Computer-Aided Design of Evanescent Mode Waveguide Bandpass Filter with Nontouching *E*-Plane Fins

KEON-SHIK KONG, STUDENT MEMBER, IEEE, AND TATSUO ITOH, FELLOW, IEEE

***Abstract*—This paper presents an efficient computer-aided design procedure for an evanescent mode waveguide bandpass filter with nontouching *E*-plane fins. The design procedure systematically utilizes a look-up table containing the scattering parameters from differently dimensioned *E*-plane fins. The main idea is to achieve an optimal combination of the filter parameters with proper selections of the *E*-plane fins from the look-up table and appropriate determinations of the other filter structure elements in order to satisfy the given filter specifications.**

The technique of selecting the proper fin from the look-up table is explained. The relationship between the desired center frequency of the filter and the approximate resonant frequency of the single fin in the table is shown. Also, the relationship between each design parameter and the filter characteristic is presented. Mean square error multiplied by the selected weight function in the range of 1.0 dB bandwidth is calculated to obtain better optimized design parameters.

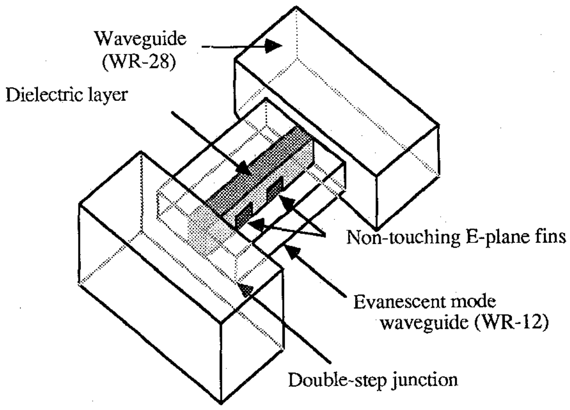

Fig. 1. The structure of the filter with two nontouching *E*-plane fins.

I. Introduction

The characteristics of the evanescent-mode waveguide bandpass filter with nontouching *E*-plane fins have been analyzed previously in [1] and [2]. However, the reverse process, that is, a systematic way of designing the filter with a given specification, is not available. In the conventional design method, the analysis program of the filter structure is iteratively used to obtain the design parameters. This trial-and-error approach is not efficient, and usually takes a large amount of time.

This paper introduces a CAD algorithm to design bandpass filters with nontouching *E*-plane fins. The parameters of the filter structure can be directly obtained from the given specifications by using this algorithm. In this paper, a design process of the bandpass filter with two *E*-plane fins in the operating frequency range of the *Ka*-band (26–41 GHz) is discussed. The equivalent ladder network from the low-pass prototype is generally used for the bandpass filter design [3]–[5]. However, this method is not appropriate for our design purpose, since there is no known relationship between equivalent circuit elements of the fin and the dimensions of the fin. Instead, an approach is established by introducing effective utilization of a look-up table which has the scattering parameters of a single fin of specific dimensions. In this look-up table, the scattering parameters from single fins of the specific dimensions are arranged in the frequency range of 26 to 41 GHz. In order to increase the accuracy of the filter response calculation, the spline-function interpolation is used to increase the sampling points. An effective technique to utilize this look-up table is one of the main topics in this paper. The correlation between each design parameter and a certain filter characteristic is discussed. Also, the technique of selecting each design parameter of the filter is explained. Then, the design process is discussed in detail. In this process, an optimization technique is included. In this technique, the value of the mean squared error multiplied by the selected weight function in the range of 1.0 dB bandwidth is calculated to obtain a filter response close to the desired filter response.

To verify the design algorithm, a filter was designed to obtain given specifications. The characteristics of the filter fabricated according to the design were measured and compared with the calculated filter characteristics.

II. Structure

As a model of the filter structure, the bandpass filter structure with two *E*-plane fins, is shown in Fig. 1. This filter structure consists of discontinuities of the step junction between the larger waveguide and the smaller waveguide, intervals between the step junction discontinuity

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The authors are with the Department of Electrical and Computer Engineering, University of Texas at Austin, Austin, TX 78712.

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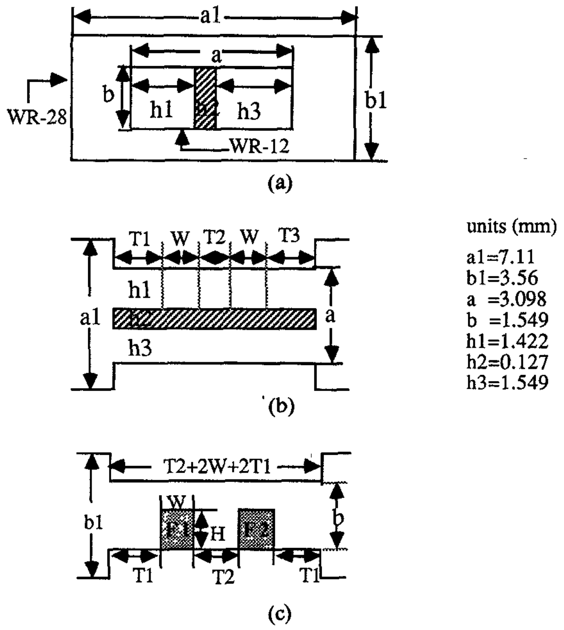


Fig. 2. Filter structure and parameters. (a) Front view. (b) Cross-sectional view. (c) Side view.

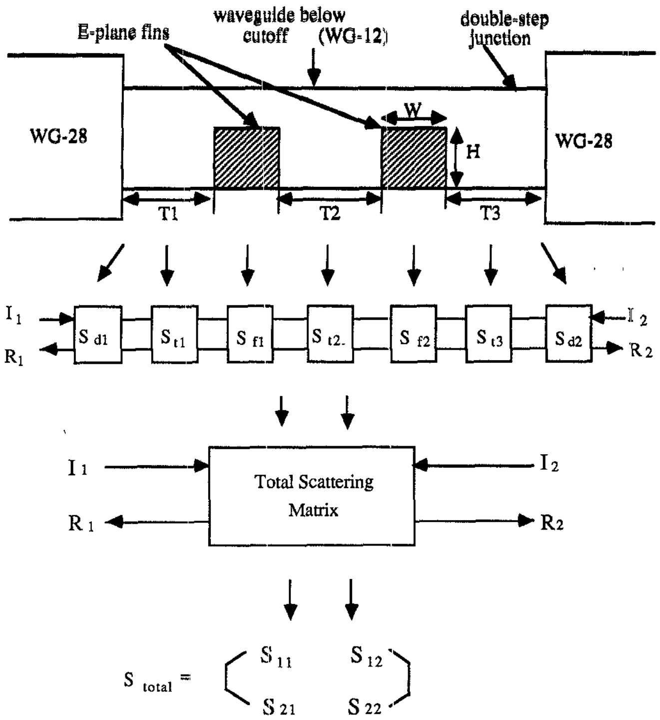


Fig. 3. The calculation of the total scattering matrix of the filter.

and the fin, and the interval between two fins. The key element for this filter structure is the nontouching E-plane fin, which is inserted in the middle of a waveguide parallel to the E-plane as shown in Fig. 2. These elements, which are responsible for the bandpass filter characteristics, act as the capacitive elements. These E-plane fins are supported by a dielectric substrate with a dielectric constant of 2.2 (Duroid substrate). The smaller rectangular waveguide shown in Fig. 2 is operated below its cutoff, so that it is an evanescent and inductive element, while the larger waveguide is operated above the cutoff frequency. The design parameters are shown in Fig. 2. In order to simplify the design problem, a symmetrical filter structure is proposed. That is, the intervals between the step discontinuity and the E-plane fin at the two sides of the smaller waveguide are the same as shown in Fig. 2 ($T1 = T3$). The two E-plane fins are also assumed to be identical. In this paper, WR-28 waveguide is used for the larger waveguide, and WR-12 is used for the smaller waveguide. Several design parameters of the filter structure are fixed from the selections of the larger waveguide and the smaller waveguide as shown in Fig. 2. Then, the determination of the remaining filter parameters, $T1$, $T2$, W, and H, is the main topic of this paper, and is explained in the following sections.

III. Calculation of the Filter Response

The design of the filter is based on the generalized scattering matrix concept, which was introduced by Mittra and Pace [6]. The filter response is calculated by obtaining the total scattering matrix of the filter structure. As the first step, the scattering matrices for the double-step junction, the nontouching E-plane fins, and the evanescent-mode waveguide sections are calculated. The scattering matrices at the step junction discontinuities are represented as S_{d1} and S_{d2}, as shown in Fig. 3. S_{f1} and S_{f2} are the scattering matrices of the two fins. The scattering matrices for the waveguide sections are S_{t1}, S_{t2}, and S_{t3}. Each matrix representing the substructure is then converted to the transfer matrix. These transfer parameters are useful in calculating the overall scattering matrix for the cascaded structures, because the output quantities of one structure become the input quantities of the following one. For a network of the type shown in Fig. 4, these parameters are defined as [7]

$$\begin{vmatrix} a_i \\ a_s \end{vmatrix} = \begin{vmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{vmatrix} \begin{vmatrix} b_s \\ b_i \end{vmatrix}. \tag{1}$$

These T parameters are not independent of the S parameters, and are expressed in terms of S parameters [7] as follows:

$$\begin{aligned} T_{11} &= 1/S_{21} \\ T_{12} &= -S_{22}/S_{21} \\ T_{21} &= S_{11}/S_{21} \\ T_{22} &= S_{12} - S_{11} * S_{22}/S_{21}. \end{aligned} \tag{2}$$

For a structure consisting of any number n of substructures, the overall T matrix is obtained by matrix multiplications as follows:

$$[T] = [T_1][T_2] \cdots [T_n]. \tag{3}$$

Then, this overall T matrix is converted to the total scattering matrix representing the filter response.

IV. Design Procedure

For a conventional method of filter design, the design parameters are obtained by the iterative use of the analysis program. Even with a computer, relying merely on repeti-

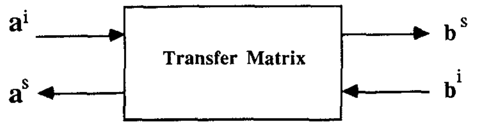


Fig. 4. Transfer parameters.

tive computations to find the optimal design parameters consumes a large amount of time. The following design algorithm reduces the portion of the work relying on repetitive computation by a considerable amount. This is partly achieved by the effective and systematic utilization of the so-called look-up table which consists of the scattering parameters from E-plane fins with different dimensions. Also, a systematic design process is conducted. The design approach is to first obtain a certain desired characteristic by choosing a certain filter element affecting that characteristic the most. Then, the other desired characteristic is obtained by adjusting the parameter which most sensitively affects that characteristic. Though each element may affect almost all filter characteristics, finding out which element is more sensitive to a certain filter characteristic reduces the complexity of the design process. Also, this leads to an effective design process.

In the following subsections, the effects of the design parameters on the filter characteristics are discussed. Also, the technique of selecting the design parameters is explained.

A. Selection of E-Plane Fins

The nontouching E-plane fins contain inductive and capacitive elements, so that they have influence on the overall filter characteristics. They are especially critical to the center frequency of the filter. By the use of the full-wave analysis program for single E-plane fins [2], the look-up table of scattering parameters from E-plane fins with different dimensions is constructed, as shown in Table I. The data in this look-up table are very accurate as they are based on the full-wave analysis. The table shows only the fin index, the dimensions of the fins, and the approximate resonant frequencies of each fin. However, in the actual look-up table structure, each fin index is linked to the scattering parameters of each fin at the sampling frequency points in the frequency range from 26.0 to 41.0 GHz. The smaller the sampling interval, the more accurate the calculated filter response. On the other hand, the computation time is increased as more sampling points are obtained. By considering these factors, a sampling interval of 0.2 GHz is chosen as a compromise between the computation time and the precision of the calculated filter characteristics. The single fins are grouped in such a way that the searching control directly reaches into a small subgroup of the data structure. For example, if the resonant frequencies of E-plane fins are between 35.0 and 35.9 GHz, the indices from 42 to 48 are assigned to the E-plane fins which form one of subsets of the fins in the Table I. Also, the single fins are arranged in order of increasing resonant frequencies, so that the look-up table structure allows an efficient and fast search for the optimal E-plane fin.

First, a systematic way of selecting fins is established by obtaining the search control parameter (RF) for the look-up table. The optimal E-plane fin is then searched in the look-up table by using this parameter. In order to obtain this control parameter, the filter responses are calculated by varying the structural parameters. From these results, a relationship between the resonant frequency of a single fin and the center frequency of the filter is obtained and is shown in Fig. 5. Next, the search control parameter, RF, which is the resonant frequency of the E-plane fin, is found from the curve fitting equation derived from the lowest graph in Fig. 5:

$$RF = 0.972 * CF + 1.628 \text{ (GHz)} \tag{4}$$

where CF is the desired center frequency. When the specific value of RF is calculated by using (4), the E-plane fin of index (I) is selected in the look-up table such that

$$RECF(I\text{-}1) < RF < RECF(I) \tag{5}$$

where $RECF$ is the approximate resonant frequency of the single fin in the look-up table, and (I) is the index of the selected fin in the look-up table. Now, let us consider why (5) is obtained. From Fig. 5, it is noticed that a certain center frequency of the designed filter is obtained by using the E-plane fin whose approximate resonant frequency is higher than the center frequency of the designed filter. By considering the design safety margin between the resonant frequency of the selected E-plane fin and the center frequency of the designed filter, (5) is obtained. As a result, the resonant frequency of the E-plane fin selected by using (5) is always higher than the value of RF.

As an example, let us consider the value of RF to be 35.4 GHz. The search then begins at the subset of the E-plane fins whose indices are from 42 to 48. According to the condition of (5), the E-plane fin of index 45 in Table I is selected. Once the fin is selected, the dimensions of the fin are found from the look-up table. If the desired filter response cannot be obtained with the present fin selection, the selection of the fin is varied systematically along the vertical line as shown in Fig. 5.

B. Selection of T1

$T1$ is the interval between the step junction discontinuity and the E-plane fin as shown in Fig. 2. The value of $T1$ mainly affects the center frequency and the ripple. As $T1$ increases, higher ripples and a higher center frequency are obtained. Also, an increase of $T1$ narrows the bandwidth. From Fig. 5, $T1$ is determined by the approximate equation depending on the selected E-plane fin with the index

TABLE I
DIMENSIONS AND APPROXIMATE RESONANT FREQUENCIES OF SINGLE *E*-PLANE FINS

Fin Index	Width (mm)	Height (mm)	Resonant freq (GHz)
1	0.600	1.450	28.10
2	0.575	1.450	28.30
3	0.550	1.450	28.39
4	0.525	1.450	28.50
5	0.500	1.450	28.70
6	0.475	1.450	28.79
7	0.450	1.450	28.90
8	0.425	1.450	29.10
9	0.400	1.450	29.30
10	0.375	1.450	29.50
11	0.350	1.450	29.70
12	0.325	1.450	29.90
13	0.300	1.450	30.10
14	0.275	1.450	30.30
15	0.250	1.450	30.50
16	0.225	1.450	30.70
17	0.210	1.450	30.90
18	0.200	1.450	31.10
19	0.950	1.300	31.30
20	0.900	1.300	31.50
21	0.850	1.300	31.70
22	0.800	1.300	31.90
23	0.775	1.300	32.10
24	0.750	1.300	32.18
25	0.725	1.300	32.30
26	0.700	1.300	32.38
27	0.650	1.300	32.50
28	0.600	1.300	32.70
29	0.575	1.300	32.90
30	0.525	1.300	33.10
31	0.500	1.300	33.30
32	0.450	1.300	33.50
33	0.425	1.300	33.70
34	0.400	1.300	33.90
35	0.375	1.300	34.10
36	0.850	1.200	34.30
37	0.825	1.200	34.50
38	0.800	1.200	34.58
39	0.775	1.200	34.70
40	0.750	1.200	34.78
41	0.700	1.200	34.90
42	0.675	1.200	35.10
43	0.625	1.200	35.30
44	0.600	1.200	35.36
45	0.575	1.200	35.50
46	0.550	1.200	35.70
47	0.525	1.200	35.78
48	0.500	1.200	35.90
49	0.450	1.200	36.10
50	0.425	1.200	36.30
51	0.950	1.100	36.50
52	0.900	1.100	36.58
53	0.850	1.100	36.70
54	0.800	1.100	36.90
55	0.750	1.100	37.10
56	0.700	1.100	37.30
57	0.400	1.155	37.50
58	0.400	1.150	37.70
59	0.350	1.150	37.90
60	0.325	1.150	38.10
61	0.300	1.150	38.30
62	0.450	1.100	38.50
63	0.425	1.100	38.70
64	0.400	1.100	38.90
65	0.350	1.100	39.10
66	0.325	1.100	39.30
67	0.300	1.100	39.50
68	0.275	1.100	39.70
69	0.250	1.100	39.90

(IU) and the desired center frequency:

$$T1 = 2.127/(RECF(IU) - 0.972 * CF - 0.5154) - 0.6121 \quad (6)$$

where CF is the desired center frequency (GHz) and $RECF$ (IU) is the resonant frequency of the selected fin.

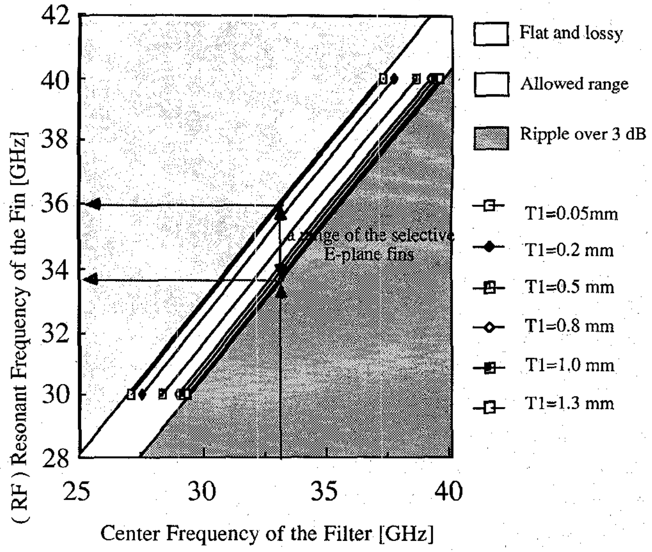


Fig. 5. Center frequency of the filter versus resonant frequency of the selected *E*-plane fin.

C. The Selection of T2

$T2$ is the interval between two E-plane fins as shown in Fig. 2. This parameter controls the magnitude of the ripple and the bandwidth. As $T2$ increases, a smaller ripple and a narrower bandwidth are obtained. As a result, an increase of $T2$ provides a trade-off between the ripple and the bandwidth. This parameter is assigned after the other design parameters are selected and is varied in discrete values in the algorithm. From the calculations using the analysis program, it has been found that there is an acceptable range of values of $T2$ in our operating frequency range of 26.0 to 41.0 GHz. $T2$ is initially set as 2.0 mm and is increased in stepwise fashion.

D. Design Algorithm

In this subsection, the design algorithm is presented. In previous subsections, the correlations between the design parameters and the characteristics of the filter have been explained. These correlations are incorporated into the algorithm routines. The techniques in selecting the design parameters, which were explained in previous subsections, are applied to the design algorithm. Since the larger waveguide and the smaller waveguide are already determined, the S parameters of the step junction discontinuity are calculated only once and are fixed for the calculation of the filter response.

The algorithm is briefly summarized in Fig. 6. The computer algorithm starts at reading the desired specifications such as the center frequency and the bandwidth of the filter. A ripple as small as possible is desired with the given specifications of the center frequency and the bandwidth. The main idea is first to choose the proper E-plane fins effectively and rapidly, so that the additional determination of $T1$ and $T2$ will complete the filter design. At this point, several aspects of the design are worth considering. As shown in Fig. 5, there is a limited range of obtainable center frequencies of the filter with the variation of $T1$ once the specific E-plane fins are selected. As an example, if the given center frequency is 33.0 GHz, the selectable range of resonant frequencies of the E-plane fins is from 33.8 to 36.0 GHz. As shown in Fig. 5, when the E-plane fin has a resonant frequency higher than 36.0 GHz, the filter characteristic is very flat. On the other hand, when the resonant frequency of the selected fin is less than 33.5 GH, the ripple becomes larger. Also, it is found that there is an obtainable range of characteristics in terms of the ripple and the bandwidth once a specific E-plane fin is selected. For example, the same center frequency can be obtained when a fin of index 22 or 23 is selected. However, the obtainable ranges of ripple and bandwidth by adjusting other parameters, such as $T1$ and $T2$, are different for E-plane fins of different index. This is explained by the fact that a smaller value of $T1$ is found with a choice of an E-plane fin of index 23 instead of 22 for the same center frequency. As a result, lower ripple can be obtained with an E-plane fin of index of 23 since the smaller value of $T1$ produces the lower ripple. Also, it is found that wider bandwidth can be obtained with increased fin index when the value of $T2$ is fixed. According to the desired center frequency, the E-plane fins are selected as described previously. Then, the center frequency is tuned closely to the desired center frequency by selecting the value of $T1$ by (6). At this point, the value of $T2$ is initialized to 2.0 mm. Once all the design parameters are selected, the total scattering parameters are calculated. The algorithm calculates the bandwidth, the ripple, and the center frequency along with the scattering parameters. At this stage, the ripple and the bandwidth might need to be adjusted. Even though the ripple can be controlled by the value of $T2$, when the selection of the fin and $T1$ falls into the wrong range, the characteristics are out of the range to satisfy the specifications. In this case, the selection of the fin is changed step by step with variations of the other parameters along the line shown in Fig. 5.

The acceptable ripple is adjusted by increasing the value of $T2$ step by step and is accomplished by loop 1 shown in Fig. 6. In this process, the variation of $T2$ hardly affects the center frequency, but as $T2$ is increased, the bandwidth narrows. Consequently, as the ripple becomes lower, the bandwidth might not be satisfied. When this process cannot satisfy the ripple and the bandwidth simultaneously, the index of the E-plane fin is increased (loop 2 and loop 3 in Fig. 6). Then, the wider bandwidth of the filter is initially obtained with the initial value of $T2$. Therefore, the increase of the fin index results in an extended range of bandwidth.

The above procedure results in a set of satisfactory design parameters which produce a filter response close to the desired one. In order to obtain the optimal design parameters, two additional design steps are incorporated. First, the number of sampling points is increased. In forming the look-up table of the scattering parameters

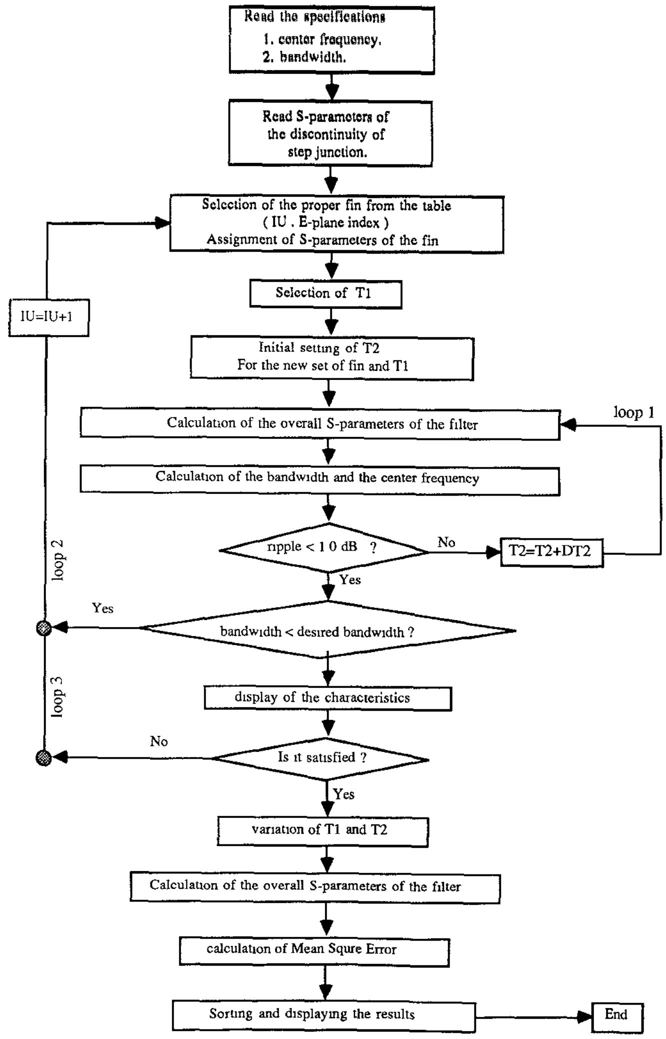


Fig. 6. Design algorithm.

from the E-plane fins, the sampling interval of the frequency is 0.2 GHz. As a result, the total scattering parameters are calculated at each of the 76 frequency sampling points from 26.0 to 41.0 GHz. This number of sampling points affects the accuracy of the center frequency and the bandwidth calculation of the designed filter. In order to increase the calculation accuracy of the filter response, interpolation by spline functions is used to increase the number of frequency sampling points [8]. The number of frequency sampling points is increased from 76 to 301, so that the frequency sampling interval is changed from 0.2 to 0.05 GHz.

Next, the design parameters $T1$ and $T2$ are changed in discrete values from the initially selected values of $T1$ and $T2$. At this stage, the selection of E-plane fins is not changed. As a result, several design parameter sets are created. The values of the mean squared error (MSE) are then calculated for the filter responses from each design parameter set:

$$MSE = \sum_{fi}^{ff} ((1.0 - S12\ (\mathbf{freq.})) * * 2.0) * WF \tag{7}$$

$$WF = (4000.0 - 800.0 * (CF - \mathbf{freq.}) * * 2.0) \tag{8}$$

where $S12$ (**freq.**) is the insertion loss at the sampling

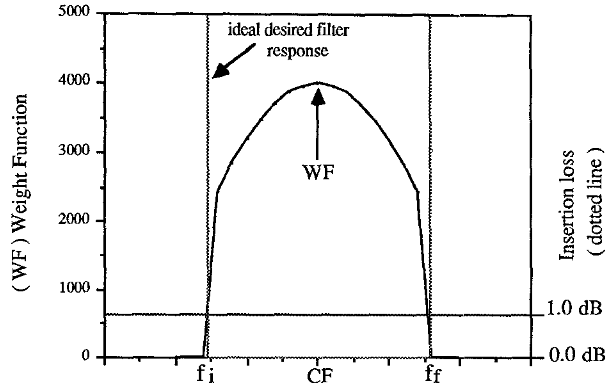
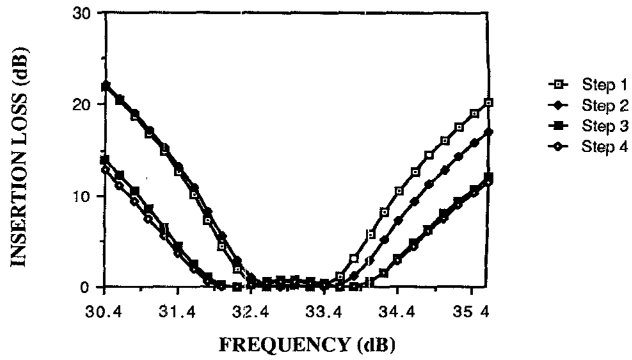


Fig. 7. Weight function.



step 1) W : 0.375 H : 1.300 T1 : 0.797 T2 : 3.500
step 2) W : 0.850 H : 1.200 T1: 0.632 T2 : 3.200
step 3) W : 0.800 H : 1.200 T1: 0.452 T2 : 2.600
step 4) W : 0.775 H : 1.200 T1: 0.396 T2 : 2.600

Fig. 8. Step changes of filter response and the design parameters.

frequency, fi is the first 1 dB point, ff is the second 1 dB point, and WF is the weight function. $S12$ (**freq.**) is the insertion loss of the obtained filter at the specified frequency, **freq**. The weight function WF is shown in Fig. 7.

The emphasis of the weight function is on the region near the center frequency. By multiplying the weight function by the MSE, the result sensitively represents the discrepancy between the calculated center frequency and the desired center frequency. Also, it reflects the discrepancy between the obtained insertion loss and the ideal insertion loss from the specifications in the range of 1.0 dB bandwidth region. The larger a ripple, the larger the value of the MSE. In (7), the insertion loss is subtracted from the insertion loss of 1.0, which assumes ideal bandpass filter characteristics in the 1.0 dB bandwidth, as shown in Fig. 7. After the values of the MSE are calculated for each design parameter set, these sets are sorted in increasing order of their values of MSE. The design parameter set with the smallest value of MSE has the closest filter response to the desired filter response, so that this design parameter set is selected as the final design.

V. Results

The design algorithm was tested with the desired center frequency of 33.0 GHz and a 1.0 dB bandwidth of 3.0 GHz. Fig. 8 shows the changes in the filter response for a few intermediate steps in the design algorithm. In each step, different parameters are selected as shown in Fig. 8. In step 1, the center frequency was near the desired center frequency while the bandwidth was narrower than the desired one. Next, by increasing the fin index and choosing corresponding values of $T1$ and $T2$, the bandwidth was consistently increased until it became close to the specified bandwidth. As the selected fins were changed, the possible range of bandwidths with a reasonable value of ripple was widened. Therefore, this algorithm selected new E-plane fins if the desired bandwidth was not obtainable with the reasonable ripple. Observing the variations of the filter responses from step 1 to step 4, we noticed that the center frequency in each step is close to the desired center frequency, 33.0 GHz. But the bandwidth and the ripple were varied in each step depending on the selected fin and the values of $T1$ and $T2$. This is from the fact that the center

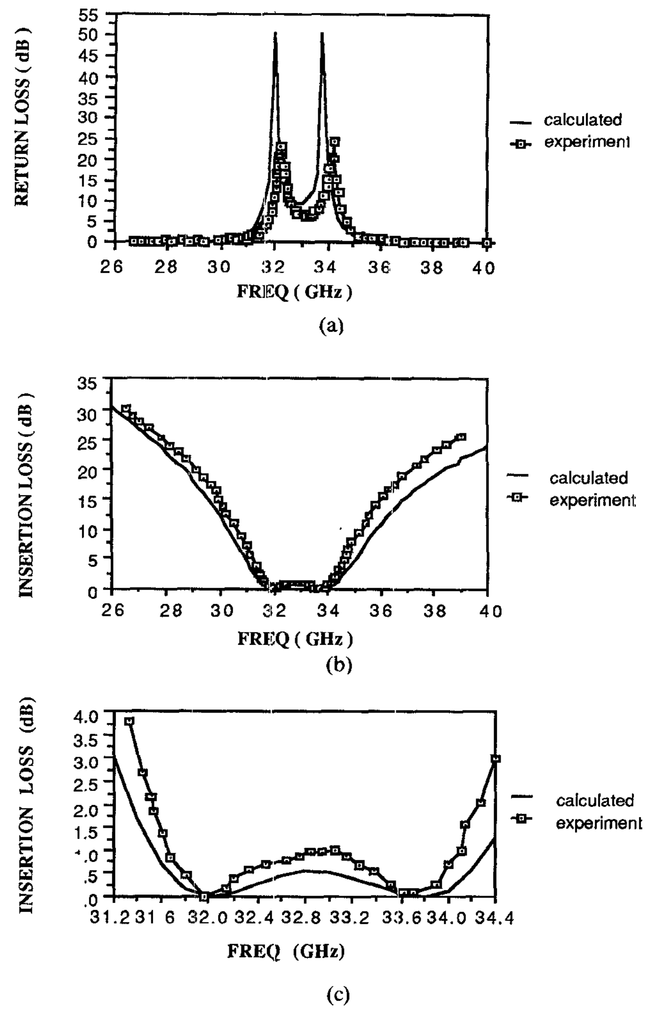


Fig. 9. Comparison between the calculated and the experimental results of the designed filter response. (a) Return loss. (b) Insertion loss. (c) Extended view of insertion loss.

frequency was first focused in this design process by choosing the right combination of the E-plane fin and $T1$. After a few steps, the final parameters are determined, and the final filter response is obtained as shown in Fig. 9. The height of the fin is 1.20 mm, and the width of the fin is 0.68 mm. The interval between the step junction discontinuity of the waveguide and the E-plane fin is 0.259 mm Also, the interval between the E-plane fins is 2.500 mm The characteristics of the evanescent mode filter constructed with these parameters have been measured. The result from the design algorithm is compared and verified with the experimental result, as shown in Fig. 9. The calculated center frequency of the designed filter is 32.9 GHz and the experimental value is 32.8 GHz. The calculated filter bandwidth is 2.90 GHz, and the experimental value is 2.80 GHz. It is observed that the given specifications are satisfied by the calculated filter characteristics, and the design is verified by the experimental results of the designed filter.

VI. Conclusion

In this paper, a design algorithm for the evanescent mode waveguide bandpass filter with nontouching E-plane fins has been presented. This algorithm is not a conventional optimization algorithm, which depends mainly on repetitive computations for obtaining the design parameters. This algorithm is based on the effective and systematic utilization of a look-up table of the scattering parameters from the E-plane fins. Also, it incorporates the correlations between the design parameters and the characteristics of the filter into the routines. By using this algorithm, all the filter parameters are directly obtained from the given specifications of the center frequency and the bandwidth of the filters. This algorithm is verified by comparing the characteristics of the designed filter with the experimental results. The characteristics of the designed filter are satisfied with the given specifications.

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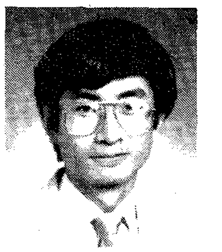

Keon-Shik Kong (S'88) was born in Seoul, Korea, on January 27, 1964. He received the B.S. and M.S. degrees in electrical and computer engineering from the University of Texas at Austin in December 1986 and December 1988, respectively. He is currently working toward the Ph.D. degree at the University of Texas at Austin. His current research deals with the application of superconductors in microwave circuits. In 1985, he obtained the Engineering Scholar Award from General Dynamics.

Mr. Kong is the member of Tau Beta Pi and Eta Kappa Nu.

Tasuo Itoh (S'69–M'69–SM'74–F'82) received the Ph.D. degree in electrical engineering from the University of Illinois, Urbana, in 1969.

From September 1966 to April 1976, he was with the Electrical Engineering Department, University of Illinois. From April 1976 to August 1977, he was a Senior Research Engineer in the Radio Physics Laboratory, SRI International, Menlo Park, CA. From August 1977 to June 1978, he was an Associate Professor at the University of Kentucky, Lexington. In July 1978, he joined the faculty at the University of Texas at Austin, where he is now a Professor of Electrical Engineering and Director of the Electrical Engineering Research Laboratory. During the summer of 1979, he was a guest researcher at AEG-Telefunken, Ulm, West Germany. Since September 1983, he has held the Hayden Head Centennial Professorship of Engineering at the University of Texas. In September 1984, he was appointed Associate Chairman for Research and Planning of the Electrical and Computer Engineering Department. He also holds an Honorary Visiting Professorship at the Nanjing Institute of Technology, China.

Dr. Itoh is a member of Sigma Xi and of the Institute of Electronics and Communication Engineers of Japan. He is a member of Commission B and Chairman of Commission D of USNC/URSI. He served as the Editor of the IEEE Transactions on Microwave Theory and Techniques during the years 1983–1985. He serves on the Administrative Committee of the IEEE Microwave Theory and Techniques Society. Dr. Itoh is a Professional Engineer registered in the state of Texas.