A Design Procedure for Bandstop Filters in Waveguides Supporting Multiple Propagating Modes

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***Abstract*—A design procedure for bandstop filters in waveguides supporting multiple propagating modes is presented in this paper. The method utilizes a cascade arrangement of resonant "block structures" to stop propagation of a number of modes across a specific band. These filters find particular application in dielectric heating facilities. The design is a two-step process: first, all the necessary block structures are assembled, and then they are cascaded to realize an optimally small filter that fulfills specifications. Two examples of designed filters are discussed. Both achieve better than 40-dB attenuation over a 5% bandwidth in the presence of five propagating modes. The measured results of one filter, realized at 19.1 GHz in WR-90, are shown to agree well with the predicted performance from the mode-matching-based analysis technique.**

***Index Terms*—CAD, multimode filters, waveguide.**

I. INTRODUCTION

DESIGN algorithms for single-mode waveguide filters have been in existence for decades, and can be regarded as a mature field of study. Recently, however, developments in commercial microwave applications, such as dielectric heating, have posed new problems, specifically in the design of filters in waveguides supporting multiple propagating modes. In these applications, conveyor belts passing through a microwave heating cavity enforce permanent large openings in the cavity sidewalls, through which dangerous levels of microwave energy can escape if not filtered. The minimum size of the input and output guides are limited by the objects that will pass through the cavity, and are not under control of the designer.

Single-mode waveguide filters rely on the modeling of some arbitrary waveguide discontinuity, illuminated by one propagating mode, as a lumped reactive circuit element, with the reactive energy stored in nonpropagating modes scattered by the discontinuity. This approach fails in the multimode environment for a number of reasons. First, because of differences in field patterns, other propagating modes will not react to the discontinuity in the same way and, therefore, will not have the same equivalent circuit. Second, some of those modes that once served to store reactive energy may now be propagating, and cause even the circuit model for the single-mode excitation to be inaccurate. Finally, cross coupling between modes at discontinuities will cause a movement of energy between the modes throughout the filter structure, resulting in a complicated response that becomes as much a function of how the filter is excited, in terms of modes, as the actual filter specification.

Solutions for microwave dielectric heating applications are limited to absorbing materials on the inside waveguide walls or empirical design strategies, both having serious drawbacks; such as heat dissipation in the first case, and the need to start each design from scratch in the second case. At present, no systematic synthesis procedure exists for the design of these filters.

This paper presents for the first time a systematic method of designing stopband filters in the multimode environment. Although the method is capable of realizing a separate bandstop filter for each mode at any frequency, the examples presented here are designed to stop propagation of all modes across the same band.

In principle, the design cascades a number of resonant "block structures," with each structure responsible for a propagation null at some frequency in the band for one or more modes. There are two steps to the design. First, the necessary block structures must be found and the zeros placed at the right frequencies, then the structures must be cascaded correctly to ensure the shortest possible filter that fulfills specifications. The second step is ideally suited to a genetic algorithm, though a very fast iterative process was also developed. All analyses are performed using the mode-matching method, which is ideally suited to this problem and is very well established in the literature [1]–[4].

This paper will start by introducing the prototype filter structure and give a very brief overview of its operation. Both steps of the design will then be dealt with in detail. Finally, this paper will deal with the construction and measurement of a filter designed to stop all five propagating modes over a 5% bandwidth around 19.1 GHz in WR-90, and compare it with predicted performance.

II. BASIC FILTER STRUCTURE

The major factor governing the shape of these filters is cross coupling between modes at discontinuities. Designing a bandstop filter under such circumstances is highly problematic, as a discontinuity that creates a null for one mode will excite a number of other modes at the same frequency. Investigation showed that cross coupling between modes of different propagation constants could be greatly reduced by using symmetrical

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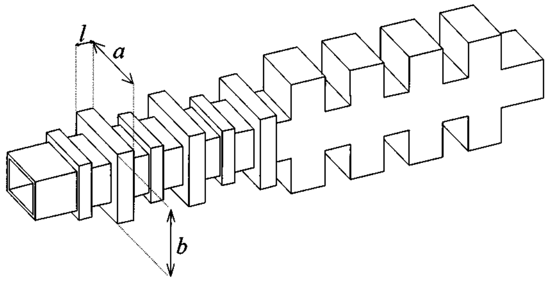

Fig. 1. Typical filter structure, serving as a bandstop filter for $\mathrm{TE}_{10,20,01,11}$ and TM_{11} modes.

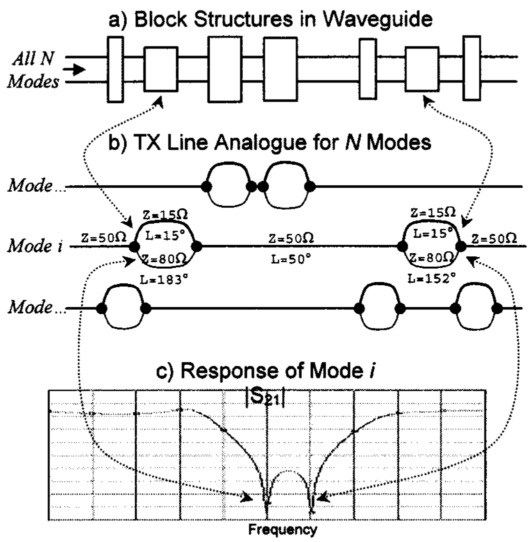

Fig. 2. Circuit analog of the filter's operation.

discontinuities consisting of back-to-back waveguide steps separated by lengths of uniform guide. When the steps are chosen to enlarge the waveguide, they form block structures, which, if chosen correctly, can cause a null in propagation and unity reflection in the multimode environment. A cascade of these structures, each resonant at a different frequency, can build up a stopband whose attenuation is dependent on the number of structures used. An example of such a structure for five propagating modes is shown in Fig. 1. An important advantage of this structure is that it does not obstruct the interior of the waveguide. This is most useful in microwave dielectric heating applications, where such an all stop filter is required to act as a choke.

Given the correct block topologies, there will be minimal cross coupling between modes of different propagation constant. The design can thus be described by using a circuit analog, such as is shown in Fig. 2.

Each transmission-line system corresponds to a mode (modes with the same propagation constant, e.g., TE_{11} and TM_{11} often cross couple unavoidably and are grouped together). Incident energy which is not reflected will be split between the two lines depending on their impedance relationships. If the line lengths can be chosen correctly at the right frequency, they will cause the energy to recombine destructively at the other end, leading to a zero in $|S_{21}|$ of the structure for a specific frequency. In the case of multimode waveguide, however, the two transmission lines are actually two propagating modes in the enlarged waveguide, and the energy is scattered to both modes at the waveguide step that initiates the block structure. The different line lengths are accomplished by using two modes with different propagation constants in the same length of enlarged waveguide. Since the dimensions of the waveguide step determine both how the energy is split between the two carriers and what their propagation constants are, and the length of the enlarged guide sets the path length that the modes must travel before recombining, it is clear that the performance of the block depends on a rather complex relationship between dimensions. Section III will show how these structures can be found and selected to reduce physical size and/or dependence on tight manufacturing tolerances.

The cascading of these blocks is the second aspect of design. In the electrical problem of Fig. 2, the length between the two sections was chosen to minimize propagation in the center of the band. The required length is easy to calculate from the properties of the two block structures and the propagation constant in the connecting line. In the multimode environment, all four systems shown in this figure would share the same physical guide space. This greatly complicates the cascading operation for a number of reasons, but also provides opportunities to reduce the filter size and even to improve its performance. This operation will be detailed later.

III. Design Stage I—Finding the Block Structures

The purpose of each block structure is to provide a transmission null for at least one mode at a specific frequency. For small cross coupling, only symmetrical single- or double-plane back-to-back waveguide steps, centered in the middle of the primary waveguide, are considered. The geometry of a typical block can then be described with three variables: a, b, and l, as indicated in Fig. 1. Blocks at different resonant frequencies are cascaded to generate, for instance, a Chebyshev distribution of transmission nulls for each mode. Two methods for finding suitable blocks are presented.

A. Method 1—Grid Search Method

Since the block structure is described by only three variables, it is quite possible to use a constrained grid search method. It should be noted that large cross-sectional dimensions often result in multiple resonances in the band, which could make for a shorter filter, but will complicate the cascading process. The search typically results in clouds of viable geometries for each mode. An example for the TE_{10} mode in WR-90 at 19.1 GHz is shown in Fig. 3.

Ideally, the block would be chosen to be as short as possible, though it is clear that a high sensitivity to the height dimension results from such a choice. At the cost of increased block length, a better choice would be a geometry from higher up on the map, where the gradient in terms of the b dimension flattens out somewhat. Also, a general petering out of viable geometries as the a-dimension increases, indicates areas where the propagation zero might not be well defined, or the rolloff might be too sharp or jagged and, thus, not particularly suited for the stopband filter. More useful geometries can often be found in denser areas.

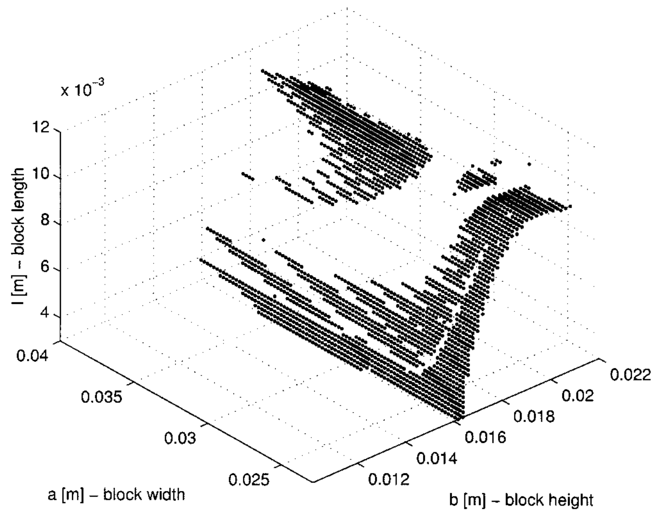

Fig. 3. Map of viable geometries for TE_{10} in WR-90 at 19.1 GHz.

One other important use of the map is to identify blocks that can serve more than one mode simultaneously, reducing the number of blocks and the size of filter greatly. This can be accomplished by superimposing two maps over each other and selecting geometries where the two maps overlap or come close to each other. All the designs presented here use some blocks that exhibit this property. Of course, this practice complicates the cascading process somewhat, as two such blocks can seldom be placed a distance apart from each other that favors all the resonant modes by reducing propagating between the nulls, as is desired.

B. Method 2—Coupling Matrix Method

The principle of destructive signal recombination described above can be used to derive a more elegant alternative method of designing the block structures. This method is based on an observation that the incident energy from the primary waveguide should split roughly evenly between only two modes in the block for optimum cancellation. The higher of these two modes can be either propagating or evanescent.

To find geometries that accomplish such a split, the frequency independent coupling matrix $[W]$ matrix is used [4]. This matrix is generated in during the mode-matching analysis of a waveguide step and relates the spatial correspondence of different modes on both sides of the step, with a large value of $W(m,n)$ indicating a strong spatial correspondence between mode m in the larger guide and mode n in the smaller guide. Each element of $[W]$ is only dependent on the cross-sectional dimensions, and can be calculated by

$$W(n,m) = \int_{s_B}\int \left(\bar{e}_m^B \times \bar{h}_n^A\right) \cdot d\hat{z}. \tag{1}$$

Here, the e and h vectors correspond to the normalized nonfrequency-dependent spatial E- and H-field patterns on different sides of the step, z is the direction of propagation, and A and B designate the larger and smaller guides, respectively.

Assuming now that it is desired to stop mode m in waveguide B, a number of the columns $W(i,m)$ are computed for a number of modes in the larger guide i for a sweep of the variables a and b. $W(m,m)$ is typically large, and the aim is to find a cross section (a,b) for which all other values are small, except for one other mode $i=j$. A figure-of-merit for rating various geometries is shown in

$$R_{mj}(a,b) = |\alpha_m|W_{ab}(m,m)| - \alpha_j|W_{ab}(j,m)|| + \sum_{i=1, i\notin(m,j)}^{N} \alpha_i|W_{ab}(i,m)|. \tag{2}$$

Here, $[W_{ab}]$ is the coupling matrix for a specific step geometry a and b and N is a large integer. α_x is a constant determined by the attenuation of mode x in the large guide at the design frequency over a length of the order of the smaller guide's dimensions (the exact length is not crucial, as long as it is within a factor of ten of the eventual length). Its purpose is to eliminate the effect of nonpropagating modes that would not have a strong influence over the length of the guide. Note that modes with the same propagation constant $j=k$ and $j=k'$ must be grouped together by adding their $W(k',m)$ and $W(k,m)$ values. For a sweep of values a and b, R can be computed very quickly. Lower values of R_{mj} indicate good geometries for resonance due to the interaction of modes m and j. Fig. 4(bottom) shows a landscape plot of R for creating a null in mode TE_{20} with the aid of modes $\mathrm{TE/TM}_{22}$, where the higher points correspond to geometries that will not lead to a resonance for that mode at any frequency, and the lowest points correspond to the most probable resonant geometries. Once a cross section is determined, the length of the block can be calculated by iteration from a starting value that causes modes m and j to fall 180° out of phase.

Fig. 4(top) shows a flattened version of the map, with the l-dimension removed, produced by the grid search method to illustrate how the two methods lead to the same viable values of a and b. Close inspection of Fig. 4(bottom) shows that resonances reported by the grid search method concur with values of R below some critical value, i.e., normally around 0.7. Note that the coupling matrix method works over a rather large band of frequencies, implying that block structures for a particular mode will generally be of the same shape. Choosing geometries that correspond to low values from Fig. 4(bottom) will, therefore, lead to good resonant blocks.

Since computation of the $[W]$ matrix involves no matrix inversion or frequency dependence, this second method is much quicker than the grid search method.

IV. Design II—Cascading the Block Structures

The block structures from stage I can be cascaded in a number of ways to form a filter. Two proven approaches are presented here. The first uses approximated design rules based on the s-parameters of the individual blocks, to calculate the required length between resonant or adjacent blocks. The second allows the entire filter structure to evolve from simple one- or two-block structure configurations using a genetic algorithm.

A. Design Method 1—Tree Search Method

Assuming that cross coupling is typically limited to modes with the same propagation constant, and that blocks that do not

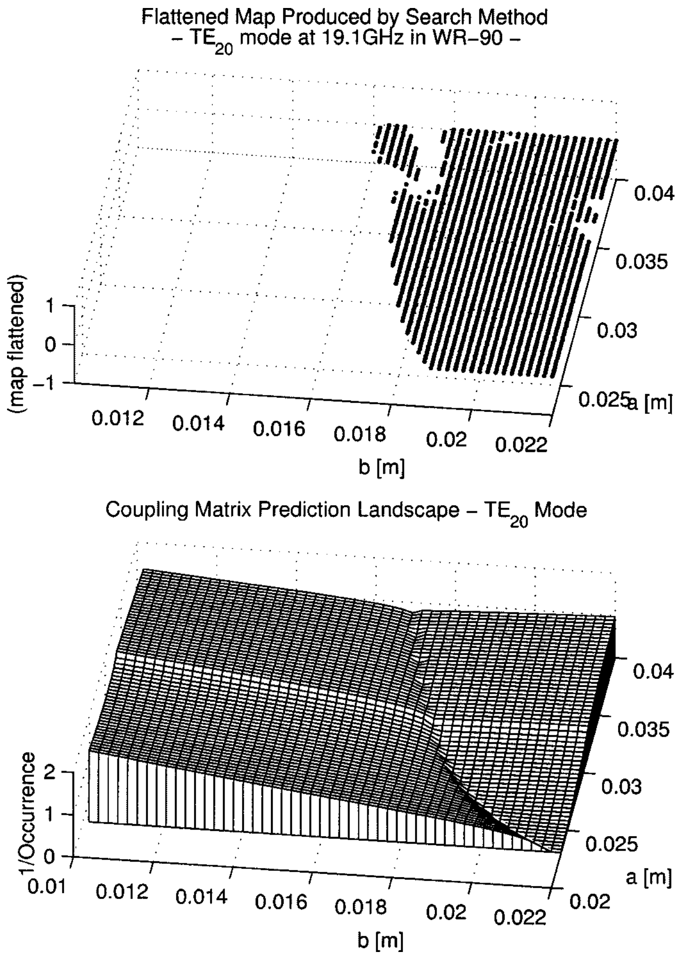

Fig. 4. Plot of the rating function for the TE_{20} mode with geometries found with the grid search.

resonate for a particular mode do little to affect its propagation beyond a phase change and a slight attenuation, it is possible to specify the ideal electrical distances between block structures resonant for a particular mode. The s_{21}-parameter of mode m of a cascade of two block structures A and B, may be calculated from the individual block S-matrices for mode m

$$s_{21} = \frac{S_{21}^A S_{21}^B e^{j\theta}}{1 - S_{22}^A S_{11}^B e^{j2\theta}}, \qquad \theta = -\beta \cdot l_{AB} \tag{3}$$

where β is the propagation constant of mode m in the connecting guide and l_{AB} is the total length of connecting guide that separates the two blocks. As the aim is to minimize $|s_{21}|$, a first design condition can be stated as follows

$$\text{Condition 1:} \quad \text{angle}\left(S_{22}^A S_{11}^B e^{j2\theta}\right) = \pi.$$

This condition forms the basis of calculating l_{AB}, and always applies between two blocks, which resonate for the same mode, even if they are separated by other structures that are not resonant for that mode. In such cases, the equivalent electrical length of the interposing block(s) is calculated by summing the angles of s_{21} of the individual block(s) for the mode in question. In the case of modes that exhibit cross coupling, this formula, though

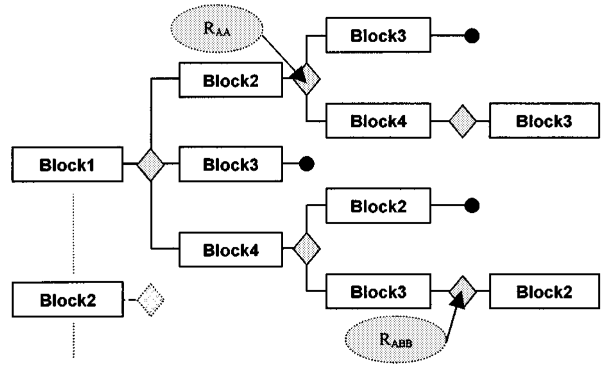

Fig. 5. Tree search algorithm for four blocks.

not strictly accurate, is still usable and provides a good idea of the necessary length.

In addition to the above procedure, a minimum separation distance can be determined. When adjacent blocks are placed too closely together, nonpropagating modes excited at the block edges by a resonant mode may not be attenuated enough over the short length of connecting guide and can interact with the adjacent block, often causing undesired results. The following second condition, therefore, has to be adhered to:

$$\text{Condition 2:} \quad \exp\left(-\alpha_i l_{AB}\right) \ll 1\big).$$

Here, α_i is the attenuation of any nonpropagating mode excited by block A or B. Ensuring that this value remains below about 0.2 for strongly excited nonpropagating modes will work well for most designs.

When blocks for a specific mode are cascaded according to condition 1, long sections of guide are typically left between blocks. These sections could be used to house a resonant block of another mode without seriously affecting the filter performance, reducing the sizes of most filters by more than one-half. Filter size can also be reduced by using one block to generate a transmission null for two modes. Implementing these refinements does, however, make it extremely difficult to find a final configuration of blocks that obeys both conditions well.

While it is possible to use the design rules to build up a filter by hand, it can become quite time consuming. It seldom assures a particularly short filter and can become completely unworkable if the number of blocks is very large. The problem can be solved by machine with the use of a recursive tree search algorithm. Fig. 5 illustrates its operation in the search for viable filter configurations with four blocks. A particular instance of the algorithm $R_{xx\ldots}$ is given the existing filter structure and the remaining blocks to cascade it then uses the conditions described above to assess the viability of cascading each available block structure with the existing series of cascaded blocks. If a block can be cascaded, the optimal cascading length is calculated, and the new block is incorporated in an updated structure, which is passed to a new instance of the algorithm, with one less available block structure to cascade. A short description of the algorithm is listed.

0 . Initiate Algorithm—Recall available blocks and current (partial) filter structure.

1 . Loop over all available blocks $(k = 1, \ldots, N)$.
- 1a . Find required cascading length of block k from current structure according to cascading criteria.
- 1b . If required length is too short or long, or if there are seriously conflicting requirements from different modes, skip to next available block (Step 2).
- 1c . Otherwise place block at the optimal cascading length to create a new (partial) filter structure.
- 1d . If $N = 1$ (the last block has been placed), save new structure as a viable configuration.
- 1e . Otherwise, call a new instance of the algorithm with the new structure, and block k removed from the available block list.

2 . Move on to next available block—return to step 1.

The algorithm above executes extremely quickly as it does not have to do any intense numerical work or work with all the permutations of possible block configurations. It builds up viable configurations in a branch-like fashion, rejecting at an early stage in its development any configuration that is not usable (—●). The shortest viable configurations are then optimized and the best one selected. Optimization can be easily and quickly performed, as the full s-parameters of the blocks are already known.

B. Design Method 2—Genetic Algorithm

The problem of finding a good configuration of block structures is an ideal challenge for an evolutionary approach. The main reason for this is the ability for the complexity of the members of the sample population to be increased by adding more blocks to certain individuals. If the genetic algorithm itself is allowed to do this, it will favor increasing complexity at the cost of length, provided performance is enhanced. Furthermore, the typical challenges of genetic algorithms, namely that of modeling reproduction and competition in a meaningful way, is relatively easy to accomplish with this problem.

Since the performance of a specific configuration is dependent on part or parts of its structure, general good qualities of a population member will proliferate if, in reproduction, segments of its structure are combined with other structures to produce the new structure. Simple replication of a structure with some changes is also viable. The code that was implemented used a combination of both approaches to produce new structures. The single replication approach allowed either addition of a new block (from a pool of available blocks), subtraction of a block from its configuration, changing of lengths between blocks, and the swapping of blocks in a specific configuration. This type of reproduction was favored in the initial stages of the evolution, while the structures described by the configuration were still quite small and simple. In later stages, reproduction favored the combination of two random parent configurations with parts of their structures combined with minor random changes in certain lengths.

Competition between members of the population was accomplished by pairing random configurations and eliminating the one whose peak $|S_{21}|$ over all the modes and all the frequencies was the highest. Competitors with similar performance were

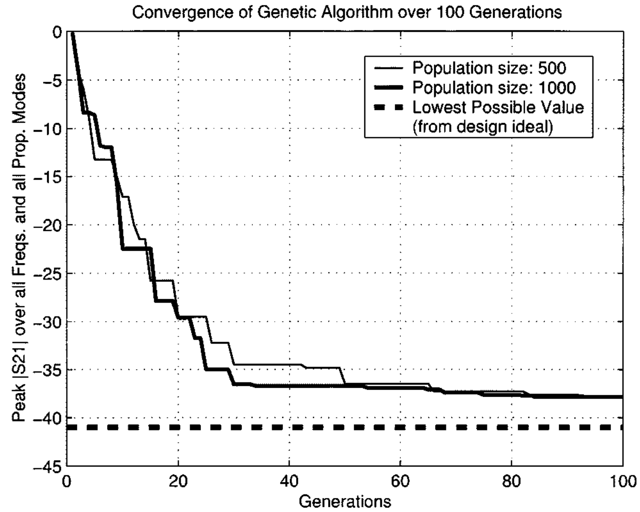

Fig. 6. Performance of the genetic algorithm.

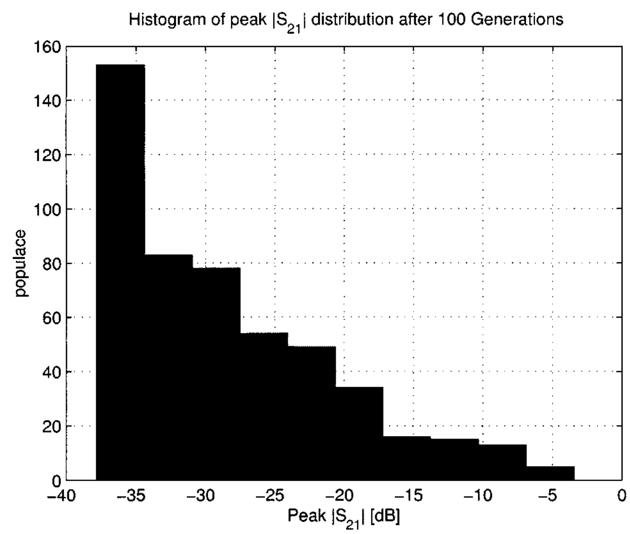

Fig. 7. Peak $|S_{21}|$ distribution.

chosen instead on the basis of their total physical length in order to encourage the evolution of short filters.

The algorithm was successfully used to generate alternative designs for the 19.1-GHz example filter to be presented in the following section. Fig. 6 shows a plot of the peak $|S_{21}|$ over all frequencies and propagating modes of the best member of the population for each generation. Considering that the lowest possible value is −41 dB, the fact that the genetic algorithm reaches this value to within only a few decibels before leveling off confirms its suitability for this problem.

Fig. 7 is a histogram of the peak $|S_{21}|$ distribution over the best 500 members of the 1000 strong populace after 100 generations. Clearly, most of the filters/populace have evolved to yield a peak value of close to −40 dB at this time. Fig. 8 is a histogram of total filter length distribution after 100 generations. Most filters have settled to a length around 110 mm, which is the same length as that of the example filter of the following section, which was designed using the nonevolutionary

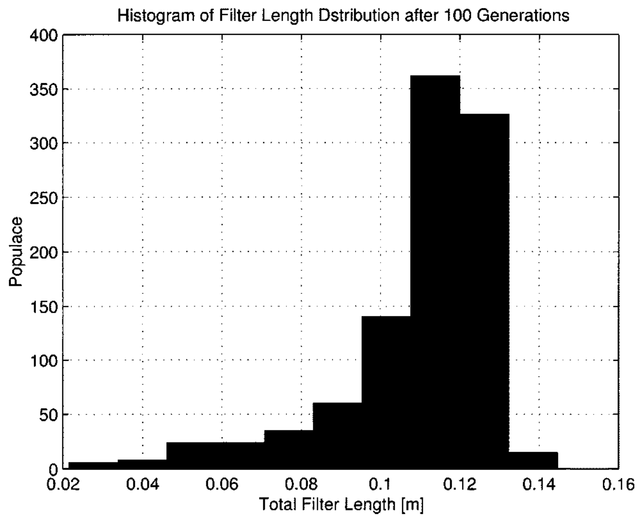

Fig. 8. Total filter length distribution.

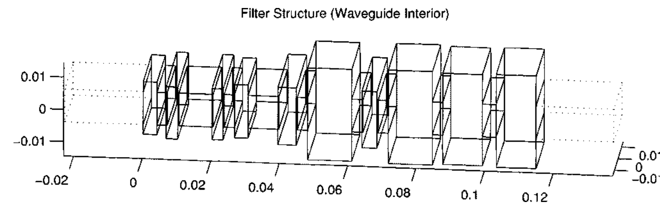

Fig. 9. 19.1-GHz filter physical structure.

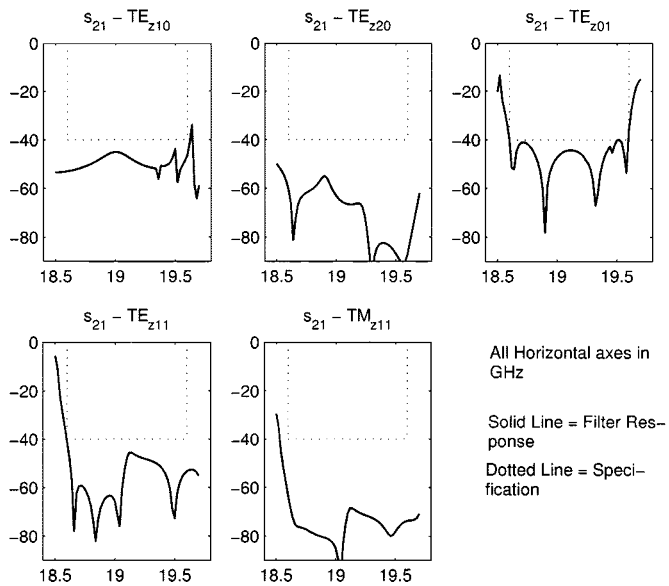

Fig. 10. Simulated $|S_{21}|$ for all modes.

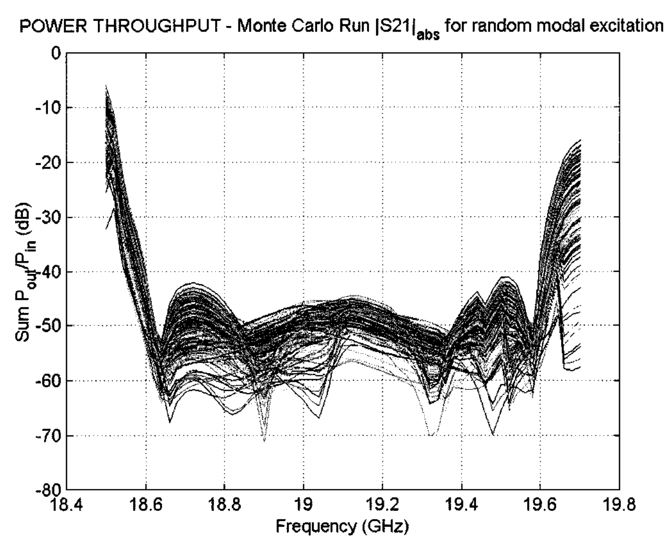

Fig. 11. Worst-case power transmission.

methods discussed above with exactly the same blocks and specifications.

In this simplified algorithm, no rules were used to determine the lengths between adjacent blocks (this was purely random) with such measures, as well as a reproductive system that looks more closely at what aspects of the structure are favorable and actively pursues in maintaining them, the algorithm would converge faster and to a better value. Once again, optimization can be used on the suggested configurations to reach specifications, and this is again to a small degree as the suggested structures perform well from the start.

Another aspect of genetic algorithm's flexibility can be used to great advantage here. The pool of available structures need not only be limited to those that are required for the filter to just reach specification. More blocks, with transmission zeros at different frequencies, can be included with a strong penalty for total structure length, and the algorithm can be used to decide which blocks to use and which to ignore. Another enhancement is to include smaller block structures whose only purpose is to provide phase lag or lead to certain modes. Such structures, if perceived as advantageous, would then be incorporated in the populace.

The cost of the genetic algorithm approach is increased design time since each new member must be analyzed with the generalized scattering matrix formulation. Fortunately, the blocks are already analyzed, thus, all that has to be done is to cascade them according to the specified block configuration. The total execution time of the genetic algorithm is no more than a few hours.

V. Predicted and Measured Results of a Sample Filter

The technique was used to design a filter at 2.45 GHz, shown in Fig. 1, with an attenuation of better than 40 dB over a 5% bandwidth in a guide of cross-sectional dimension, 150 mm $\times$ 100 mm, which supports five propagating modes at the design frequency.

In order to verify the analysis and design techniques, a scaled down version, shown in Fig. 9, was redesigned at 19.1 GHz in WR-90 with the same specifications and number of propagating modes. Fig. 10 shows the simulated transmission parameter of each mode, while Fig. 11 is a simulated graph of the performance as measured in terms of the ratio of total output power to total input power for a number of random incident modal excitations, shown in a Monte Carlo plot. This analysis assumes that incident power will be distributed in an unknown fashion between the modes—the worst-case distribution provides an upper boundary of the plot and gives an idea of the maximum power

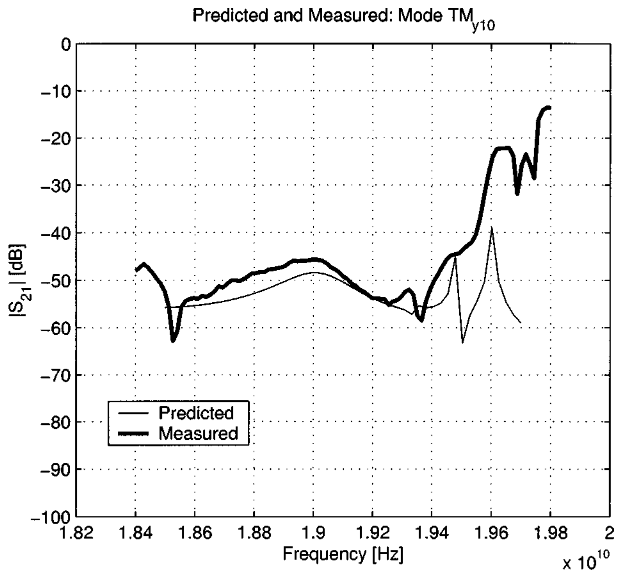

Fig. 12. $|S_{21}|$-mode TM_{y10}—measured.

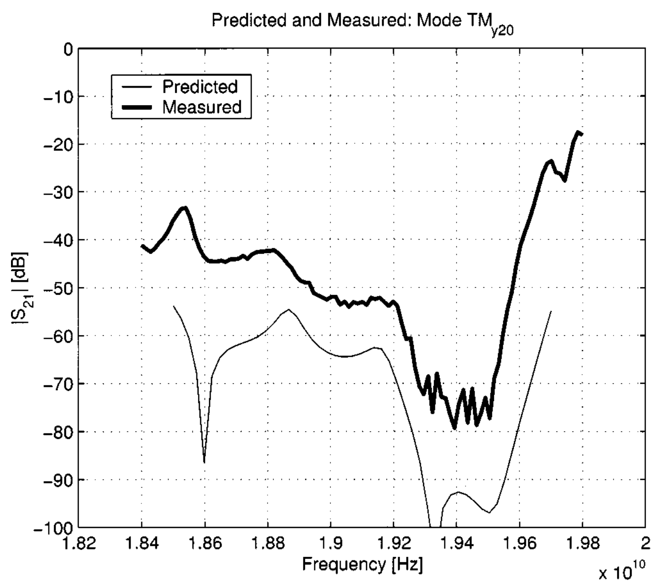

Fig. 13. $|S_{21}|$-mode TM_{y20}—measured.

that will be allowed to propagate through the filter under the worst conditions.

The measurement of these filters are by no means trivial, due to the number of propagating modes. For instance, finding the scattering matrix of the embedding network, consisting of a simple coaxial to waveguide transition, entails the determination of a 6 $\times$ 6 complex matrix containing 21 different values. When this is viewed against the single-mode case, where only three separate values need to be determined, the magnitude of the problem becomes clear. In addition, due to the stopband nature of the filter, both the well-known k-spectrometer [5] and far-field radiation pattern [6] methods for measuring modal content cannot be used, as the amplitudes of the modes exiting the filter is very small.

A completely new measuring procedure was, therefore, designed, using small probe coupling into waveguides terminated at one end. This makes it possible to approximate the embedding

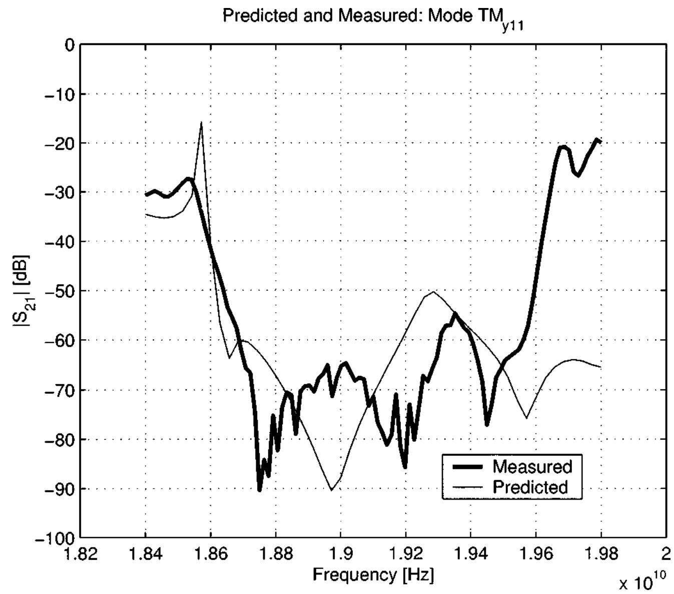

Fig. 14. $|S_{21}|$-mode TM_{y11}—measured.

matrices by only a few terms, equal to the number of modes that are excited, which can be characterized by the same number of through measurements. When the device-under-test (DUT) is also measured in cascade with a number of lengths of waveguide, the transmission parameter for each mode can be extracted. Note that this is an approximate measurement, but large numbers of statistical analysis of the method showed it to be accurate down to 60 dB, as long as the loads terminating the feeding guides show reflections of less than 30 dB to the main guide, for all modes. A detailed description of the underlying theory is unfortunately beyond the scope of this paper, but it will be presented in a separate paper.

The measured results for the TM_{y10}, TM_{y20}, and TM_{y11} modes for this filter are shown in Figs. 12–14, together with the predicted responses. These three modes are excited by simple probe coupling and are, therefore, the easiest to measure. To measure the two other TE_y modes, aperture coupling should be used. It is clear that the transmission parameters are all below -40 dB across the band, with good comparison to the predicted results in most cases.

VI. Conclusion

This paper has introduced a new method of designing multimode bandstop filters in oversize waveguide. The design uses multiple resonant block structures that stop propagation of one or more modes at a particular frequency in the band, and cascades them to build up the entire desired stopband. The filters are particularly suited to applications where the interior of the waveguide cannot be obstructed by, for example, pins or septa, such as would be required of a choke for microwave dielectric heating applications.

Two design aspects were identified. The first involves finding the required block structures. Two methods, one based on a grid search and one based on knowledge of the block's operation, were detailed and their results compared. The second design aspect involves cascading the block structures to yield a short, but workable filter. Once again, two methods were proposed. The first uses a recursive algorithm that builds up viable configurations using simple design conditions. The second uses a genetic algorithm that evolves a population of filters from simple one- or two-block structures to complex N-block structures that strive to fulfill the filter specifications. The methods were compared and evaluated in terms of execution time and flexibility.

Finally, two filters designed and constructed to test the analysis and design principles were measured and found to agree, within the limitations of the measurement method, with the predicted results.

Further research will examine the genetic algorithm approach more closely and attempt other types of filters using the same approach.

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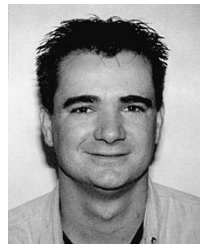

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