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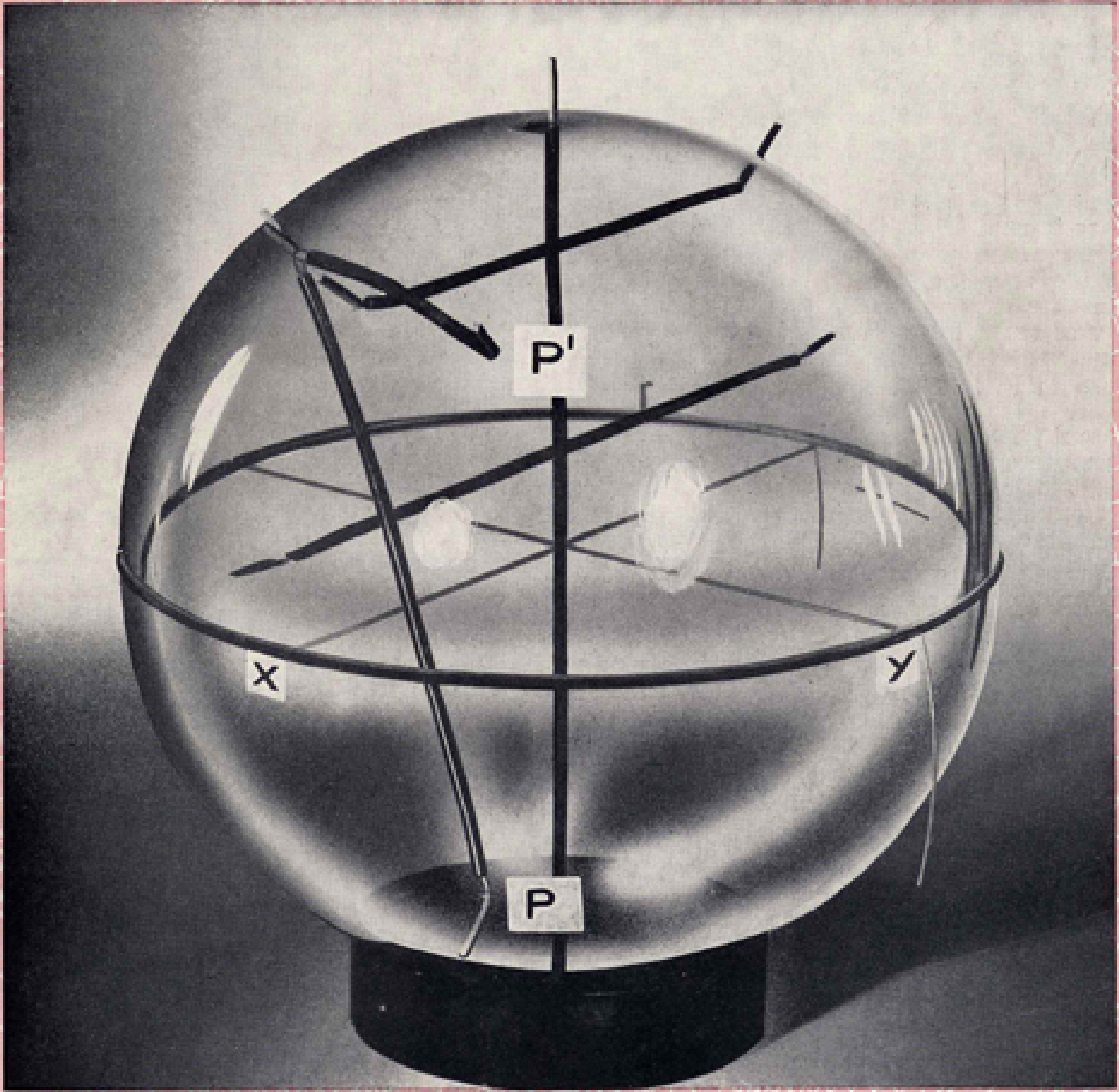

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MICROWAVE FILTER DESIGN TECHNIQUES

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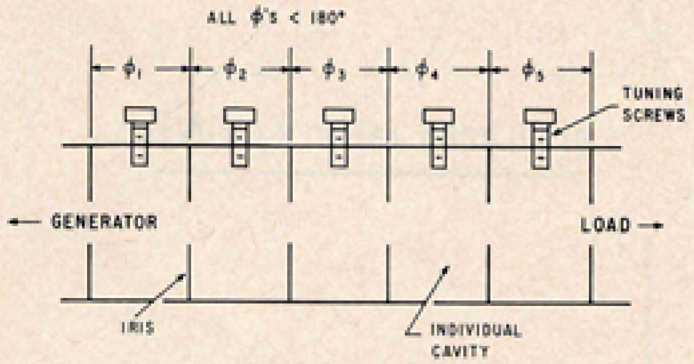
Introduction

Many papers have been written on the theoretical design of microwave filters and the methods for computing the theoretical constants of a particular filter are known. The gap between the computation of the constants of the filter parameters and the fabrication and alignment of the filter to realize the required response is one that requires some attention since this is the stage which generally consumes much of the time in any development program. This paper will discuss a filter technique which has been developed for the design of direct coupled microwave filters permitting the design engineer to build and align the filter so that the resulting response curve will essentially duplicate the theoretical performance curve.

A direct coupled filter consists of a number of waveguide cavities, each cavity being coupled to an adjacent cavity by an aperture or iris. The theoretical design of these filters is well known and design data for networks capable of realizing a Butterworth or maximally flat response and the Tchebyscheff or equal ripple response is available[1,2,3,4] A typical arrangement and associated low frequency equivalent circuit is shown in Figure 1. The series resonant circuits are represented by the cavities and the irises represent the shunt inductance in Figure 1b. Having computed the constants of a particular filter such as the number and length of individual cavities, and iris susceptances, the next step in the development program is the fabrication process. This is a very important stage since the final performance of any filter relies heavily on the tolerances and surface finishes of the individual parts. These factors behave in such a manner as to widen the gap between the theoretical and actual response.

WAVEGUIDE DIRECT COUPLED FILTER



LOW FREQUENCY EQUIVALENT CIRCUIT

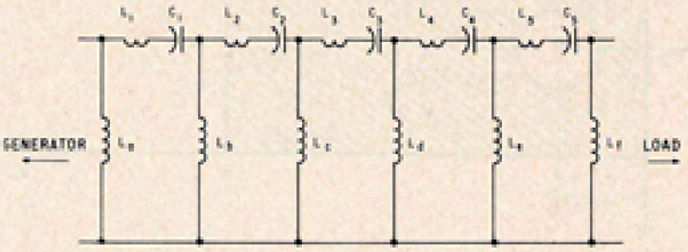


Figure 1.

A control of three basic parameters is required in any filter design so that the final filter response will closely approximate the theoretical response. These are

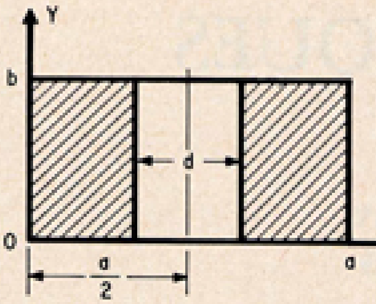
1. Resonant frequency of the individual cavities
2. Loaded Q of the individual cavities
3. Mutual coupling between the adjacent cavities, input and output terminations.

The usual technique for varying the frequency of the cavities in a microwave filter consists of a capacitive screw located at a point of maximum electric field. The insertion of a screw into the cavity lowers the resonant frequency and in effect increases its length. Cavities are usually cut shorter than required and the capacitive screw allows the designer to vary the frequency of the individual cavity above and below the design frequency. Penetration of the screw into the cavity has the effect of reducing the unloaded Q of the section; therefore, the penetration of this tuning element should not be in excess of tuning requirement. A rule of thumb which has worked out successfully at X-band is to cut the cavities about 0.015 inch below the theoretical length. All screws should be silver plated to realize a lower insertion loss per cavity.

The loaded Q of the individual cavities and the mutual coupling between them is a function of the irises terminating each section of the filter. Two of the more commonly used irises are shown in Figure 2. Both types are useful and yield essentially the same results. Variation in the iris parameters required in any filter alignment is usually achieved by interchanging iris sizes until an acceptable response curve results. This tuning arrangement requires a large library of irises of different sizes and is very costly, inefficient and time consuming; in addition, it does not result in achieving the ultimate response curve (especially for a Tchebyscheff filter having greater than 1 db ripples) since the irises are varied in steps, the size of which are limited by cost and machining techniques.

A more desirable arrangement is one providing a smooth continuous variation in iris susceptance and utilizing only one iris to replace the library of fixed irises. This iris is

THIN SYMMETRICAL RECTANGULAR IRIS



THIN CIRCULAR IRIS

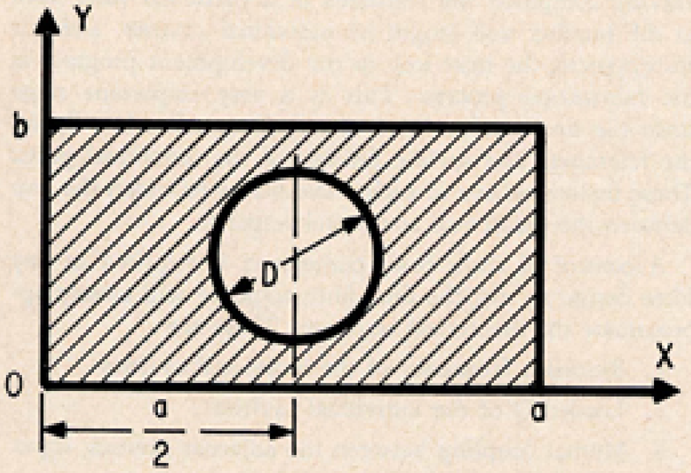


Figure 2.

known as the "adjustable or variable iris" and is the new technique which will be described in this paper.

Iris Considerations

The realization of the proper value of the shunt inductive susceptance in the direct coupled filter represents the most important requirement if one is interested in achieving a selectivity curve which essentially duplicates the theoretical response. The field configurations within the rectangular guide for the dominant TE_{10} mode are such that the iris is located in a region where the transverse magnetic field as shown in Figure 3 is a maximum. For zero thickness irises, the following formulas are available for computing the inductive susceptances[5,6,7,8,9]

(a) for a circular iris centrally located across the guide

$$B_o = \frac{3}{2\pi} \frac{ab}{D^3} \lambda_g$$

where

B_o = normalized iris susceptance, B_{actual}/Y_0; for $D << b$
a is the width of the waveguide
b is the height of the waveguide
λ_g is the guide wavelength
D is the diameter of the iris

(b) for a rectangular iris or window centrally located across the guide

centrally located across the guide

$$B_o = \frac{\lambda_g}{a} \cot^2 \pi \frac{d}{2a} \qquad (2)$$

where

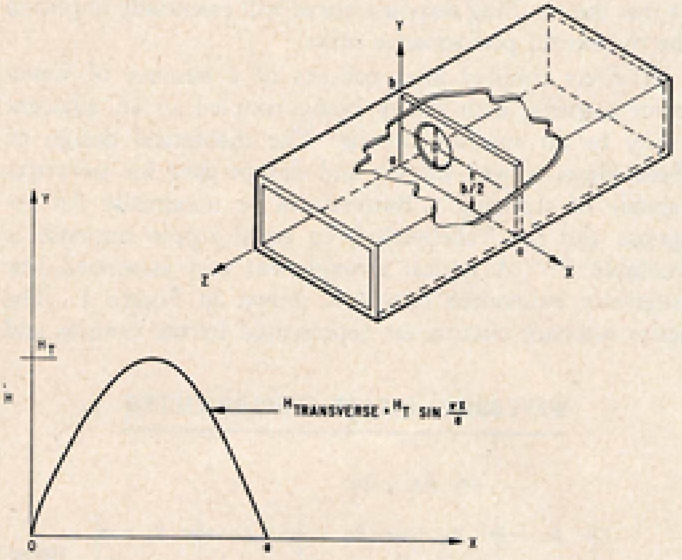
B_o = normalized iris susceptance, for $\frac{d}{a} << 1$
a is the width of the waveguide
d is the width of window
λ_g is the guide wavelength

As the thickness of a particular iris increases, the equivalent shunt inductive susceptance of the iris increases and series impedance terms are introduced into the equivalent circuit. A rule of thumb generally used for irises is that the effective susceptance of a thick iris having an aperture, D, is equal to the susceptance of a theoretical iris having an aperture equal to (D−t), where t is the thickness of the iris, i.e.,

$$B_{thick}(D) \approx B_{thin}(D - t) \qquad (3)$$

The circular iris is preferred over the rectangular window because it is easier and less expensive to machine and consequently has been used in all filters discussed in this paper. Coupling between the adjacent cavities varies as D varies, increasing if D increases and vice versa. This same phenomenon can be displayed by using an iris of fixed diameter, D, and varying the position of the iris across the waveguide as shown in Figure 3. As the iris is displaced from

MAGNETIC FIELD IN PLANE OF IRIS



DISPLACED IRIS: $X_0 < a/2$

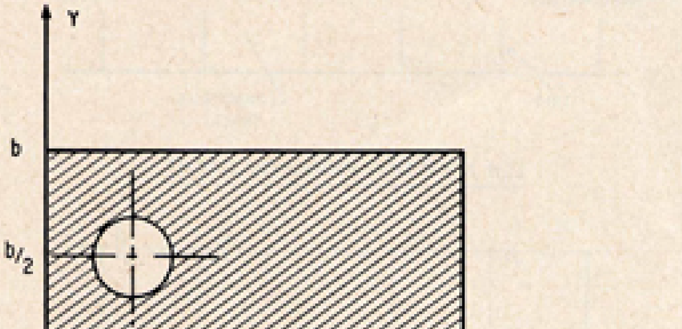


Figure 3.

the center of the guide, the susceptance increases and is analogous to utilizing a *centrally located circular iris of smaller diameter.* The displaced iris is now located at a point in the guide where the transverse magnetic field is less than that at the center of the guide and as a result the mutual coupling between adjacent cavities is reduced. Expressions for the displaced (off center) iris susceptance have been developed by Motz[5] resulting in the following for the susceptance of a displaced thin iris.

For RG-52/u waveguide operating in the TE_{10} mode (refer to Figure 4)

$$B = B_o \csc^2 \frac{\pi x_o}{a} \qquad (4)$$

where

B_o is the normalized iris susceptance at $x_o = a/2$ (center of waveguide cross section)

$$B_o = \frac{3}{2\pi} \frac{ab}{D^3} \lambda_g$$

B = susceptance at x_o

Figure 4 is a plot of Equation (4) showing the variation between the normalized iris susceptance and the location of the iris in the waveguide; thus a 1/8 inch displacement of the circular iris raises the effective susceptance by 20 per cent. The ratio of the actual diameter of the displaced circular iris to the effective diameter of centrally located iris versus the displacement in the guide is plotted in Figure 5. From this plot it can be seen that displacing the iris 1/8 inch off center is analogous to replacing a displaced iris of diameter D by a centrally located iris of diameter D_{eff} where

$$D_{eff} = 0.935\ D$$

This curve also shows that a displacement of 0.050 inch reduces effective diameter of the iris by approximately 2 per cent so that for a circular iris having D equal to 0.100 inches, above shift corresponds to a diameter change of 2 mils. The configuration for the adjustable iris is shown in Figure 6 and a typical cavity employing the iris is shown in Figure 7. A graduated scale is used for accurately positioning the iris and serves to indicate the location of the circular iris at all times. Allowance must be made in establishing the length of the iris for the displacement anticipated so that no rf leakage will exist at this junction.

NORMALIZED IRIS SUSCEPTANCE VERSUS LOCATION OF IRIS IN WAVEGUIDE

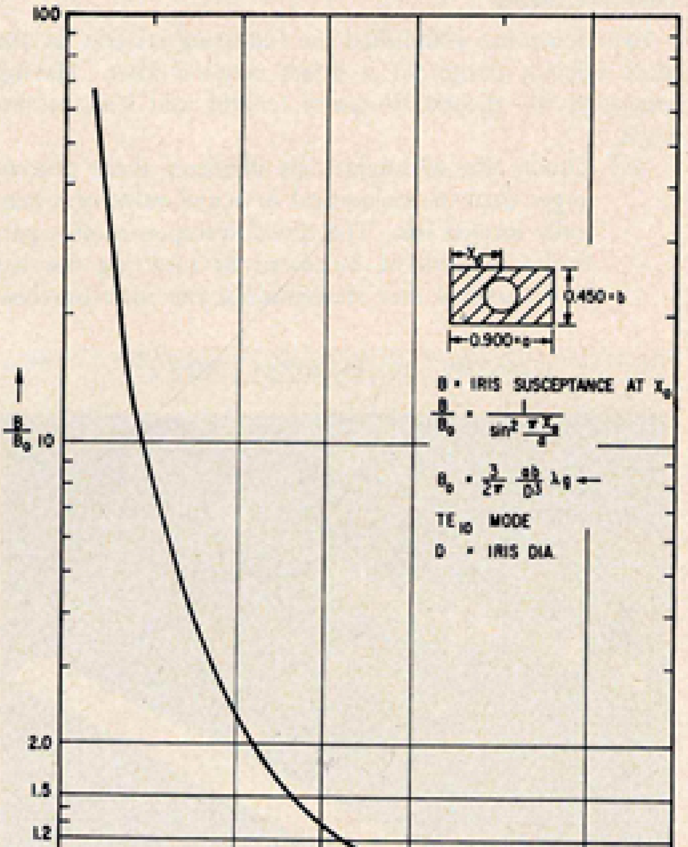


Figure 4.

EFFECTIVE DIAMETER OF A CIRCULAR IRIS VERSUS DISPLACEMENT X_0

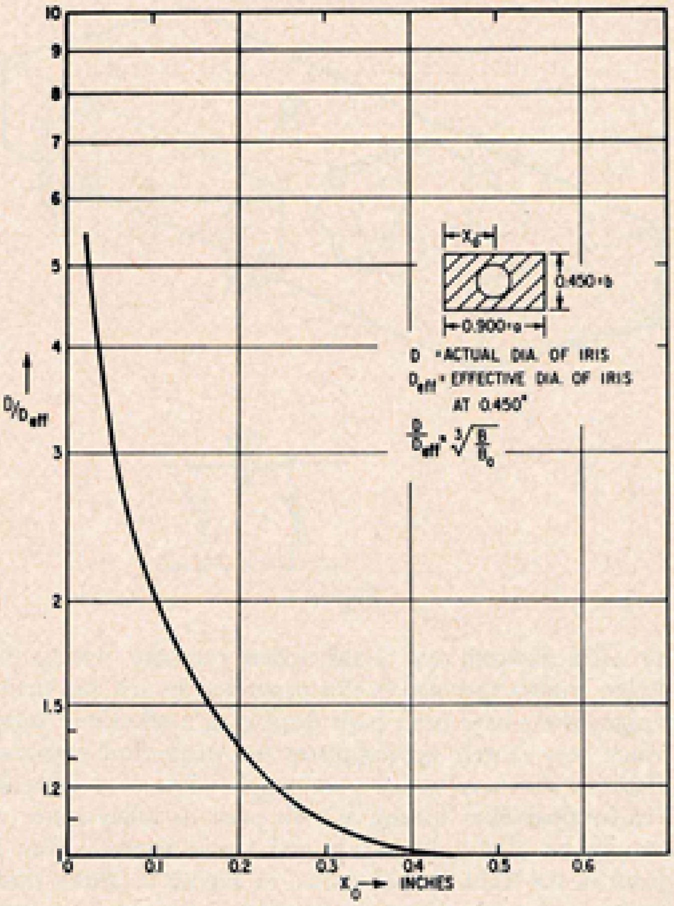


Figure 5.

Five pole filters have been designed by the Cohn method

ADJUSTABLE IRIS FOR RG-52/U WAVEGUIDE

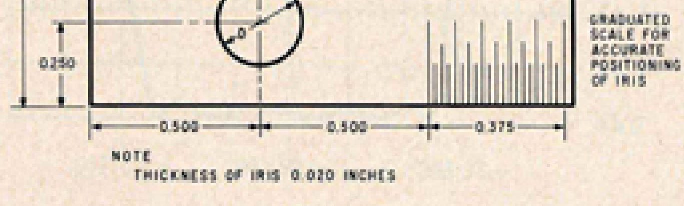
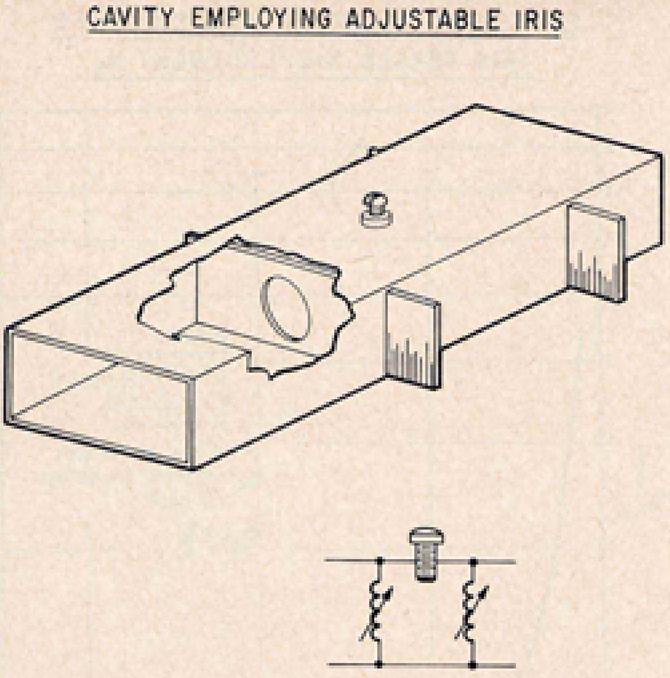


Figure 6.

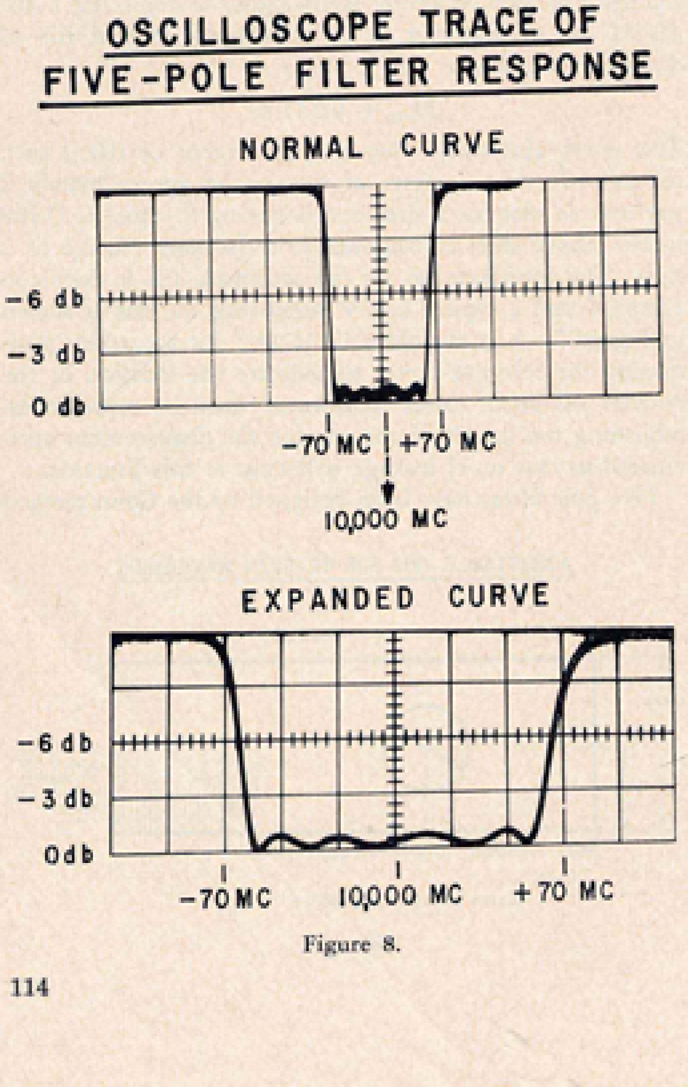


CAVITY EMPLOYING ADJUSTABLE IRIS

Figure 7.

for a Butterworth and Tchebyscheff response. Using the design criteria specified in this paper for the iris and cavity design, filters have been built displaying a selectivity curve which very closely approximates the theoretical response. Figure 8 shows an actual photograph taken of a five-pole Tchebyscheff filter having a 1 db peak to valley ratio. A comparison of the theoretical and actual response data is given in the Table 1 and shown in Figure 9. From these results it can be seen that excellent correlation has been achieved by using the adjustable iris technique.

Photographs in Figures 10 and 11 show the typical individual cavities, irises, filter structure and an assembled five-pole direct coupled filter.

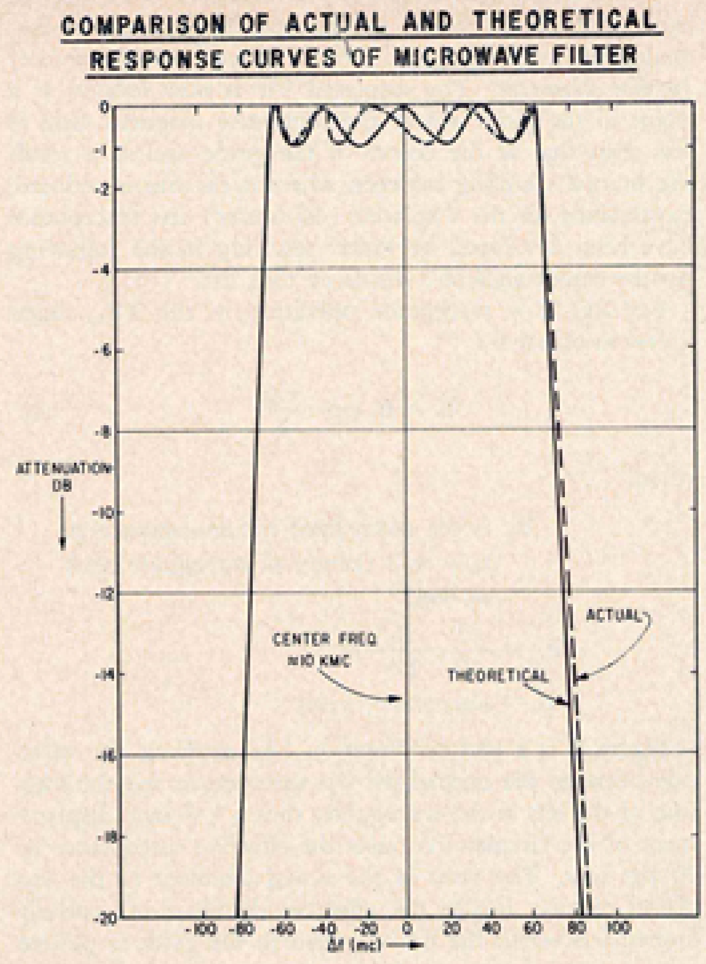


OSCILLOSCOPE TRACE OF FIVE-POLE FILTER RESPONSE

NORMAL CURVE

EXPANDED CURVE

Figure 8.



COMPARISON OF ACTUAL AND THEORETICAL RESPONSE CURVES OF MICROWAVE FILTER

Figure 9.

Design Criteria

Experience has established the following criteria for the most efficient design of a direct coupled filter. Having computed the theoretical cavity lengths and iris susceptances,

(a) Choose the adjustable iris diameter three percent larger than the theoretical or actual value of a centrally located iris. The actual susceptance of a particular iris can be measured by inserting the iris in a matched line, determining the insertion loss,

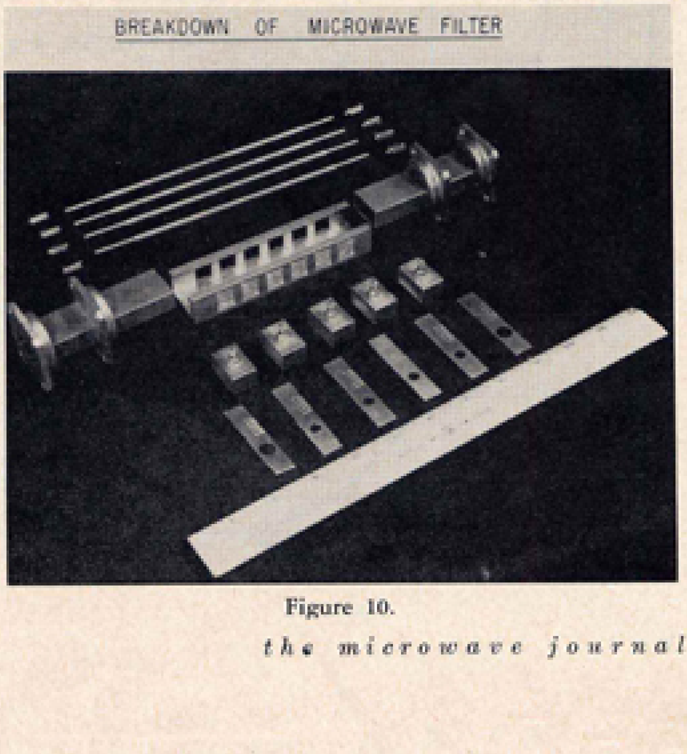


Figure 10.

and then converting this loss to susceptance. Figure 12 is a family of curves showing the variation of the normalized susceptance with frequency of a circular iris (zero thickness) of diameter "D" located in the center of a RG-52/u waveguide operating in the dominant (TE_{10}) mode. These curves are a plot of Equation 1 and serves as a good estimate of the actual iris susceptance having a thickness of 0.020 inch. By making the aperture diameter larger than required, the final or desired position of the iris is approximately 0.090 inch off the waveguide center and provides a ±10 per cent change in the effective susceptance when the displacement x_o varies from 0.450 to 0.330 inches.

(b) Operation of the adjustable iris should be restricted to a range of x_o from 0.450 inch (center of RG-52/u waveguide) to 0.263 inch. Outside of this 0.187 inch range the slope of the susceptance versus x_o curve increases rapidly and the positioning of the iris becomes critical. Within this range, B/B_o varies from 1 to 1.5 and D/D_{eff} varies from 1 to 1.15.

TABLE COMPARING THEORETICAL AND ACTUAL FIVE POLE TCHEBYSCHEFF FILTER WITH 1 DB RIPPLE

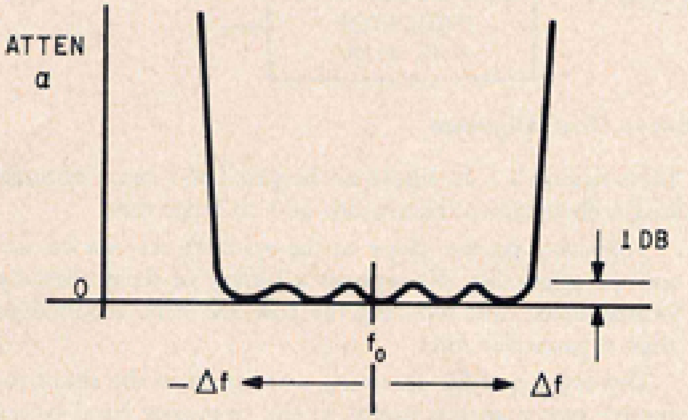


TABLE I

db	Actual* $-\Delta f$	Actual* $+\Delta f$	Theoretical* $-\Delta f$	Theoretical* $+\Delta f$
1	65	65	65	65
3	69	68	67	67
6	72	73	71	71
10	74	76	74	74
15	77	80	78	78
20	84	87	84	84

* *Peak to Valley Ratio in Pass Band = 1 db.*
$f_o \approx 10$ *KMC.*

(c) Surface finish of the machined edges of the individual cavities should have a surface roughness of less than 16 microinches and the parallelism of the two edges of the individual cavity should be less than 0.005 inch. This close control over the surface finishes and the final clamping together of the complete assembly (as shown in figures 10 and 11) eliminates contact difficulties.

(d) The individual cavities used in the filter should have a length of approximately 0.015 inch below the theoretical value. This assures an adequate tuning range for the capacitive screw; also, the penetration of the screw into the cavity is held to a minimum which results in a higher unloaded cavity Q and consequently a lower insertion loss for the overall filter. The insertion loss of a typical filter due to copper loss compares very favorably to the theoretical calculations. Five pole Tchebyscheff filters fabricated from RG-52/u to above mentioned surface finishes with 1 db ripples and 1.5 per cent fractional bandwidth at X band had insertion losses of approximately 3 to 4 db. Three pole Butterworth filters having fractional bandwidths of 0.6% at X band had an insertion loss of 1 db.

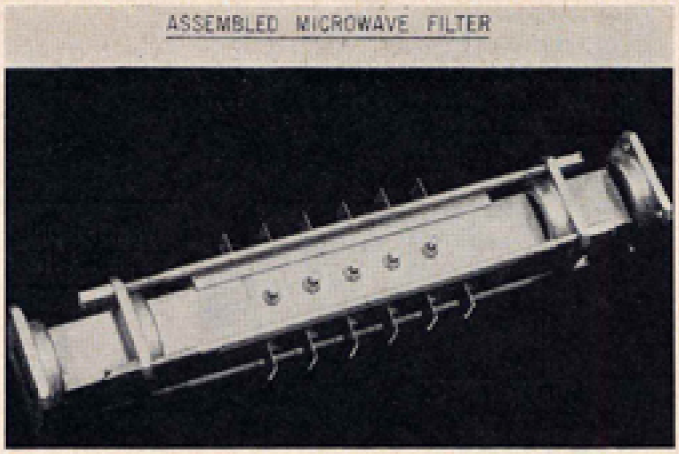

ASSEMBLED MICROWAVE FILTER

Figure 11.

Filter Alignment Guides

A swept frequency technique was employed in the alignment of the microwave filters and a block diagram of the test set-up is shown in Figure 13. The following guides

NORMALIZED SUSCEPTANCE VERSUS FREQUENCY: CIRCULAR IRIS OF DIAMETER "D" CENTRALLY LOCATED

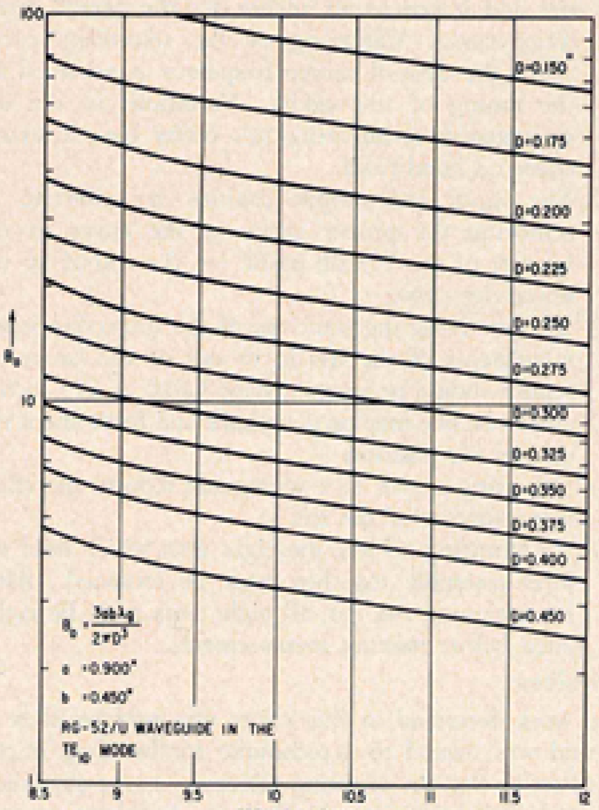


Figure 12.

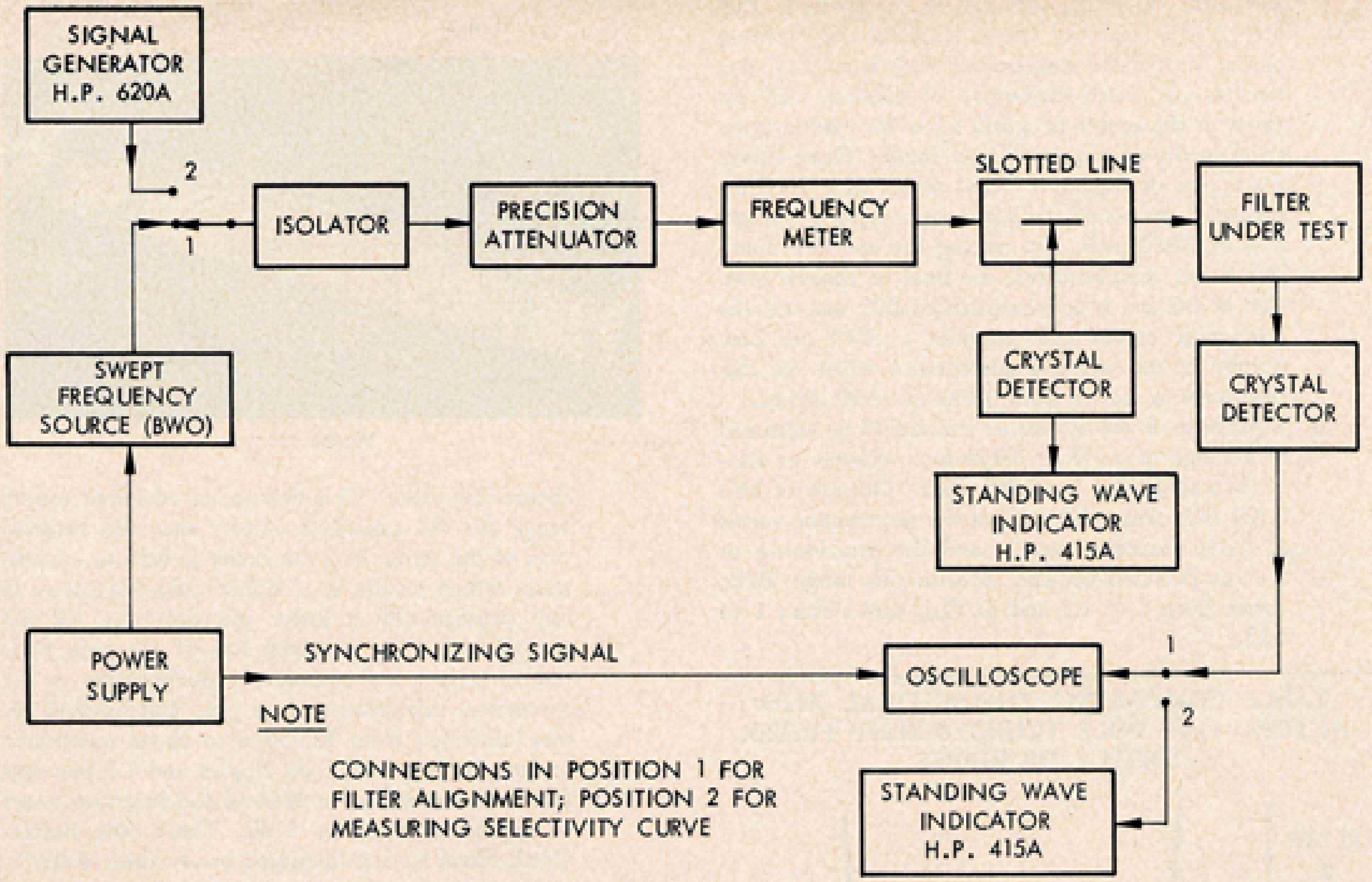


Figure 13. Block Diagram for Microwave Filter Alignment

are important in achieving an efficient alignment of any filter.

(a) The center three cavities have the highest Q and thus have a major effect on the filter bandwidth and ripples.

(b) The center cavity has the highest Q of all the cavities and it acts as an anchor for the overall selectivity curve. Centering of the selectivity curve about the desired center frequency is achieved by the tuning of this cavity. Variations in the iris susceptances terminating this cavity have a strong effect on bandwidth.

(c) The input and output cavities are effective in achieving the proper shape of the curve in the vicinity of the -3 db point, i.e., the roll-off of the selectivity curve.

(d) In optimizing the positions of the respective irises, movements of the iris in or out of the cavity assembly should be in small steps (.010 to .015 inch); otherwise one may oscillate back and forth about the desired iris position.

(e) Offsetting an iris in a waveguide reduces the effective diameter of the iris.

(f) In offsetting an iris, the eight nuts which hold the filter assembly together must be loosened. After repositioning the iris, all eight nuts must be tightened before making measurements.

Conclusions

The work described in this paper was performed at X band and was related to a technique for building microwave filters so that the resulting selectivity curve essentially duplicated the theoretical calculations. Excellent correlation has been achieved for Butterworth and Tchebyscheff filters having a 1 db ripple in the pass band and a normalized 3 db fractional bandwidth of 1 to 2 per cent.

Tolerances on the shape of the aperture are not critical and the adjustable iris replaces a library of fixed centrally located irises, thus reducing the cost and time required to align a particular filter.

This technique for obtaining a variation in the shunt inductive susceptance is useful in any frequency band where waveguide elements are used. Variation of the iris susceptance is continuous and much finer than could be achieved by a fixed iris design. As an example, for an iris having an aperture diameter of 0.200 inch, a displacement of 0.050 inch from the center of the waveguide (operating in the TE_{10} mode) effectively changes the diameter of the iris by 0.002 inch.

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