On the design of waveguide devices using multiple propagating modes

Petrie Meyer[1], Christopher A Vale[1], Werner Steyn[1]

Abstract - **This paper presents a number of strategies which can be used when designing waveguide devices with multiple propagating modes. Three types of devices are discussed by way of example, namely bandstop filters for microwave heating applications, narrow band coupled resonator filters, and rectangular monopulse feeds.**

Keywords - **Waveguide, modes, bandstop filter, monopulse feed**

I. INTRODUCTION

Multiple modes exist on all guiding structures, but dimensions are normally chosen in such a way that all except one of these modes are below cut-off, as most design algorithms are based on single-mode transmission line models. A number of applications where multiple propagating modes were not only allowed, but used to good effect, have however been proposed through the years. Examples of this include the use of dual and triple mode cavities to reduce the size of waveguide filters [1,2,3], the improvement of aperture distributions in antenna feeds for reflector type antennas [4,5], and more recently, the shaping of power distributions in waveguides for spatial amplifier applications [6,7]. Multiple propagating modes have also been utilized effectively to implement complicated designs elegantly, such as cross-coupled filters. Finally, the dimensions of a given problem are not always under the control of the designer, forcing him to deal with these modes.

The design of devices utilizing multiple propagating modes are complicated by a few problems. In general, a typical discontinuity separating two waveguides A and B is represented by an nxm port scattering matrix, which can be implemented as the equivalent circuit shown in Fig. 1 [8]. Here, W(n,m) represents a transformer ratio directly linked to the mode-matching method, and $Z_A(n)$ and $Z_B(m)$ the impedance of modes *n* and *m* in waveguides *A* and *B* respectively. In the case of single-mode propagation, only two of the terminating impedances are replaced by ports, resulting in a standard two-port network. All the other impedances are imaginary, and can be lumped together in one frequency dependant reactive element. For design purposes however, models that contain elements with non-linear frequency dependencies are virtually useless. In practice, the model in Fig. 1 is approximated for a specific structure and frequency range, by a few ideal elements like inductors, capacitors and sections of transmission line. This approach is inherently narrowband and approximate, although excellent models do exist.

In the case of multiple propagating modes, the equivalent circuit is a multiport system with each mode represented by one port, and all the ports linked together through a complicated circuit. With the exception of the even and odd mode analysis which can be used for the two mode case, no formal synthesis techniques exist for cascaded n-ports. Also, general optimization techniques have great difficulty with these structures, as one dimensional change normally affects a number of output parameters, some positively and others negatively.

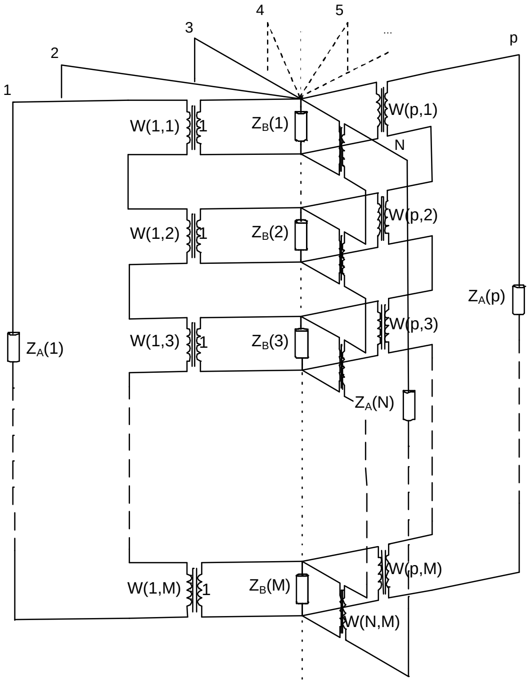

Figure 1: Circuit model of a general waveguide discontinuity

This paper will present a number of techniques that have been developed by the authors over the past few years to approach the design problem of devices with multiple propagating modes. The techniques are mostly a combination of synthesis and intelligent optimisation, and rely on the careful choice of structures (called functional blocks) which contain a limited modal set, and can be cascaded to produce a required characteristic. These choices require good knowledge of the field patterns in different structures, and are very important, as they are normally under the control of the designer, and as the wrong choices result in building blocks which are just too complicated to use.

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[1] Authors are with the Department of Electrical and Electronic Engineering, University of Stellenbosch, Private Bag X1, Matieland, 7602, South Africa, Email: pmeyer@sun.ac.za

II. Bandstop Filters for Microwave Heating Applications [9]

A. Introduction

In many microwave heating facilities, 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. A typical system is shown in Fig. 2. The solution to this problem is the placement of ‘chokes’ on either side of the cavity to reflect and/or absorb any energy before it can do harm to people or equipment outside. These chokes must at the same time allow the free movement of product through the facility.

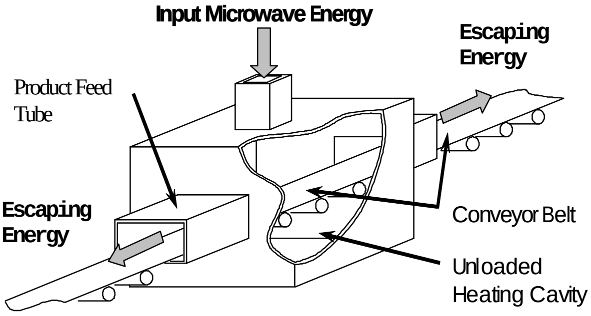

Figure 2: Microwave Heating Cavity with Conveyor Belt Feed

The preferred choke design solution is a reactive choke. This typically reflects the escaping energy back into the cavity using equivalent reactive elements, such as stub lines, in a similar fashion as would be used in a conventional bandstop filter design. Because of the complex nature of the microwave design problem, however, standard reactive choke designs typically enforce limitations on the aperture geometry, so as to apply single mode equivalent approaches. When such limited aperture geometries conflict with the physical requirements for aperture size set by the size of the product feed tube, the designer must resort to other solutions such as tunnels with absorbing walls, special arrangements of doors timed to open and close to admit product or ‘maze openings’ that force the product to ‘meander through a folder corridor lined with absorbing walls’ [10]. These approaches have many drawbacks, specifically since the use of absorbing materials requires bulky cooling and imposes power limitations, and the free flow of product may be impeded by obstacles such as doors and chain walls. Alternative empirical designs have the drawback of being limited to specific geometries and require redesign from scratch for each new situation.

B. Choice of functional blocks

As the aim in this case is to stop power flow at specific frequencies for specific modes, the functional blocks used should create a null in transmission for at least one mode at one frequency. Additional constraints are that blocks do not intrude into the aperture, and do not cause cross-coupling between modes. Designing a bandstop filter under such circumstances is highly problematic, as a functional block which creates a null for one mode will excite a number of other modes at the same frequency. Analysis indicates that null-creation with limited cross-coupling can be achieved by functional blocks consisting of back-to-back waveguide steps separated by lengths of uniform guide, as shown in Figs. 3 and 4. If the steps go from small to large to small again, and the size of the small waveguide is the same as the product feed tubes discussed above, then such functional blocks in cascade would fulfill the requirements of a reactive choke structure in terms of geometric limitations.

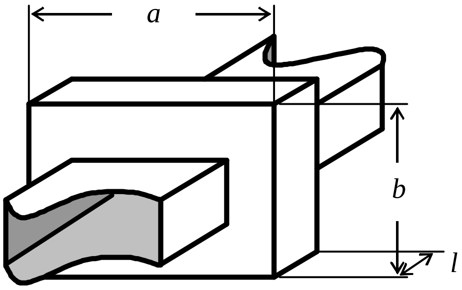

Figure 3: Functional Block

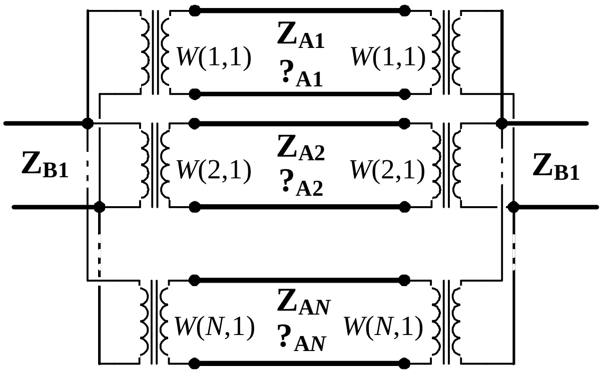

Figure 4: Functional Block Equivalent Circuit

The fundamental field activity in this block can easy be understood. In geometries which exhibit resonance, incident energy in the small guide is found to split relatively evenly between two modes of different propagation constant in the large waveguide. The electrical length of the large guide is different for the two modes, and, if chosen correctly, can allow destructive recombination of the energy in the two modes at the opposing step, leading to a null in propagation at a specific frequency. 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. In fact, a whole host of viable geometries is found for a specific frequency, as shown in Fig. 5. The designer must choose from these, according to the next step in the design, i.e. the cascading procedure.

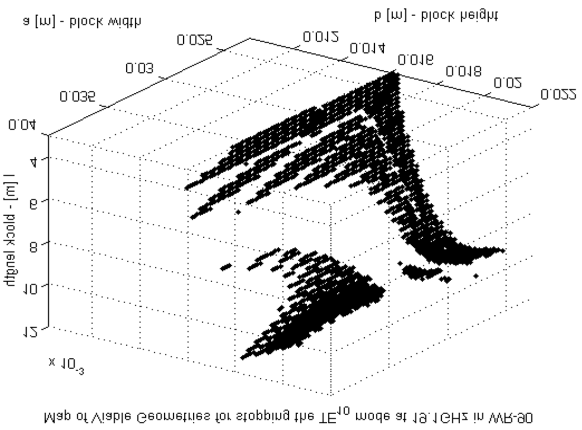

Figure 5: Example of Viable Geometries

C. Design

The result of the previous phase of design should be a series of functional blocks, each responsible for a propagation null of one or more modes at some point in the stop band. All the nulls provided by all the blocks should be enough to build up a suitable stop band for all the individual modes. This may require a relatively large number of blocks, depending on the specifications.

To cascade the blocks, two criteria must be kept in mind. The first is that blocks that resonate for the same mode must be separated by an electrical length that ensures maximum attenuation at the frequencies between the two resonances, and the second that a minimum separation length exists between adjacent blocks to ensure that localized modes do not interact. This measure is necessitated by the approximation made in the functional block selection stage, where it is assumed that functional blocks can be independently tuned to resonance before being cascaded.

A tree search strategy is used to cascade the functional blocks. This strategy is particularly suited to this problem, due to the availability of the cascading criteria listed above, which allows the insertion of the functional blocks at the end of the structure without any optimization through the use of prior knowledge of the problem. In addition, since it is known that each functional block need only be used once in the design, the extent of tree search strategy can be limited by constraining each block to be only used once in the structure. Under such circumstances, the simplified tree search strategy becomes much more efficient. A diagram of the search as applied to a 4-block problem, is shown in figure 6.

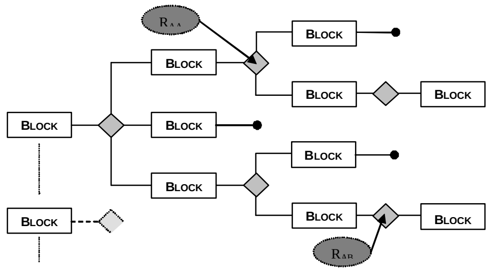

Figure 6: Tree Search Algorithm

The algorithm uses one of the available functional blocks as a starting structure. It then attempts to cascade each of the remaining blocks to this starting structure. The principle behind the search is that only a selection of these blocks will successfully cascade, and the rest will be rejected. Only those blocks for which these conditions predict non-conflicting cascading lengths are allowed to form a new branch of the search.

To favour short filter structures, the search can be further restricted by disallowing excessive cascading lengths. Each time a block is successfully placed, a new branch is formed and that block is removed from the pool of available blocks for that branch. Should it occur at some point that none of the available blocks fits, that branch of the search is 'killed' off and the algorithm steps back a level to attempt the remaining untried branches. Should all the blocks be successfully placed in a branch, then a viable solution has been found and can be stored. Typically a number of viable solutions are found, depending on the stringency of the cascading requirements. Stricter cascading rules lead to fewer solutions, but typically of a higher quality.

D. Results

As example, a scaled model of a practical 2.45GHz filter at 19GHz is shown in Fig. 7. The input and output waveguides support five propagating modes at this frequency, all to be attenuated by at least 30dB across a 4% bandwidth. The predicted and measured transmission results for two of the modes are shown in Figs. 8 and 9. The filter worked equally well for the other three modes.

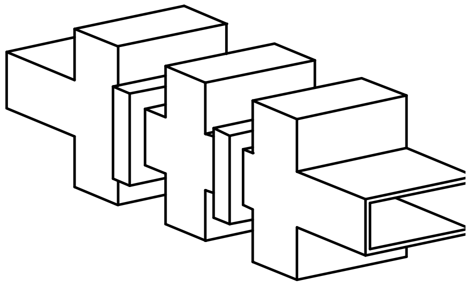

Figure 7: 19GHz Overmoded Bandstop Filter

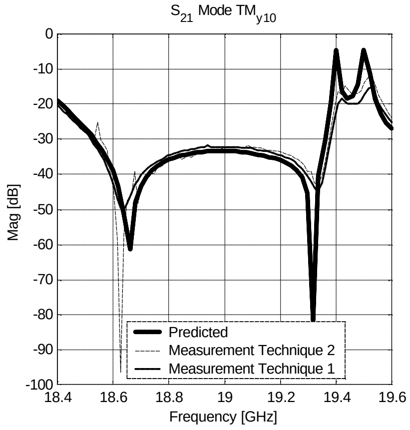

Figure 8: Transmission Results for TM_{y10} Mode

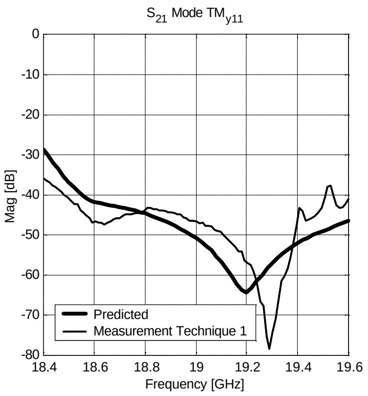

Figure 9: Transmission Results for TM_{y11} Mode

III. IRIS DESIGN FOR NARROW BAND MULTIMODE FILTERS [11]

A. Introduction

The history of coupled waveguide cavity filters dates from 1948 with the description and implementation of a direct-coupled cavity filter by Fano and Lawson [12], consisting of a number of waveguide cavities separated by thin inductive irises. Irises were designed using the small aperture theory derived by Bethe [13] in 1944 and the measured polarisability data presented by Cohn in 1952 [14]. The possibilities of reducing filter size by allowing more than one mode to be resonant in the same cavity, were soon realised, and in 1951 Lin [15] demonstrated a fifth order filter realised in a single cylindrical cavity. At this time prototypes were deemed to be impractical, since the authors could not achieve independent control of the wanted degenerate modes, as well as suppression of unwanted modes.

This was the state of coupled cavity filter design until the launch of the first commercial satellite communications systems in the late 1960s. New technology calling for reduction in filter size and weight was required, sparking new interest in the use of multi-mode coupled cavity filters. The first dual-mode cavity filter was developed by Atia and Williams [1] at Comsat Laboratories in 1970 and showed that multi-mode cavity filters were indeed commercially viable, and could reduce the number of physical cavities (and thereby the size and weight) of standard coupled cavity filters by a factor of two.

Another significant advantage of multi-mode cavities is that the structure allows coupling to non-adjacent resonators. This can be achieved by using cross-shaped irises or coupling screws. This cross-coupling between resonators results in transfer function zeros along the real or imaginary axis, thereby permitting the realisation of elliptical and linear phase filter functions – the first multiple-coupled waveguide cavity filters. It was therefore possible to improve filter performance without increasing the physical dimensions, at the cost of increased design complexity.

After dual-mode filters, the obvious step towards the design of triple-mode filters was taken. A number of filter structures employing various resonant modes and realising a variety of filter functions were presented [2] between 1971 and 1989. For an elliptical triple-mode filter, three inter-cavity coupling coefficients must be controlled uniquely and simultaneously by an iris containing more than one aperture. With the introduction of quadruple-mode filters [3] in 1987 the number of required couplings increased to four.

The increasing complexity of coupling elements inevitably led to the use of numerical techniques for analysis and design. The first EM-evaluation of a coupled cavity coupling coefficient was presented in 1991 using the mode-matching technique [16]. A study by Yao [17] in 1994 compared the accuracy of coupling coefficients determined by small aperture theory and the mode-matching method. Even for simple geometries where only one coupling mode is evaluated, errors of up to 10% on the part of the small aperture theory was found, clearly illustrating the importance of numerical methods in iris design.

Today, most designers follow a two-step procedure to design coupled cavity filters. In the first stage, the iris dimensions are determined by using either small aperture theory, or by calculating the two natural resonant frequencies of each mode coupled by the iris numerically. In the second stage, the full filter is optimised with a numerical code.

B. Choice of functional blocks

In narrowband filter applications, the functional blocks are chosen to couple specific modes on both sides of the block to each other, with very accurate coupling values. The problem is made a lot simpler by the narrowband application, as the coupling block is embedded on both sides in resonant sections of waveguide. The block is therefore designed to work at only one or two frequencies, with at the most four modes on either side. A typical functional block is that of the thin circular iris coupling two sections of cylindrical waveguide, shown in Fig. 10.

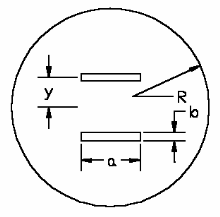

Figure 10: Typical Coupling Iris

C. Design

Two identical iris coupled cavities are shown in Fig. 11, with the corresponding circuit model in Fig. 12.

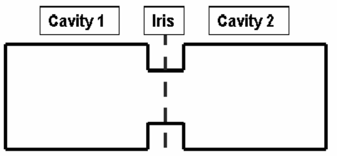

Figure 11: Identical Iris Coupled Cavities

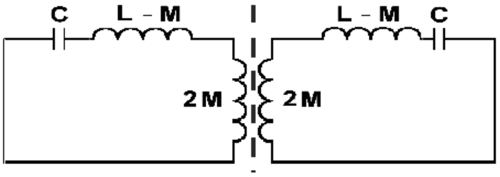

Figure 12: Equivalent Circuit for Coupled Cavities

The problem can be solved numerically by calculating the scattering matrix of the cavity-iris interface, and cascading it with the guides forming the cavities and the iris, as shown in Fig. 13. By shorting the end ports, the natural frequencies of the full system can be obtained by solving Eq. 1.

$$\Re(f) = \det\left[\mathbf{S}^c + \mathbf{I}\right] = 0 \qquad (1)$$

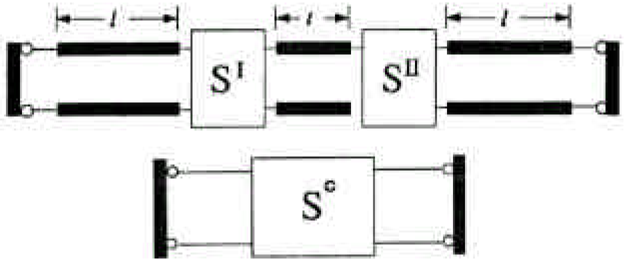

Figure 13: S-matrix Model of Coupled Cavities

In the case of single mode propagation, only two roots are obtained, and the coupling is given by Eq. 2, with f_e and f_m the two frequencies. This method is very standard and has been used for the last decade to compute coupling coefficients.

$$K = \frac{f_e^2 - f_m^2}{f_e^2 + f_m^2} \qquad (2)$$

In the case of multiple resonant modes, the numerical aspects of this procedure become difficult and time consuming. The roots of Eq. 1 becomes very close together, and the turning points of the function move to extremely close to the axis. This has the effect that many EM evaluations of the structure are necessary to find the required roots. Once this has been done, only one coupling value analysis has been completed. The next stage is to optimise the structure to give the required coupling values for all the modes, which requires a large number of coupling value analysis steps. For one complete design, the number of EM analysis points quickly become prohibitive.

To sole this problem, three techniques are combined, i.e. (a) reduction of the general scattering matrix (GSM) [11], (b) adaptive sampling interpolation [18] and (c) Agressive Space Mapping [19].

(a) When no cross-coupling between modes exists, i.e. $s_{21}^c(i,j) \approx 0,\ i \neq j$, two modes can be isolated by adding short circuits to their ports and terminating the remaining modes in their respective wave impedances as is shown in Fig. 14 for a three mode example.

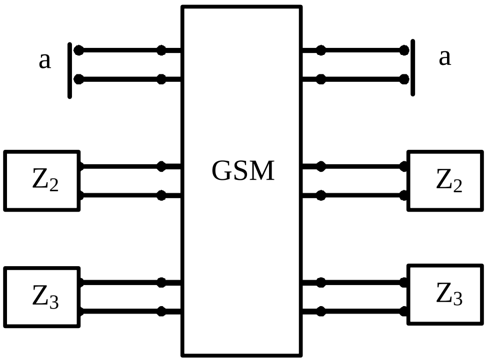

Figure 14: Reducing the Scattering Matrix

This has the result of reducing the generalised scattering matrix of the problem, and causing Eq. 1 to once again have only two roots instead of six.

(b) To limit the amount of EM evaluations needed to determine the roots, the function in Eq. 1 is first replaced by a rational interpolation model, created by an adaptive sampling algorithm. This algorithm is remarkably effective, and generates very accurate approximations to the function with typically 8-10 samples.

(c) The optimisation of the structure is performed by Agressive Space Mapping, with the coarse model being that given by small aperture theory, and the full EM analysis the fine model.

D. Results

These three techniques combine to give excellent results, as shown in Fig. 15 for the design of a triple mode coupling iris at 10GHz. The reduction in EM evaluations is marked.

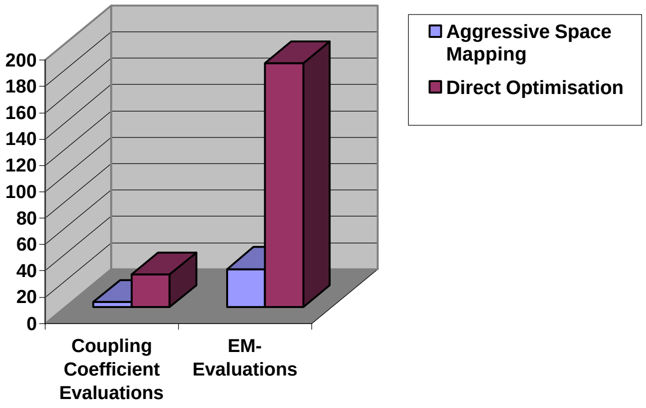

Figure 15: Reduction in EM Evaluations

With some extensions, these techniques were used to design a multimodal diplexer, consisting of three cavities which support three resonant modes each, and an input port which couples to different modes at the two diplexer frequencies. This enhances isolation between the two channels of the diplexer, as a spatial isolation is combined with a filter characteristic. A photograph of the diplexer is shown in Fig. 16, with measured results in Fig. 17.

Figure 16: Multimodal Diplexer

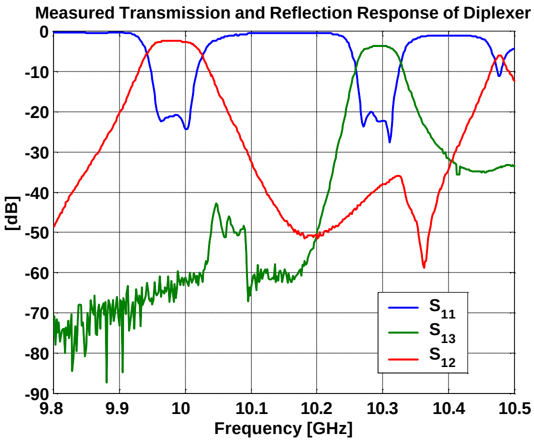

Figure 17: Measured results for Diplexer

IV. MULTIMODE WAVEGUIDE ANTENNA FEED FOR MONOPULSE APPLICATION

A. Introduction

In 1961, PW Hannan presented design objectives for optimum antenna feed systems for reflector type antennas in monopulse applications. The implementation of these ideas were found to be best achieved with multimode antenna feeds where, typically, a number of waveguide feeds are first combined into one overmoded waveguide, which terminates in the radiating aperture [20,5]. The basic problem is shown in Fig. 18. By exciting the four input waveguides in three different ways, three antenna patterns are obtained, called the plus, elevation and azimuth channels.

One of the problems with these types of feed, is the achievement of good input match across a wide band for all three excitations. As late as 1988, a system with an input match of -18dB for all three excitations, was reported with a bandwidth of only 10% [21]. The fundamental problem in reaching the objective of low input reflection, is that one physical structure, i.e. the overmoded waveguide, has to match three different terminating impedances to the impedance of the source guide. In addition, each excitation generates a different mode or set of modes in the overmoded guide, each of which has a different propagation constant.

Designing a quarter wave step into the guide to match for one excitation, can therefore easily be the worst choice of step length for another mode.

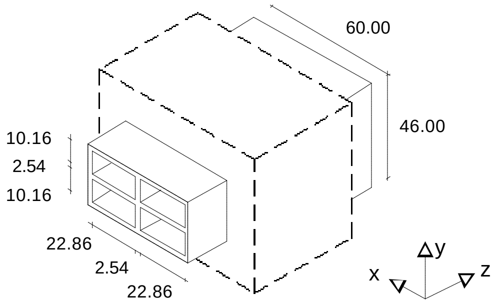

Figure 18: Monopulse Feed Structure

B. Choice of functional blocks

In this type of problem, the functional blocks can be determined by first using symmetry to subdivide the problem into three different problems. This is an extension of the even and odd mode symmetries used in two-mode problems, such as coupled lines. The symmetry walls for the three excitations are shown in Fig. 19, with 'e' denoting a perfect electrical conductor and 'h' a perfect magnetic conductor.

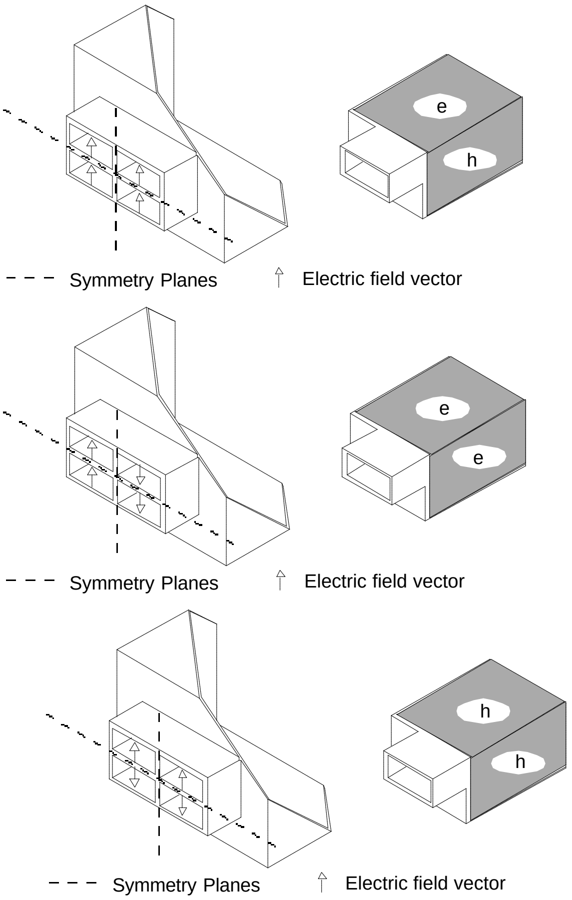

Figure 19: Division of the Problem in terms of Symmetry (plus at top, azimuth in middle, elevation at bottom)

From these subproblems, it is clear that the obvious functional blocks will be horizontal and vertical steps, as they will have the smallest amount of cross-coupling between modes. The division also makes it possible to see exactly what the influence of any step will be on all of the three problems, for instance, a thin vertical pin in the center of the overmoded guide will have almost no effect on the azimuth channel.

C. Design

The cascading of the functional blocks is performed in three stages. First, each of the input guides are reduced in width to ensure that only the wanted modes are excited when they open up into a bigger guide. This step is trivial, as only one mode exists in each of these guides. The resulting structure and calculated reflection coefficient is shown in Fig. 20.

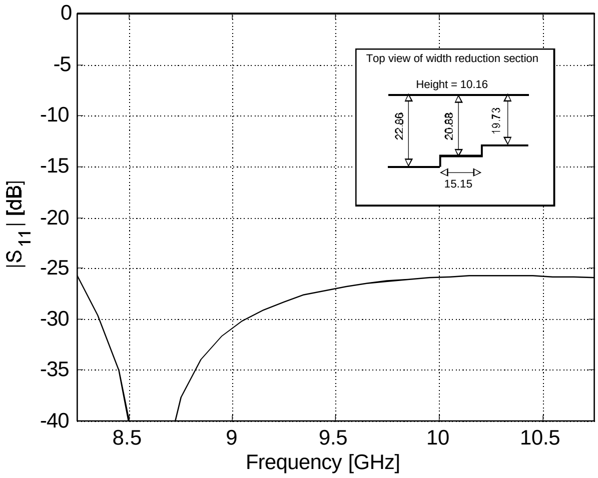

Figure 20: Reduction in Width of Input Guides

The next stage is to cascade a number of vertical steps to remove the vertical wall separating the guides. These blocks affect the plus and elevation channels in the same way, with a relatively small effect on the azimuth channel. The final stage is to cascade a number of horizontal steps to remove the horizontal wall separating the guides. These steps have a big influence on the elevation channel, and a smaller effect on the other two channels. Both these stages are performed by optimising all three problems together.

D. Results

The final feed structure is shown in Fig. 21, with the calculated results shown in Fig. 22. An input match of better than 19dB is achieved over a 20% band. At the time of publication, measured results are not yet available.

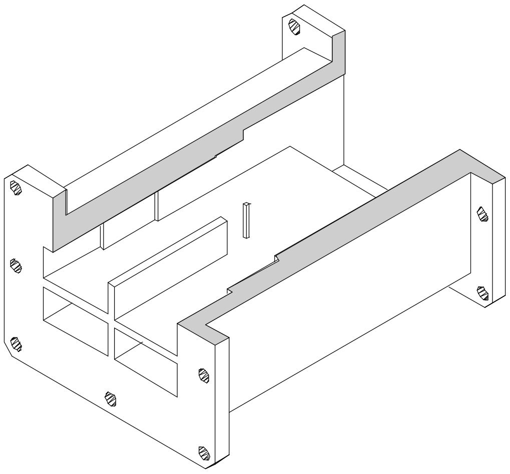

Figure 21: Monopulse Feed

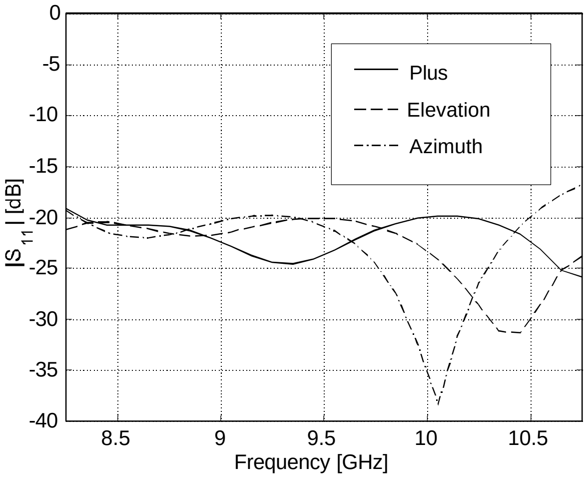

Figure 22: Predicted Results for Monopulse Feed

V. CONCLUSIONS

A number of designs have been presented to illustrate an approach to the design of devices utilising multiple propagating modes. All the designs are based on the identification of functional blocks which are cascaded to form a device. The devices include wideband and narrowband designs, as well as passband and stopband topologies. Numerical analysis and optimisation play a large role in the designs, but must be preceded by intelligent choices of functional blocks, which in turn depend on a good understanding of the electromagnetic properties of the problem, and the field distributions.

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