY MODEL *TOUCHSTONE* CIRCUIT FILE

```
! FILE:  Two-Path Section (TPSEC)
! USER: LT Gregory Miller
! DATE: 18 OCT 91
! REVISED:  11 DEC 91
! CIRCUIT:  Two-path section with dielectric

! COMMENT:  This file examines the affect of varying the distance
!      between the edge of a long bifurcating strip in X-band
!      waveguide and a block of dielectric material in the
!      below-cutoff section.  As the dielectric block is moved
!      closer to the edge, the more its presence will change
!      S11.  This file will be used to match S11 to that found
!      experimentally using the optimizers available in
!      Touchstone.

DIM
  FREQ GHZ
  RES OH
  IND NH
  CAP PF
  LNG CM
  TIME PS
  COND /OH
  ANG DEG

VAR
  A=2.286          ! Standard WR-90 WG
  B=1.016
  Fc=6.562
  L_TOT=17         ! Total length of the structure
  L_D=1.32         ! Length of the dielectric block
  L_A1=0.762       ! Length of first air-filled section
  ER=4.61          ! Relative permittivity of block
  Lps=14.0         ! Inductor on air-filled side
  Cps=0.003        ! Capacitor on air-filled side
  Lpm # 14.0 15.21 20.0     ! Inductor on dielectric-loaded side
  Cpm # 0.0001 0.0001 0.005 ! Capacitor on dielectric-loaded side

EQN
  L_A2=L_TOT-L_A1-L_D   ! Length of remaining air-filled section
  Al=A/2                ! Width of left & right halves
  Ar=A/2

CKT
! Define LEFT and RIGHT halves
  PLC 1 0 L^Lpm C^Cpm
  RWG 1 2 A^Al B^B L^L_A1 ER=1 RHO=1
```

```
  RWG 2 3 A^Al B^B L^L_D ER^ER RHO=1
  RWG 3 4 A^Al B^B L^L_A2 ER=1 RHO=1
  DEF2P 1 4 LEFT

  PLC 1 0 L^Lps C^Cps
  RWG 1 2 A^Ar B^B L^L_TOT ER=1 RHO=1
  DEF2P 1 2 RIGHT

! Connect the halves together as a Two-Path Model (TPMOD)
  LEFT 1 2
  RIGHT 1 2
  DEF2P 1 2 TPMOD

! Set up termination of matched load
  RWGT 1 A^A B^B ER=1 RHO=1
  DEF1P 1 WEDGE

! Set up split section terminated with a matched load as a 1-port
! network and call it Loaded Two-Path Model (LD_TPMOD)
  TPMOD 1 2
  WEDGE 2
  DEF1P 1 LD_TPMOD

! Define a 1-port Two-Path WG (TPWG) based on data from the
! BIFWGXXX.S1P data file (XXX is the distance from the edge to
! the dielectric block in mils).
  S1PA 1 0 BIFWG300.S1P
  DEF1P 1 TPWG200

TERM
  LD_TPMOD WEDGE

PROC
   MOD_ERR=LD_TPMOD/TPWG300 ! The result is the angle difference

OUT
  LD_TPMOD DB[S11] GR1      ! Return loss
  LD_TPMOD MAG[S11] GR2
  LD_TPMOD ANG[S11] GR3
  LD_TPMOD S11 SC2

  TPWG300 DB[S11] GR1       ! Return loss
  TPWG300 MAG[S11] GR2
  TPWG300 ANG[S11] GR3
  TPWG300 S11 SC2

FREQ
  SWEEP 8 12 0.1
!  SWEEP 9.3 9.5 0.01

GRID
  RANGE 8 12 0.5
```

```
  GR3 90 150 10
!  RANGE 9.3 9.5 0.025

OPT
  RANGE 8 9
  MOD_ERR ANG[S11]=0
  RANGE 9.5 12
  MOD_ERR ANG[S11]=0

TOL
```

APPENDIX D. FINAL MODEL *TOUCHSTONE* CIRCUIT FILE

```
! FILE:      Two-Path Dielectric Resonator Filter (TPDRF)
! USER:      LT Gregory Miller
! DATE:      24 SEP 91
! REVISED:   16 DEC 91
! CIRCUIT:   Two-path cutoff waveguide dielecrtic resonator filter

! COMMENT:  This file is a trial of some different WG/dielectric
!      combinations.  It is based on a design in Ref.2
!
!      It simulates both halves of a split WG, with a different
!      parallel inductor and capacitor on the two paths to model
!      the losses due to the dicontinuity between the standard
!      WG and the split section.
!
!      It also incorporates capacitive windows implemented as
!      frequency-dependent capacitors.  The frequency dependence
!      is represented as an equation relating Bc/Yo to
!      capacitive window geometry found in Ref. 6.

DIM

  FREQ GHZ
  RES OH
  IND NH
  CAP PF
  LNG CM
  TIME PS
  COND /OH
  ANG RAD

VAR
   Ag=2.286  ! WR-90 WG
   Al=1.18   ! Left and right halves are not symmetric
   Ar=1.09
   B=1.016

   ER=3.78   ! Dielectric constant used by Shigesawa, et al.

   L1=0.69   ! Length of 1st & last air-filled section, main path
   L2=1.33   ! Length of 2nd & 3rd air-filled section, main path
   L3=2.01   ! Length of 1st & last air-filled section, subs path
   D1=0.40   ! Length of 1st & last er-filled section, main path
   D2=0.40   ! Length of middle er-filled section, main path
   D3=1.22   ! Length of er-filled section, subsidiary path

   Cpm=0.002   ! Value of parallel capacitor, main path (pF)
   Lpm=19.8    ! Value of parallel inductor, main path (nH)
```

```
   Cps=0.003   ! Value of parallel capacitor, subsidiary path (pF)
   Lps=14.0    ! Value of parallel inductor, subsidiary path (nH)

   d=0.1138    ! Size of capacitive window (cm)

EQN
! Equations for FREQ-dependent element (capacitive window)
   PI=3.1415927
   Fc=6.562                         ! Cutoff frequency
   Fo=9.5                           ! Center frequency
   lam=30/FREQ                      ! Wavelength in cm if FREQ in GHz
   Gfac=(1-(Fc/FREQ)**2)**0.5       ! Guide factor
   lamg=lam/Gfac                    ! Guided wavelength
   Zo=(120*PI*2*B/Ag)/Gfac          ! Characteristic impedance
   Bc_Yo=(4*B/lamg)*LN(1/SIN(PI*d/(2*b)))! Normalized susceptance
   Cc=1000*Bc_Yo/(Zo*2*PI*FREQ)  ! FREQ-dependent capacitance
   Gfaco=(1-(Fc/Fo)**2)**0.5        ! Guide factor at Fo
   Lc=0.5*(30/Fo)/Gfaco             ! Half a guided wavelength at Fo


CKT
! Define each block
   RWG 1 2 A^Al B^B L^L1 ER=1 RHO=1
   DEF2P 1 2 LWG1

   RWG 1 2 A^Al B^B L^D1 ER^ER RHO=1
   DEF2P 1 2 LWGD1

   RWG 1 2 A^Al B^B L^L2 ER=1 RHO=1
   DEF2P 1 2 LWG2

   RWG 1 2 A^Al B^B L^D2 ER^ER RHO=1
   DEF2P 1 2 LWGD2

   RWG 1 2 A^Ar B^B L^L3 ER=1 RHO=1
   DEF2P 1 2 RWG1

   RWG 1 2 A^Ar B^B L^D3 ER^ER RHO=1
   DEF2P 1 2 RWGD

! Connect the elements, and define them as LEFT and RIGHT halves.
   PLC 1 0 L^Lpm C^Cpm
   LWG1 1 2
   LWGD1 2 3
   LWG2 3 4
   LWGD2 4 5
   LWG2 6 5
   LWGD1 7 6
   LWG1 8 7
   PLC 8 0 L^Lpm C^Cpm
   DEF2P 1 8 LEFT
```

```
   PLC 1 0 L^Lps C^Cps
   RWG1 1 2
   RWGD 2 3
   RWG1 4 3
   PLC 4 0 L^Lps C^Cps
   DEF2P 1 4 RIGHT

! Connect them together and define it as a two-path bandpass
! filter (TPBPF).
   LEFT 1 2
   RIGHT 1 2
   DEF2P 1 2 TPBPF

! Connect a capacitive window at the proper length and define
! this as the LEAD section.
   CAP 1 0 C^Cc
   RWG 1 2 A^Ag B^B L^Lc ER=1 RHO=1
   DEF2P 1 2 LEAD

! This is a filter with capacitive windows (FIL_CW).
   LEAD 1 2
   TPBPF 2 3
   LEAD 4 3
   DEF2P 1 4 FIL_CW

! Set up termination of matched load.
   RWGT 1 A^Ag B^B ER=1 RHO=1
   DEF1P 1 WEDGE


TERM
   FIL_CW WEDGE WEDGE

PROC


OUT
   FIL_CW  DB[S21]  GR1  ! Insertion loss
!   FIL_CW  DB[S11]  GR1  ! Return loss


FREQ
   SWEEP 8 13 0.05
   SWEEP 8.0 8.3 0.01
   SWEEP 10.75 11.1 0.01
   SWEEP 9.2 9.9 0.02


GRID
   RANGE 8 13 0.5
!   RANGE  9.0 10.0 0.25
!   GR1 -3 0 1
```

APPENDIX E. SEPARATED PATHS *TOUCHSTONE* CIRCUIT FILE

```
! FILE:      Left and Right Paths (L_R_PATH)
! USER:      LT Gregory Miller
! DATE:      12 DEC 91
! REVISED:   13 DEC 91
! CIRCUIT:   Two-path cutoff waveguide dielecrtic resonator filter

! COMMENT:   This file is a trial of some different WG/dielectric
!       combinations.  It is based on a design in Ref.2
!
!       It simulates both halves of a split WG, with a different
!       parallel inductor and capacitor on the two paths to model
!       the losses due to the dicontinuity between the standard
!       WG and the split section.
!
!       It also incorporates capacitive windows implemented as
!       frequency-dependent capacitors.  The frequency dependence
!       is represented as an equation  relating Bc/Yo to
!       capacitive window geometry found in Ref. 6.
!
!       This file looks specifically at the magnitude and phase
!       of S21 of the main and subsidiary paths.

DIM

  FREQ GHZ
  RES OH
  IND NH
  CAP PF
  LNG CM
  TIME PS
  COND /OH
  ANG DEG

VAR
   Ag=2.286 ! WR-90 WG spilt in half
   Al=1.18  ! left and right halves are not symmetric
   Ar=1.09
   B=1.016

   ER=3.78  ! Dielectric constant used by Shigesawa, et al.

   L1=0.69  ! Length of 1st & last air-filled section, main path
   L2=1.33  ! Length of 2nd & 3rd air-filled section, main path
   L3=2.01  ! Length of 1st & last air-filled section, subs path
   D1=0.40  ! Length of 1st & last er-filled section, main path
   D2=0.40  ! Length of middle er-filled section, main path
   D3=1.22  ! Length of er-filled section, subsidiary path
```

```
   Cpm=0.002 ! Value of parallel capacitor, main path (pF)
   Lpm=19.8  ! Value of parallel inductor, main path (nH)
   Cps=0.003 ! Value of parallel capacitor, subsidiary path (pF)
   Lps=14.0  ! Value of parallel inductor, subsidiary path (nH)
   d=0.1138  ! Size of capacitive window (cm)

EQN
! Equations for FREQ-dependent element (capacitive window)
   PI=3.1415927
   Fc=6.562                         ! Cutoff frequency
   Fo=9.5                           ! Center frequency
   lam=30/FREQ                      ! Wavelength in cm if FREQ in GHz
   Gfac=(1-(Fc/FREQ)**2)**0.5       ! Guide factor
   lamg=lam/Gfac                    ! Guided wavelength
   Zo=(120*PI*2*B/Ag)/Gfac          ! Characteristic impedance
   Bc_Yo=(4*B/lamg)*LN(1/SIN(180*d/(2*b)))!Normalized susceptance
   Cc=1000*Bc_Yo/(Zo*2*PI*FREQ)  ! FREQ-dependent capacitance
   Gfaco=(1-(Fc/Fo)**2)**0.5        ! Guide factor at Fo
   Lc=0.5*(30/Fo)/Gfaco             ! Half a guided wavelength at Fo


CKT
! Define each block
   RWG 1 2 A^Al B^B L^L1 ER=1 RHO=1
   DEF2P 1 2 LWG1

   RWG 1 2 A^Al B^B L^D1 ER^ER RHO=1
   DEF2P 1 2 LWGD1

   RWG 1 2 A^Al B^B L^L2 ER=1 RHO=1
   DEF2P 1 2 LWG2

   RWG 1 2 A^Al B^B L^D2 ER^ER RHO=1
   DEF2P 1 2 LWGD2

   RWG 1 2 A^Ar B^B L^L3 ER=1 RHO=1
   DEF2P 1 2 RWG1

   RWG 1 2 A^Ar B^B L^D3 ER^ER RHO=1
   DEF2P 1 2 RWGD

! Connect the elements and define them as LEFT and RIGHT halves.
   PLC 1 0 L^Lpm C^Cpm
   LWG1 1 2
   LWGD1 2 3
   LWG2 3 4
   LWGD2 4 5
   LWG2 6 5
   LWGD1 7 6
   LWG1 8 7
   PLC 8 0 L^Lpm C^Cpm
   DEF2P 1 8 LEFT
```

```
   PLC 1 0 L^Lps C^Cps
   RWG1 1 2
   RWGD 2 3
   RWG1 4 3
   PLC 4 0 L^Lps C^Cps
   DEF2P 1 4 RIGHT

! DUMMY sides with no dielectric blocks in them will be needed
   PLC 1 0 L^Lpm C^Cpm
   RWG 1 2 A^Al B^B L=5.24 ER=1 RHO=1
   PLC 2 0 L^Lpm C^Cpm
   DEF2P 1 2 DUM_L

   PLC 1 0 L^Lpm C^Cps
   RWG 1 2 A^Ar B^B L=5.24 ER=1 RHO=1
   PLC 2 0 L^Lpm C^Cps
   DEF2P 1 2 DUM_R

! Connect a capacitive window at the proper length and define
! this as the LEAD section.
   CAP 1 0 C^Cc
   RWG 1 2 A^Ag B^B L^Lc ER=1 RHO=1
   DEF2P 1 2 LEAD

! Set up left and right halves by themselves.
! Connect the left and right sides to the lead and define them as
! MAIN path and SUBSidiary path, respectively.
   LEAD 1 2
   LEFT 2 3
   DUM_R 2 3
   LEAD 4 3
   DEF2P 1 4 MAIN

   LEAD 1 2
   RIGHT 2 3
   DUM_L 2 3
   LEAD 4 3
   DEF2P 1 4 SUBS

! Check the lead section by itself.
   LEAD 1 2
   PLC 2 0 L^Lpm C^Cpm
   PLC 2 0 L^Lps C^Cps
   DEF2P 1 2 LEAD_D

! Set up termination of matched load.
   RWGT 1 A^Ag B^B ER=1 RHO=1
   DEF1P 1 WEDGE


TERM
   MAIN WEDGE WEDGE
```

```
   SUBS WEDGE WEDGE
   LEAD_D WEDGE WEDGE

PROC


OUT
   MAIN   DB[S21]   GR1A
   MAIN   ANG[S21]   GR1
   SUBS   DB[S21]   GR2A
   SUBS   ANG[S21]   GR2
   LEAD_D   DB[S21]   GR3A
   LEAD_D   ANG[S21]   GR3


FREQ
   SWEEP 8 13 0.05
   SWEEP 8.0 8.2 0.01
   SWEEP 9.3 9.8 0.01
   SWEEP 10.75 10.95 0.01
   SWEEP 12.8 13 0.01

GRID
   RANGE 8 13 0.5
   GR1 -180 180 20
   GR1A -95 0
   GR2 -180 180 20
   GR2A -95 0
   GR3 -180 180 20
   GR3A -6 0

OPT

TOL
```

APPENDIX F. OPTIMIZED FILTER DESIGN *TOUCHSTONE* CIRCUIT FILE

```
! FILE:     A Two-Path Cutoff Waveguide Dielectric Resonator
!           Filter Designed w/ optimizer (DES_O)
! USER:     LT Gregory Miller
! DATE:     20 DEC 91
! REVISED:  9 JAN 92
! CIRCUIT:  Two-path cutoff waveguide dielecrtic resonator filter

! COMMENT:  This file is the first attempt to design a two-path
!       cutoff waveguide dielectric resonator filter.  It
!       simulates both halves of a split WG, with a parallel
!       inductor and capacitor to model the losses due to the
!       dicontinuity between the standard WG and the split
!       section.
!
!       It also incorporates capacitive windows similar to
!       previous programs.  They are implemented as
!       frequency-dependent capacitors.  The frequency dependence
!       is represented as an equation relating Bc/Yo to
!       capacitive window geometry found in Ref. 6.
!
!       Optimizers are used to find values of D1, D2, D3, L2, L3,
!       and d.  The main path will first be specified according
!       to the passband requirements, and then the subsidiary
!       path according to stopband requirements.  To do this, the
!       subsidiary path is first replaced by a long below cutoff
!       section (7 cm should be long enough).  Only after the
!       values for the main path are set will the subsidiary path
!       be found.  L1 must be specified before optimization can
!       begin because it is associated with the discontinuity
!       elements.

DIM

  FREQ GHZ
  RES OH
  IND NH
  CAP PF
  LNG CM
  TIME PS
  COND /OH
  ANG RAD

VAR
   Ag=2.286 ! WR-90 WG
   Al=1.143 ! Left and right halves are symmetric
   Ar=1.143
   B=1.016
```

```
   ER=2.54   ! Dielectric constant

   L1=0.762 ! Length of 1st & last air-filled section, main path
   L2\1.50883 ! Length of 2nd & 3rd air-filled section, main path
   D1\0.63037 ! Length of 1st & last er-filled section, main path
   D2#0.5 0.60423 0.66 ! Length of middle er-filled section, main
             ! path
   D3=1.74    ! Length of er-filled section, susidiary path

   Cpm=0.001 ! Value of parallel capacitor, main path (pF)
   Lpm=15.21 ! Value of parallel inductor, main path (nH)
   Cps=0.003 ! Value of parallel capacitor, subsidiary path (pF)
   Lps=14.0  ! Value of parallel inductor, subsidiary path (nH)

   d\0.14934 ! Size of capacitive window (cm)

EQN
   L_TOT=2*(L1+L2+D1)+D2   ! Total length of filter
   L3=(L_TOT-D3)/2         ! Length of 1st & last air-filled
                           ! section, subs path

! Equations for FREQ-dependent element (capacitive window)
   PI=3.1415927
   Fc=6.562                      ! Cutoff frequency (GHz)
   Fo=10.5                       ! Center frequency (GHz)
   lam=30/FREQ                   ! Wavelength in cm if FREQ in GHz
   Gfac=(1-(Fc/FREQ)**2)**0.5    ! Guide factor
   lamg=lam/Gfac                 ! Guided wavelength
   Zo=(120*PI*2*B/Ag)/Gfac       ! Characteristic impedance
   Bc_Yo=(4*B/lamg)*LN(1/SIN(PI*d/(2*b)))! Normalized susceptance
   Cc=1000*Bc_Yo/(Zo*2*PI*FREQ) ! FREQ-dependent capacitance
   Gfaco=(1-(Fc/Fo)**2)**0.5     ! Guide factor at Fo
   Lc=0.5*(30/Fo)/Gfaco          ! Half a guided wavelength at Fo


CKT
! Define each block
   RWG 1 2 A^Al B^B L^L1 ER=1 RHO=1
   DEF2P 1 2 LWG1

   RWG 1 2 A^Al B^B L^D1 ER^ER RHO=1
   DEF2P 1 2 LWGD1

   RWG 1 2 A^Al B^B L^L2 ER=1 RHO=1
   DEF2P 1 2 LWG2

   RWG 1 2 A^Al B^B L^D2 ER^ER RHO=1
   DEF2P 1 2 LWGD2

   RWG 1 2 A^Ar B^B L^L3 ER=1 RHO=1
   DEF2P 1 2 RWG1
```

```
   RWG 1 2 A^Ar B^B L^D3 ER^ER RHO=1
   DEF2P 1 2 RWGD

! Connect the elements, and define them as LEFT and RIGHT halves.
! First the LEFT half (main path).
   PLC 1 0 L^Lpm C^Cpm
   LWG1 1 2
   LWGD1 2 3
   LWG2 3 4
   LWGD2 4 5
   LWG2 6 5
   LWGD1 7 6
   LWG1 8 7
   PLC 8 0 L^Lpm C^Cpm
   DEF2P 1 8 LEFT

! The RIGHT half (subsidiary path) is replaced by a long below
! cutoff section during the design of the main path.  After the
! main path is determined, the subsidiary path is designed.
   PLC 1 0 L^Lps C^Cps
   RWG1 1 2
   RWGD 2 3
   RWG1 4 3
!   RWG 1 2 A^Ar B^B L=7 ER=1 RHO=1
   PLC 2 0 L^Lps C^Cps
   DEF2P 1 2 RIGHT

! Connect them together and define it as a two-path bandpass
! filter (TPBPF).
   LEFT 1 2
   RIGHT 1 2
   DEF2P 1 2 TPBPF

! Connect a capacitive window at the proper length and define it
! as the LEAD section
   CAP 1 0 C^Cc
   RWG 1 2 A^Ag B^B L^Lc ER=1 RHO=1
   DEF2P 1 2 LEAD

! This is a filter with capacitive windows (FIL_CW).
   LEAD 1 2
   TPBPF 2 3
   LEAD 4 3
   DEF2P 1 4 FIL_CW

! Set up termination of matched load
   RWGT 1 A^Ag B^B ER=1 RHO=1
   DEF1P 1 WEDGE


TERM
   FIL_CW WEDGE WEDGE
```

```
PROC

OUT
   FIL_CW  DB[S21]  GR1  ! Insertion loss
!   FIL_CW  DB[S11]  GR1  ! Return loss

FREQ
   SWEEP 8 13 0.05
   SWEEP 10.3 10.7 0.02
   SWEEP 9.1 9.8 0.02
   SWEEP 10.8 11.1 0.02
   SWEEP 11.8 12.2 0.02

GRID
   RANGE 8 13 0.5
!   RANGE  10 11 0.25
!   GR1 -1 0 0.1

OPT
   RANGE 10.35 10.65
   FIL_CW DB[S21] > -0.1

TOL
```

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