Practical Design of Strip-Transmission-Line Half-Wavelength Resonator Directional Filters*

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Summary—**Strip-transmission-line directional filters have been found extremely useful since they serve as a combination multiplexer and filter assembly. A step by step procedure has been developed for the quarter-wave coupled filter design having a prescribed bandwidth, skirt selectivity, and passband ripple tolerance for narrow band multiplexing applications.**

An experimental study of the strip-transmission-line resonator as an integral part of the directional filter utilizing direct and quarter-wave coupling between the half-wave resonants has been carried out; and an efficient method of tuning a filter is described. This study has included not only problems of insertion loss caused by dissipation but also effects on filter characteristics caused by variations in environmental temperature.

INTRODUCTION

DIRECTIONAL filters are circuits commonly used in multiplexing signals of different frequencies. In a previous paper[1] several unique strip-transmission-line directional filter circuits were described, including the half-wavelength resonator directional filter. The purpose of this paper is to present one design procedure for the development of this type of filter, having a prescribed bandwidth, skirt selectivity, and pass-band ripple tolerance with no undesirable spurious responses over a two to one band of frequencies for narrow band multiplexing applications in the frequency spectrum where strip-transmission-line techniques are useful.

The basic half-wavelength resonator directional filter is shown in Fig. 1(a). The input and output lines shown are reversible since the network is a symmetrical passive network. A study of the phase relationships shows that a wave at the center frequency of the filter entering arm 1 will couple to arm 4. Arm 3 is always isolated from the input. The input line is nonreflecting when the other arms are connected to their characteristic impedances. Representative response characteristics of a maximally flat filter are shown in Fig. 2. By direct or quarter-wave coupling the resonators in cascade, as shown in Fig. 1(b) and 1(c) respectively, greater selectivity is achieved. The filters shown in Fig. 1 will not produce very low midband insertion loss due to the relatively large initial input gap widths that are required in narrow band filters. It was observed that a relatively high mismatch existed in the line 1–2 when the first resonator of a narrow band filter was directly coupled to this line. By inserting a very short length of line in the input and output coupling regions, as shown in Fig. 3, the coupling of power to the filter is improved as a result of less than a 2 to 1 VSWR in the through line and the midband insertion loss is greatly reduced to an acceptable value of less than 2 db.

A number of strip-transmission-line directional filters using direct and quarter-wave coupling were tested. As a result of these tests, it was found experimentally that to obtain a bandwidth tolerance of ± 2 per cent or less, low Q filters ($Q_0 \lesssim 40$) may utilize either direct or quarter-wave coupling of the half-wave resonants. Filters with a higher Q ($Q_0 \gtrsim 40$) should employ quarter-wave coupling only, since direct coupling requires relatively large coupling reactances (wide gaps), which in turn present spurious transmission effects when the strip-transmission-line gaps are greater than approximately $\lambda/10$. Since the design of direct coupled strip-transmission-line filters is given quite adequately by Cohn,[2] this paper will be devoted almost entirely to the design and development of quarter-wave coupled strip-transmission-line directional filters. The theory of quarter-wavelength coupling is described by Ragan.[3] As the Q of a given microwave filter is increased, the fabrication and adjustment of the resonant cavities or strips (as in this case) utilizing direct coupled resonators becomes increasingly more difficult. Thus by employing quarter-wave coupling between the filter resonators, the tolerances on the dimensions of the coupling elements are eased which in turn meet bandwidth tolerance specifications more readily. Tuning of the half-wavelength resonator strips with screws centered above and below the strips was necessary to obtain an acceptable symmetrical band-pass characteristic. Representative tuning screws for each half-wavelength strip are sketched in Fig. 4.

Experimental strip-transmission-line half-wavelength resonator directional filters having one to five per cent bandwidths at S band have been developed with less than 2 db mid-band insertion loss. A three-section Tchebycheff filter with two per cent bandwidth, having a rejection greater than 25 db at frequencies two per cent from the center frequency, had a midband insertion loss of 1 db with no spurious responses over a two to one band of frequencies. The air-strip-transmission-line

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[1] S. B. Cohn and F. S. Coale, "Directional channel-separation filters," PROC. IRE, vol. 44, pp. 1018–1024; August, 1956.

[2] S. B. Cohn, "Direct-coupler-resonator filters," PROC. IRE, vol. 45, pp. 191–192; February, 1957.

[3] G. L. Ragan, "Microwave Transmission Circuits," M.I.T. Rad Labs. Ser., vol. 9, McGraw-Hill Book Company, Inc., New York, N. Y., pp. 677–706; 1948.

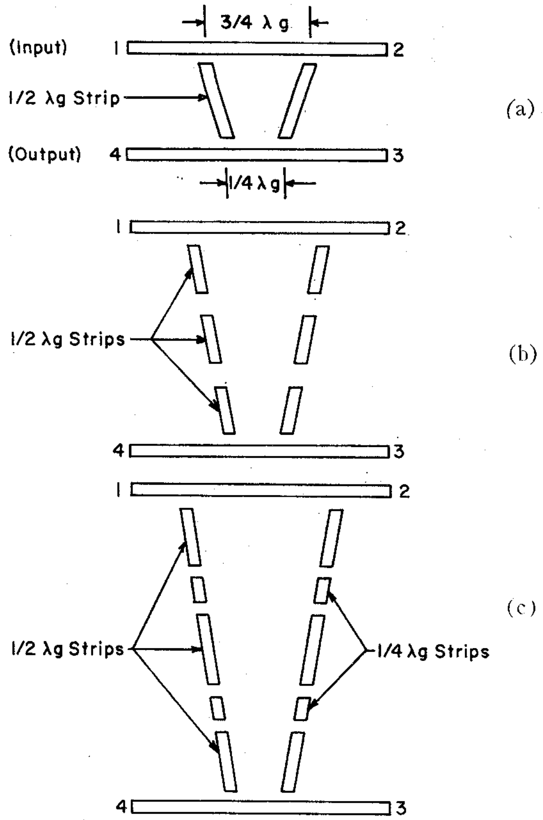

Fig. 1—Half-wavelength resonator directional filter configurations. (a) Basic half-wavelength resonator directional filter. (b) Three section direct coupled directional filter. (c) Three section quarter-wave coupled directional filter.

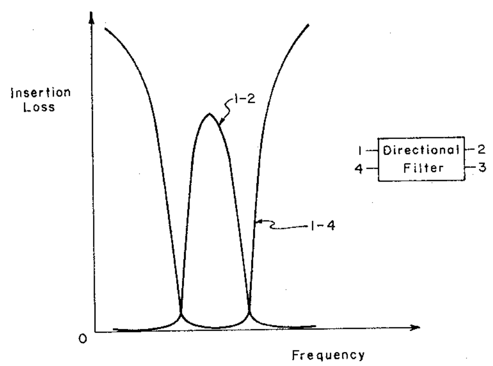

Fig. 2—Insertion loss response characteristics of a directional filter.

filters were fabricated from copper clad Teflon-fiberglass sheets by using engraving techniques. The design techniques discussed in this paper are general and thus are not confined to the above-stated filter characteristics.

Design Procedure

This design procedure is for quarter-wave coupled directional filters. The major portion of the development of this type of filter lies in the design of the band-pass filter which contains the half-wavelength resonators between the input and output transmission lines of the filter. The first step in the synthesis of such filters is the selection of the transmission coefficient corresponding

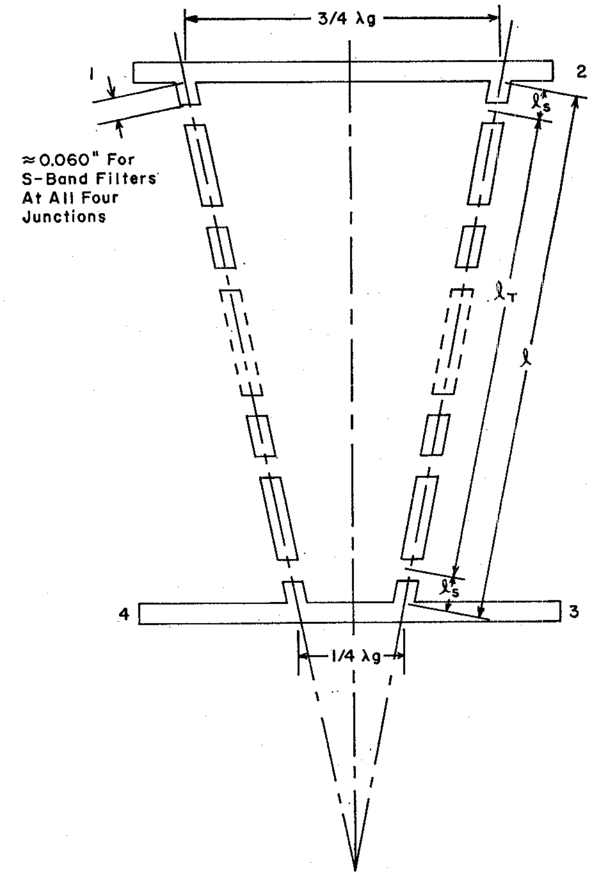

Fig. 3—n-section quarter-wave coupled half-wavelength resonator directional filter.

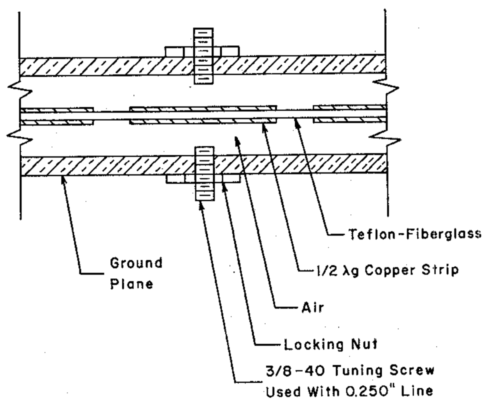

Fig. 4—Tuning screws for one resonant strip in a balanced air strip-transmission-line.

to a network having the desired rejection-band characteristics. In multiplexing signals of closely spaced frequencies, the skirt selectivity specification of each filter in the multiplexer is very important as well as utilizing a minimum of space as most present-day applications require. Therefore, for given band rejection characteristics or skirt selectivity, fewer elements are required when the synthesis is based on a Tchebycheff distribution of the first kind with small tolerable ripple rather than a Butterworth distribution. Following the selection of the transmission coefficient, the corresponding low-pass prototype filter can be synthesized from which a low-pass to band-pass transformation is to be made. From the low-pass prototype the normalized reactive parameters can be obtained for use in the following procedure.

Assuming a narrow bandwidth and infinite unloaded Q, the loaded Q, Q_0, of the filter may be stated as follows:

$$Q_0 = \frac{f_0}{\Delta f} \tag{1}$$

where f_0 is the center frequency and Δf is the filter bandwidth of the band-pass filter. In practice, (1) is very accurate even though the unloaded Q is far from infinite. The loaded Q, Q_{Ln}, of each nth half-wavelength element is determined by the prototype normalized reactive element values, C_n, from the equation:

$$Q_{Ln} = \tfrac{1}{2} C_n Q_0. \tag{2}$$

Since the end discontinuity is the same at both ends of a resonant strip of a quarter-wavelength coupled filter when the filter is loaded at each end by equal resistances, the normalized coupling reactance, $|\bar{X}_n|$, of these end gaps for each nth half-wavelength resonant element is specified[4]

$$|\bar{X}_n| = \sqrt{\frac{4}{\pi} Q_{Ln}}. \tag{3}$$

This condition exists in the subject filter due to the fact that the input and output tabs will present equal resistances at the terminals of the conventional filters which are utilized to construct the V arms of the directional filter.

For filters with 10 per cent or less bandwidth, (3) is accurate enough for most applications. Thus by substituting (2) into (3) a very useful relation is found:

$$|\bar{X}_n| = \sqrt{\frac{2}{\pi} C_n Q_0}. \tag{4}$$

By synthesizing the desired transmission coefficient or utilizing Weinberg's tables,[5] the low-pass prototype normalized element values, C_n, are obtained which determine each normalized gap reactance, $|\bar{X}_n|$. By utilizing a reference table of normalized capacitive reactance, $|\bar{X}|$, vs gap spacing, g, in inches, the gap distance between strips can be determined. For narrow band filters at S band such a graph is shown in Fig. 5. This data was obtained by utilizing Bradley's method[6] of one stage strip-transmission-line filters having different gap spacings at a specified frequency.

[4] E. H. Bradley, "Design and development of strip-line filters," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 86–93; April, 1956.

[5] L. Weinberg, "Modern synthesis network design from tables I–IV," *Electronic Design*, vol. 4, pp. 22–25; September 15, 1956, pp. 22–25; October 1, 1956, pp. 46–47; October 15, 1956, pp. 34–37; November 1, 1956.

[6] E. H. Bradley, *op. cit.*, p. 89.

From Cohn[7] the separation of gap reactances, l_n, for each nth resonant element when the two end gap discontinuities for each nth resonant strip are equal may be stated

$$l_n = \frac{\lambda_{g0}}{2}\left[\frac{\pi - \tan^{-1}\left(\frac{2}{|\bar{X}_n|}\right)}{\pi}\right], \tag{5}$$

where

$$\lambda_{g0} = \frac{\lambda_0}{\sqrt{\epsilon_r}} \tag{6}$$

λ_{g0} = strip-transmission-line wavelength at center frequency of filter

λ_0 = electrical wavelength at center frequency of filter in air

ϵ_r = relative dielectric constant of transmission medium.

A band-pass filter layout with designated dimensions is shown in Fig. 6. The quarter-wavelength coupling dimensions, $S_{n-1,n}$ between the $n-1$ and nth resonant elements are set simply by

$$S_{n-1,n} = \frac{l_{n-1} + l_n}{2} - \frac{\lambda_{g0}}{4}. \tag{7}$$

By inserting one of these band-pass filters into each of the two V arms of the directional filter, the resultant configuration is as shown in Fig. 3. In Fig. 3 the distance, l_T, corresponds to that in Fig. 6.

For the filter to present a high impedance to the main transmission line (arm 1–2 in Fig. 3) in the stop bands of the band-pass filter, the length, l_s, in Fig. 3 must necessarily be a small part of a wavelength. It was found experimentally that the filter will have a low acceptable mid-band insertion loss when l_s satisfies the following equation:

$$l_s = 0.060'' + \frac{g_1}{2} \tag{8}$$

where g_1 is the width of the first and last gap of the filter in inches.

Experimental Results

By utilizing the design procedure for quarter-wave coupled directional filters, filters with band-pass response characteristics of the Butterworth or Tchebycheff type can be designed and fabricated with a midband insertion loss of less than 2 db. When utilizing either type of coupling technique, especially direct coupling, close electrical tolerances on the pass-band characteristics require extreme mechanical fabrication tolerances. Since all the filters to be discussed were fabricated by engraving methods, copper residue fibers within the coupling gaps, which normally remained after the en-

[7] S. B. Cohn, *op. cit.*, p. 192.

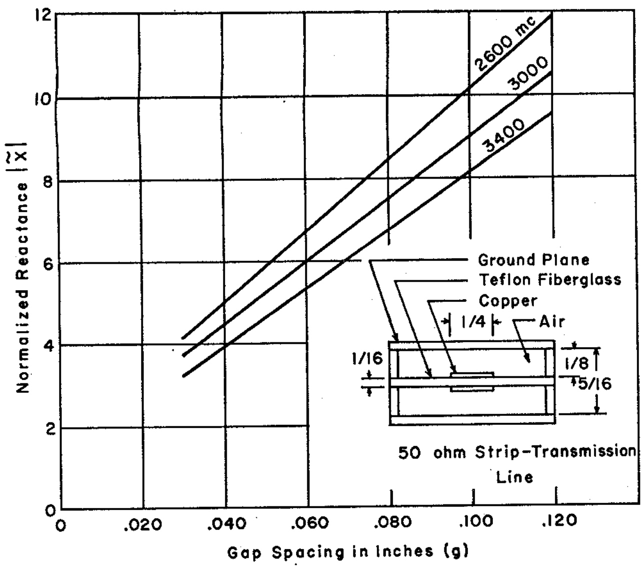

Fig. 5—Reference data of normalized reactance vs gap spacing for strip-transmission-line S-band filters.

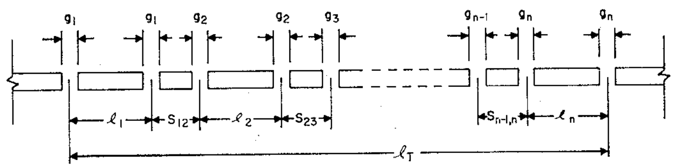

Fig. 6—n-section quarter-wave coupled filter.

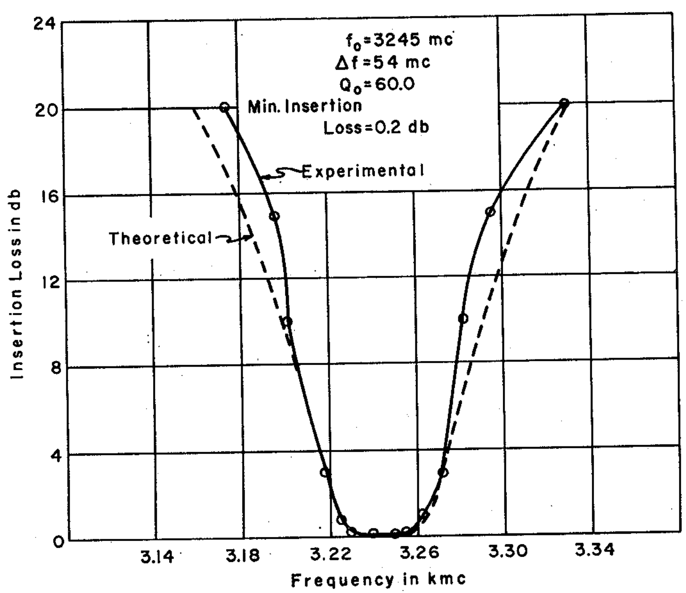

Fig. 7—Butterworth response characteristics of a two section quarter-wave coupled directional filter.

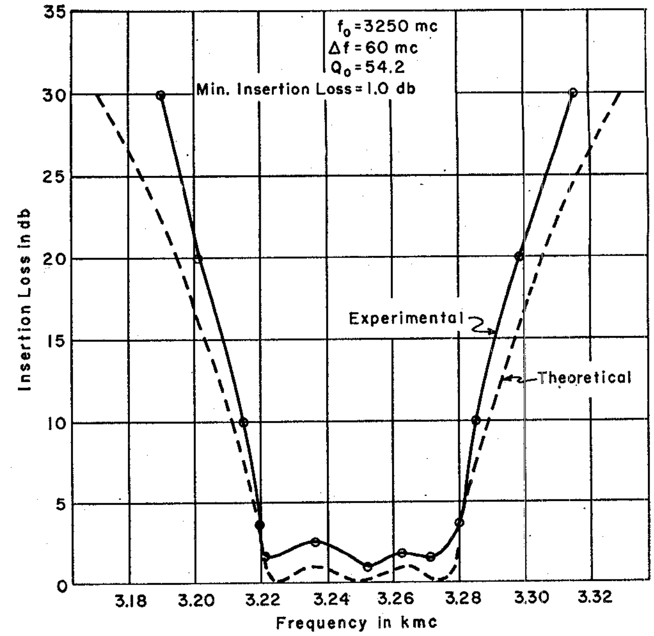

Fig. 8—Tchebycheff response characteristics of a three section quarter-wave coupled directional filter.

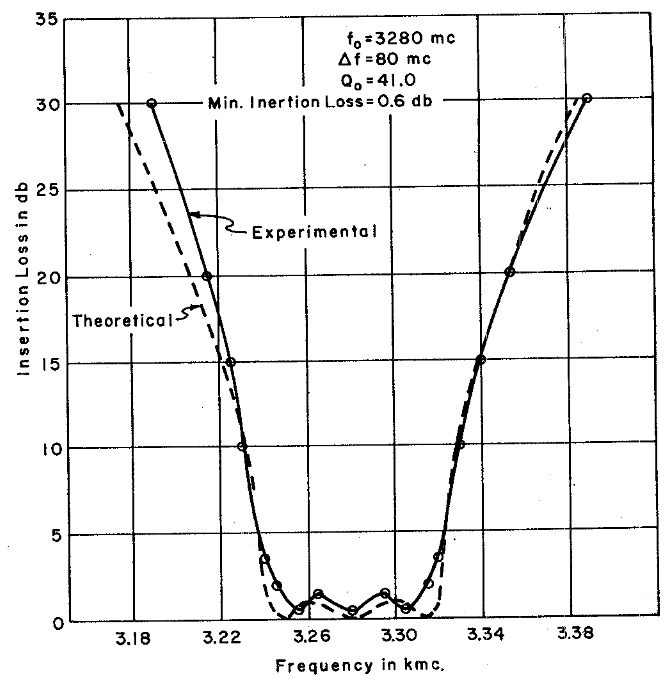

Fig. 9—Tchebycheff response characteristics of a three section direct coupled directional filter.

graving process was completed, were removed by cleaning with ferric chloride and subsequent washing with methyl alcohol. Thus, by cleaning the coupling gaps a more reproducible band-pass characteristic can be obtained.

Figs. 7 and 8 show insertion loss response characteristics of quarter-wave coupled Butterworth and Tchebycheff filters respectively. It should be noted in these two filters, each with a loaded Q of the same order of magnitude, that the Butterworth filter has a midband insertion loss of 0.2 db as compared to the Tchebycheff filter with a 1.0 db loss. The Tchebycheff design of Fig. 8 has the desirable feature of possessing more than 25 db selectivity at frequencies two per cent from the center frequency. The response characteristic of a direct coupled Tchebycheff filter is shown in Fig. 9. Both Tchebycheff filters of Figs. 8 and 9 were designed to have a 1 db ripple in the pass band.

In many applications, filters of the type described in this paper must have a large insertion loss over a wide frequency spectrum outside of their fundamental pass bands. Spurious responses were observed at approximately integer multiples of the fundamental but were less pronounced as the frequency increased. Spurious responses of this type can be removed with a low-pass filter having a cutoff frequency somewhat less than that of the first spurious response.

By properly placing an adjustable short in arm 3 of the directional filter, any mismatch which may be due to improperly tuned filter elements or the crystal output detector in arm 4 may be partially tuned out. The results of such a test are plotted in Fig. 10. It is seen that the adjustable short improves the midband insertion loss as well as decreasing pass-band ripple. As the bandwidth becomes relatively wider, the short is less effective since it is a frequency-sensitive device. This situation was made possible since the directivity of arm 3 was far from infinite.

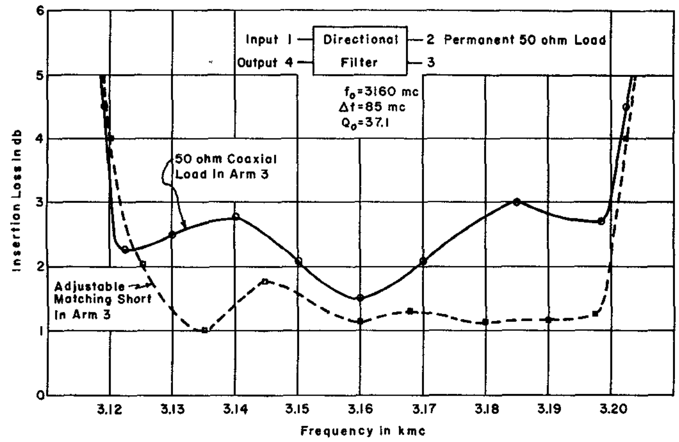

Fig. 10—Directional filter Tchebycheff response characteristics with different loading of the directivity arm number 3.

In an effort to further improve the midband insertion loss of narrow band directional filters, the copper clad Teflon-fiberglass was silver-plated several times the thickness of the skin depth at S-band frequencies, after which the filter was engraved. Although it was felt that this would increase the unloaded Q of the strip-transmission-line structure, no improvement of the midband insertion loss over the standard copper clad dielectric was observed. The most noted improvement of insertion loss was obtained using a Butterworth design rather than a Tchebycheff of the same loaded Q. Experimentally the improvement varied from 0.2 to 0.8 db, depending on the loaded Q and the selectivity desired.

Three of these directional filters engraved on one copper clad Teflon-fiberglass card as shown in Fig. 11 had a multiplexed insertion loss characteristic as shown in Fig. 12. The bandwidth of each filter is 60 mc and the center frequencies were spaced 60 mc apart. From the insertion loss and VSWR plots of these filters, it is seen that the theory of the directional filter proves to be excellent in practice.

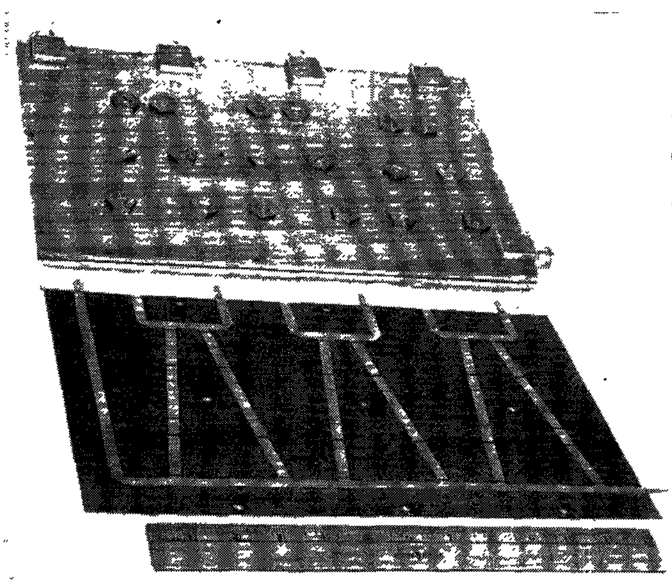

Fig. 11—Three multiplex directional filters: assembled unit and center conductor.

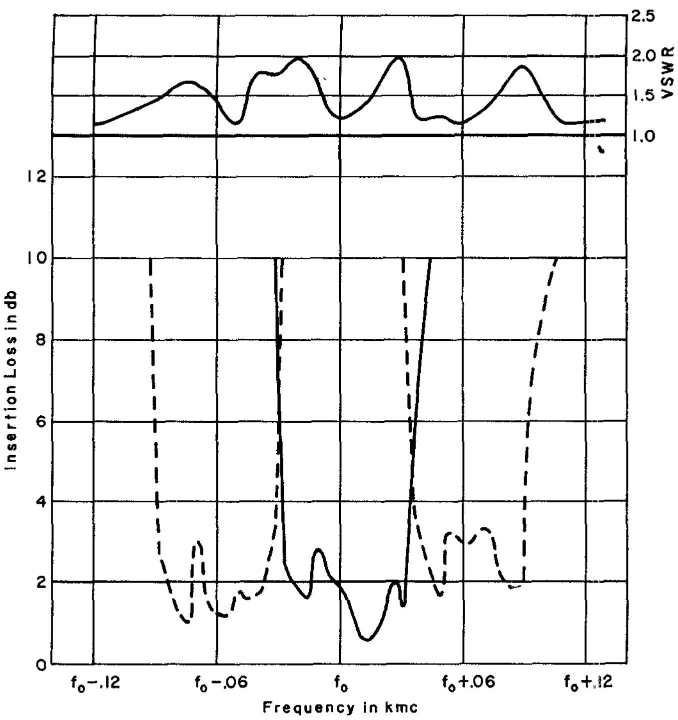

Fig. 12—Insertion loss and VSWR characterissics of three S-band multiplexed directional filtter.

A multiplexed filter array consisting of a number of filters operated very well under extreme environmental temperature. The center frequency of the S-band filters shifted approximately one mc at a temperature of 125°C as compared to room temperature.

The tuning procedure developed for these directional filters is an easy and rapid technique of tuning and will be discussed in the next section. It was found experimentally that the center frequency of these narrow band directional filters could be shifted approximately ±2 per cent about the designed center frequency without *noting any* deleterious effects on the band-pass characteristics.

Tuning Procedure

The tuning procedure for direct or quarter-wave coupled filters involves a method of quarter-wave shifting the VSWR nulls on the input transmission line to the filter. The procedure to follow will refer to the circuit layout in Fig. 13. Adjustment of any tuning screws for a meter deflection must carefully be made for the maximum possible meter deflection while keeping each pair of tuning screws equidistant from the resonant balanced strip-transmission-line.

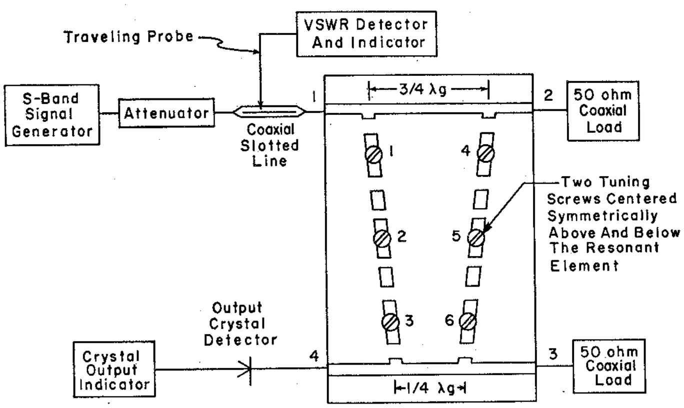

Fig. 13—Circuit for tuning a directional filter.

Procedure:

1) With the signal generator calibrated to the filter center frequency and all tuning screws shorted to the resonant strips, place a 50 ohm coaxial load in arms 2 and 3 and a crystal detector in arm 4.

2) Adjust the second resonant section (containing screws 4, 5, and 6) by turning the screws out from the strips until they are flush with the ground plane. Then adjust these three screws one at a time for a rough minimum insertion loss as measured with the crystal output detector.

3) Remove the 50 ohm load in arm 2 and replace with a variable short. Carefully adjust this short until minimum insertion loss is measured with the output crystal detector. This short reflects an open circuit to the input junction of this second resonant section.

4) Re-short all the tuning screws (4, 5, and 6) and with the slotted line locate two nulls in the standing wave pattern. Interpolate the position of these nulls to locate the maximum point between the nulls and place the slotted line probe at this maximum.

5) Tune the pair of tuning screws (4) nearest the input line of the second resonant section until maximum VSWR is obtained and lock in place.

6) Move the slotted-line probe one-quarter wavelength in either direction to one of the original nulls (now a maximum). Tune the middle pair of tuning screws (5) for a maximum and lock in place.

7) Tune the last pair of tuning screws (6) for minimum insertion loss as measured with the output crystal detector (the VSWR will become a minimum) and lock in place.

8) Readjust the variable short in arm 2 for a maximum VSWR. The short will now reflect a short circuit at the input junction to the second tuned resonant section and an open circuit to the input junction of the first untuned resonant section due to the $\frac{3}{4}\lambda_g$ coupling distance between junctions.

9) Tune screws 1, 2, and 3 in the first resonant section respectively the same as screws 4, 5, and 6 in the second resonant section according to the steps 5, 6, and 7 of this procedure.

10) Replace the variable short in arm 2 with a 50 ohm coaxial load and insert a variable short in place of the load in arm 3. Adjust this short for an optimum band-pass characteristic. This short in arm 3 when positioned properly will partially tune out any small mismatched reactances in the output line (3–4) which may be present due to the filter, crystal detector, or both.

11) If more than one directional filter is connected to line 1–2, screws 1 and 4 of all untuned filters should be shorted to the strip-transmission-line while one filter is being tuned. Once a filter is tuned properly it should have no effect on adjacent filters while they are being tuned.

Conclusion

The design formulas presented here provide the engineer with a practical design procedure for the development of narrow band half-wavelength resonator directional filters having a specified bandwidth and skirt selectivity in a strip-transmission-line structure. Since the tuning of this filter is relatively simple, the authors feel that this type of filter will prove desirable for some multiplexing applications.

Acknowledgment

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