Ferrite-Loaded, Circularly Polarized Microwave Cavity Filters*

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Summary—Circularly polarized cavities have made possible a group of compact, high-Q, microwave waveguide filters having useful directional properties. When these cavity filters are ferrite loaded, frequency sensitive circulators result and magnetic tuning becomes possible. This paper presents several new three- and four-port ferrite-loaded filters, some with 3-db waveguide couplers, which can be used as tunable band-pass filters, tunable band-rejection filters, or as passive, selective duplexers. As duplexers, they can be operated at a fixed frequency or can be magnetically tuned over a one to five per cent frequency range at X band depending upon the allowable loss. Experimental loss, bandwidth, isolation, and tuning data are presented. Temperature stability and power handling capacity are also discussed.

Introduction

CAVITIES utilizing degenerate modes phased to produce circularly polarized microwave magnetic fields at some point in the cavity have been used extensively to measure ferrite permeability parameters. The circularly polarized cavity fields have been excited in several ways. A quarter-wave plate in a circular or square waveguide can be used to produce circularly polarized waveguide fields which are then coupled through a small aperture to the cavity.[1–3] Two apertures, which are 90 electrical degrees apart in the cavity have been used to excite orthogonal linear modes; by exciting them 90° apart in time phase circular polarization results. A single aperture has also been used to couple into a degenerate cavity with a ferrite placed in a region where a circularly polarized magnetic field can exist.[4–6] When a magnetic field is applied to the ferrite, the cavity degeneracy is removed in the sense that the resonant frequencies for positive and negative circular polarization separate. The single aperture thus sees two resonant frequencies, and at each of these resonances, couples primarily to only one sense of polarization. For some applications such as the tunable, band-pass filter, only one resonant frequency is desired, and a multiport filter which can distinguish between directions of field rotation is desirable.

In most of these experiments for the determination of ferrite properties, the desire has been to make the polarization at the ferrite as nearly circular as possible and to keep the ferrite samples as small as possible to increase the accuracy of the perturbation calculations. The coupling apertures used were generally much smaller than required for microwave filter applications.

Circularly polarized cavities have recently been incorporated as microwave circuit elements, and several compact, nearly reflectionless microwave filters have resulted.[7–9] The use of circular polarization in effect replaces two cavities and associated connecting plumbing with a single cavity. (Two previous filters requiring two cavities are described by Lewis and Tillotson[10] and Bowers and Curtis.[11] Another reflectionless filter requiring only one cavity is described by Klopfenstein and Epstein.[12]) In general, these filters have used coupling from two waveguide field components—for example, H_x and H_z—through a single aperture. This symmetrical type of coupling makes it possible to essentially eliminate reflections in the waveguide over a wide band of frequencies including the cavity resonant frequency. This property greatly simplifies cascading of the cavity filters. Band-pass and band-elimination filters have been built using these cavities, but perhaps the most interesting filter is a four-port device which can be used as a reflectionless, channel-separation filter.

Ferrite loading has been applied to these filters[13] with the object of producing tunable, nonreciprocal microwave elements while preserving the desirable features of the low-loss cavity. (Ferrite tuning of linear cavity

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[2] E. G. Spencer, R. C. LeCraw, and F. Reggia, "Measurement of microwave dielectric constants and tensor permeabilities of ferrite spheres," Proc. IRE, vol. 44, pp. 790–800; June, 1956.

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[4] A. D. Berk and B. Lax, "Cavities with complex media," 1953 IRE Convention Record, pt. 10, pp. 65–69.

[5] B. Lax and A. D. Berk, "Resonance in cavities with complex media," 1953 IRE Convention Record, pt. 10, pp. 70–74.

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[7] S. B. Cohn and F. S. Coale, "Directional channel-separation filters," Proc. IRE, vol. 44, pp. 1018–1024; August, 1956; also, 1956 IRE Convention Record, pt. 5, pp. 106–112.

[8] C. E. Nelson, "Circularly polarized microwave cavity filters," IRE Trans., vol. MTT-5, pp. 136–147; April, 1957.

[9] C. E. Nelson and W. L. Whirry, "Development of circularly polarized microwave cavity fiters," 1957 National IRE Convention Record, pt. 1, pp. 191–196.

[10] W. D. Lewis and L. C. Tillotson, "A nonreflecting branching filter for microwaves," *Bell Sys. Tech. J.*, vol. 27, pp. 83–95; January, 1948.

[11] E. O. Bowers and C. W. Curtis, "A resonant cavity frequency duplexer," 1956 IRE Convention Record, pt. 5, pp. 113–118.

[12] R. W. Klopfenstein and J. Epstein, "The polarguide—a constant resistance waveguide filter," Proc. IRE, vol. 44, pp. 210–218; February, 1956.

[13] C. E. Nelson, "Ferrite-Tunable microwave cavities and the introduction of a new reflectionless, tunable microwave filter," Proc. IRE, vol. 44, pp. 1449–1455; October, 1956.

mode filters is described.[14–16] One can show from perturbation theory that for a given mode, a symmetric ferrite placed at a point where the rf magnetic field is circularly polarized should give a greater total magnetic tuning range for a given allowable loss than a ferrite placed at a point of linearly polarized rf magnetic field. The above presumes a ferrite with small zero field magnetic loss which will allow the total tuning range to include zero field.

Ferrite-loaded band-elimination filters have been constructed using the TE_{111} and the TM_{110} circular cylindrical modes. Ferrite-loaded four-port filters have been described using the TE_{112} and TM_{110} modes with coupling to the end of the cylindrical cavity. These devices can be used as magnetically-tunable band-pass filters or as selective, passive duplexers.

The TE_{112} mode, with coupling apertures at each end of the circular cylinder, requires that the ferrite be supported in the center of the cavity, making the application of the dc magnetic field from a permanent magnet difficult. The TM_{110} mode is desirable for use with ferrites because a long rod can be located in the circularly polarized magnetic field and yet remain magnetically small in a perturbation sense.[6] For ease of ferrite support and to allow the magnetic air gap to be as small as possible, it is convenient to have both ends of the cylindrical cavity free. This paper describes several four-port filters which meet these requirements. Three-port variations are then described; these, when ferrite loaded, will perform many of the useful functions of the four-port filters.

Four-Port Filters Using Directional Couplers

By using two 3-db directional waveguide couplers to satisfy the power splitting and 90° phase shift requirements for exciting circular polarization with two apertures, a group of compact, four-port, single-cavity, reflectionless filters has been developed which are well suited to ferrite loading. One version is shown in Fig. 1(a): a degenerate TM_{110} circular cavity is coupled magnetically by four apertures to four rectangular waveguides. One 3-db side-wall coupler is used on each side, as shown. Apertures 1 and 3 couple to one TM_{110} cavity mode and apertures 2 and 4 couple to the orthogonal TM_{110} mode. The frequency sensitivity of the quarter-wave aperture-short distance could be eliminated by coupling to the end of the waveguides. Energy entering port A will be divided by the 3-db coupler. One half of the incident input energy reaches aperture 1 and the other half arrives at aperture 2, lagging that at aperture 1 by 90° in time. Thus, a counterclockwise rotating cavity mode tends to be excited. At or near resonance,

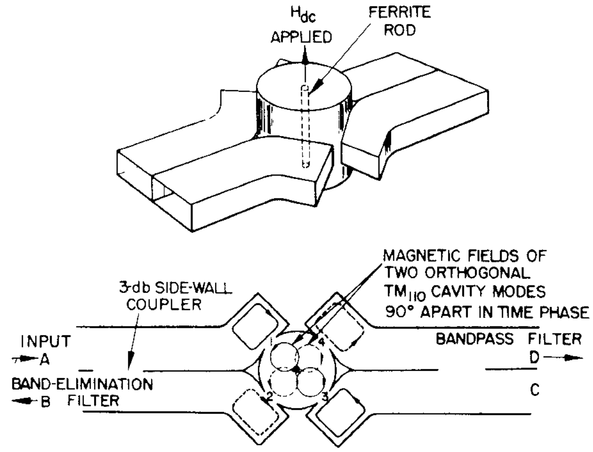

Fig. 1(a)—Four-port, circularly polarized filter using two 3-db couplers.

energy will be coupled out of apertures 3 and 4 and will be 90° out of time phase so that addition occurs in arm D and cancellation in arm C.

Consider the behavior of the cavity without the ferrite, or with the ferrite demagnetized. In terms of linear modes; two orthogonal cavity modes which have equal amplitudes but are 90° out of time phase are excited by apertures 1 and 2. There are band-pass filters between apertures 1 and 3 and between 2 and 4. At the cavity resonant frequency (each mode will be resonant at the same frequency), energy will be coupled out apertures 3 and 4 and will be of the proper phase so that addition occurs in arm D and cancellation occurs in arm C. Ideally, energy reflected at apertures 1 and 2 and at the short circuits, both on and off resonance, will add in arm B and cancel in arm A. Therefore, there is a reflectionless, band-pass filter between ports A and D, and a band-elimination filter between ports A and B. The characteristics are, of course, reciprocal and symmetrical with respect to any port, in this case.

When a longitudinally magnetized ferrite rod is placed in the center of the cavity, the normal modes of the cavity become rotating field patterns with different resonant frequencies for positive and negative senses of rotation.[4] Energy entering port A will tend to couple into a clockwise rotating mode, which corresponds to positive circular polarization with resonant frequency f_+ for the direction of dc magnetic field shown. Energy entering port B will tend to excite negative circular polarization, resonant at f_-. At f_+, the filter is essentially a four-port circulator with energy circulating between ports in a clockwise direction. At f_-, energy circulates in a counterclockwise direction. A magnetically tunable band-pass cavity acts in series with legs A–D and B–C. Far from resonance, the device is no longer a circulator, and a waveguide path which will take high power exists between ports A and B and between ports C and D.

For an experimental model of this filter, curves of frequency shift due to the ferrite vs applied dc field are shown in Fig. 1(b) for three Ferramic R-1 rods of different sizes. The rods are slightly shorter than the length

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[15] G. R. Jones, J. C. Cacheris, and C. A. Morrison, "Magnetic tuning of resonant cavities and wide band frequency modulation of klystrons," Proc. IRE, vol. 44, pp. 1431–1438; October, 1956.
[16] C. E. Fay, "Ferrite-tuned resonant cavities," Proc. IRE, vol. 44, pp. 1446–1449; October, 1956.

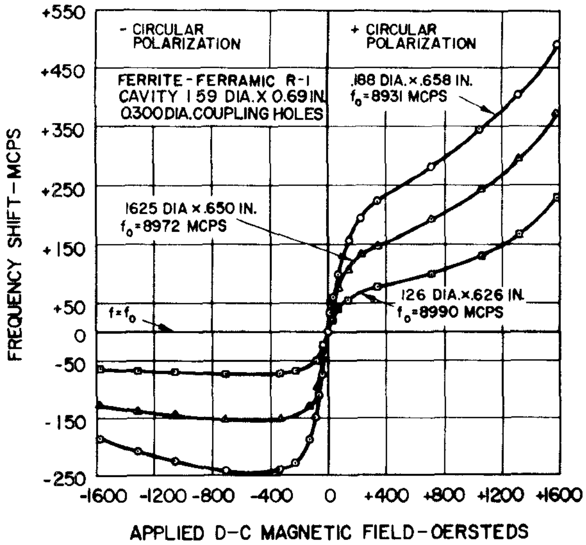

Fig. 1(b)—Resonant frequency, port A to port D, vs dc magnetic field.

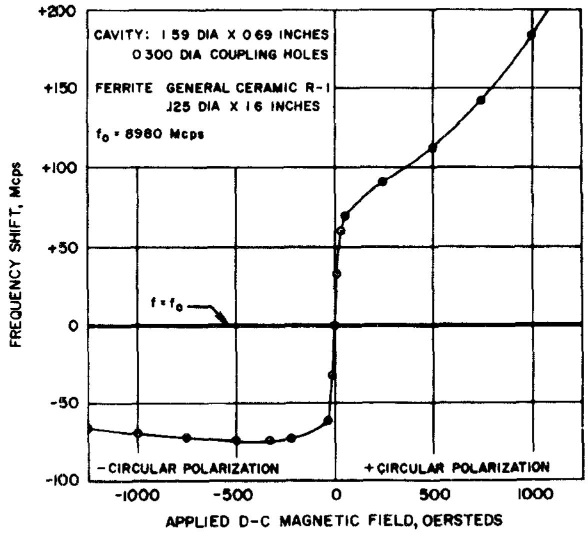

Fig. 1(c)—Resonant frequency, port A to port D, vs dc magnetic field.

of the cavity in each case. The curves have the general shape of the effective permeability curves for circular polarization. The way in which the frequency shift for the larger diameter rod is departing from a simple perturbation might be roughly seen by comparing the ratio of the frequency shifts due to the large and small ferrites at a given magnetic field, to the ratio of their volumes. At a field of -500 oersteds, the 0.188-inch-diameter rod gives nearly 50 per cent more frequency shift than would be predicted from the shift for the 0.126-inch-diameter rod and the increase in volume. At $+500$ oersteds, it gives approximately 30 per cent more. For positive fields greater than about 1300 oersteds, the larger rods give less frequency shift than would be expected. The different value of f_0 for each rod is due primarily to the zero field permeability of the ferrite. Because of the severe effect of ferromagnetic resonance

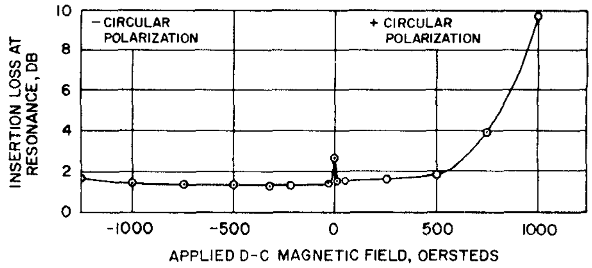

Fig. 1(d)—Insertion loss, port A to port D, vs dc magnetic field.

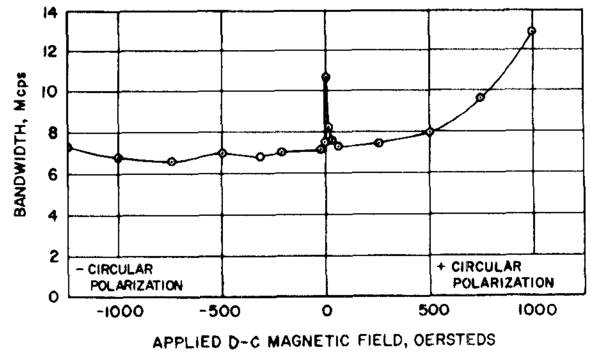

Fig. 1(e)—Bandwidth, port A to port D, vs dc magnetic field.

losses on the total cavity loss, it will be seen that the useful operating region of these cavities as tunable, band-pass filters is the region near and below saturation for both positive and negative circular polarization. Above saturation for negative circular polarization, the frequency shift moves back toward zero.

A ferrite rod which is longer than the cavity would be expected to give a more uniform dc field in the ferrite and more uniform circularly polarized rf fields. Fig. 1(c) shows the frequency shift curve for a $\frac{1}{8}$-inch diameter Ferramic R-1 rod which extends beyond each end of the cavity. The frequency shift at a given dc field is seen to be slightly larger than for the shorter R-1 rod, as expected.

Figs. 1(d) and 1(e) illustrate the insertion loss at resonance and bandwidth of the tunable band-pass filter between ports A and D for the long ferrite rod. The higher loss and larger bandwidth at zero field are due to stray coupling and consequent loss in the unwanted sense of circular polarization, since both senses are resonant at the same frequency with the ferrite unmagnetized. The loss and bandwidth could undoubtedly be reduced by closer mechanical tolerances. When magnetized, the ferrite actually improves the performance of this filter. For larger negative fields than are shown in the curves, the insertion loss and bandwidth for negative circular polarization rise rapidly. This is presumably due to the component of positive circular polarization present off the cavity axis. For most applications, this effect is unimportant.

The insertion loss of the band-pass filter and the unloaded cavity Q, including ferrite losses, for a given frequency shift are plotted in Fig. 1(f) for the three shorter ferrites. The empty cavity, without ferrite, has an unloaded Q of approximately 9000. Each window has a window-coupling factor, Q_w, of 3000 for coupling to a linear cavity mode or a Q_w of 6000 for coupling to a single rotating mode using a magnetized ferrite. When coupling to a rotating mode, the two windows on one side of the filter give a combined window Q of 3000. It can be seen that a tuning range of 175 mc can be obtained with an unloaded Q near 6000 using the smallest diameter ferrite, while a tuning range of 550 mc can be obtained with an unloaded Q of 3000 to 4000 using the largest diameter rod. This behavior is the result of the ferrite permeability and loss characteristics considered as perturbations, but the broadening and flattening of the central portion of the curve for the larger rods is aided by the way in which the operation is departing from a simple perturbation.

As this filter is a circulator at resonance, it might also be used as a selective, passive duplexer. The transmitter is connected to port A and operates at f_-. The antenna is connected to port B and the receiver to port C. Energy from the transmitter encounters a cavity off resonance and is reflected to the antenna. Incoming energy from the antenna at f_- sees a resonant cavity and is coupled out port C. Since reflections from the antenna reach the receiver directly, this system requires a very well matched antenna to operate without some additional protective tr device for the receiver. There is some remote possibility of using the cavity itself as the tr switch. The duplexer can be operated at a fixed frequency or it can be tuned over a limited range by varying the dc field. Zero field must be avoided. To minimize antenna-receiver losses, the 0.125-inch-diameter×1.69-inch ferrite was used in the experimental cavity. From Figs. 1(c)–1(e), it is seen that for fixed-frequency operation with minimum loss and bandwidth, transmission through the cavity should be via negative circular polarization with magnetic fields between about 100 and 1000 oersteds. Over this range, stray variations in magnetic field have little effect on the resonant frequency. A small Alnico 5 permanent magnet ($\frac{1}{2}$ by $\frac{1}{2}$ by $2\frac{1}{2}$ inches) was chosen which gave an effective field of approximately 175 oersteds. At this field strength the nonuniformity of the field was found to have little effect on loss. The separation between the resonant frequencies for positive and negative polarization was about 150 mc, and the loss between transmitter and antenna was 0.2 db. The loss between antenna and receiver was 1.36 db and the bandwidth was 7.0 mc. The theoretical cavity-wall losses for silver would produce a loss of 0.85 db. Normally, the cavity-wall losses are from 25 to 40 per cent higher than this value. Therefore, in this case the added loss due to the ferrite is small. Fig. 1(g) shows the isolation between transmitter and receiver for a perfectly matched antenna, as a function of frequency. At the operating frequency the isolation, before any attempts at maximizing

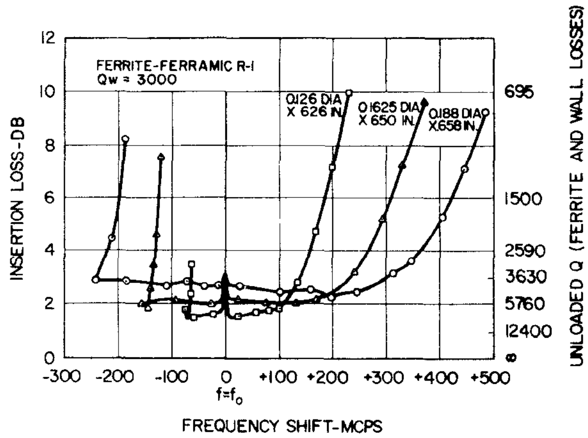

Fig. 1(f)—Insertion loss and unloaded Q, port A to port D, vs frequency shift.

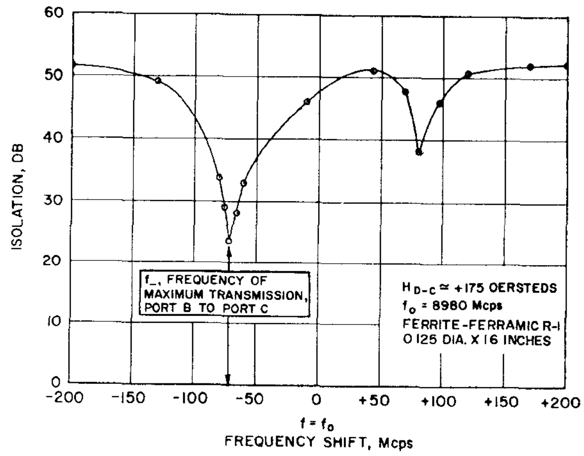

Fig. 1(g)—Isolation, port A to port C, vs frequency.

it, was only 23 db. Fig. 1(g) is included because it gives a good indication of the way in which stray coupling is occurring between transmitter and receiver. The large dip near the operating frequency f_- is mainly due to energy transmitted through the cavity via negative circular polarization. This energy can reach the cavity because of imperfect power division and phase errors in the left-hand 3-db coupler, unequal coupling-hole sizes in apertures 1 and 2, and phase errors due to unequal line lengths or coupling holes not spatially at 90°. By correcting the phase and equalizing the power division on the transmitter side, the isolation was raised above 40 db at the operating frequency. The smaller dip in Fig. 1(g) near $\Delta f = +80$ mc, is a measure of the energy coupled through the cavity by positive circular polarization. This energy is directly coupled into the cavity which is off resonance to this frequency and can reach the receiver only through phase and power-splitting errors occurring on the right-hand side of the filter.

The input vswr of the filter is less than 1.25 over the range of the couplers. At resonance it drops to 1.1. In tentative tests, the device operated at a transmitter-pulsed peak power of 250 kw without breakdown into a load vswr in arm B of 1.1.

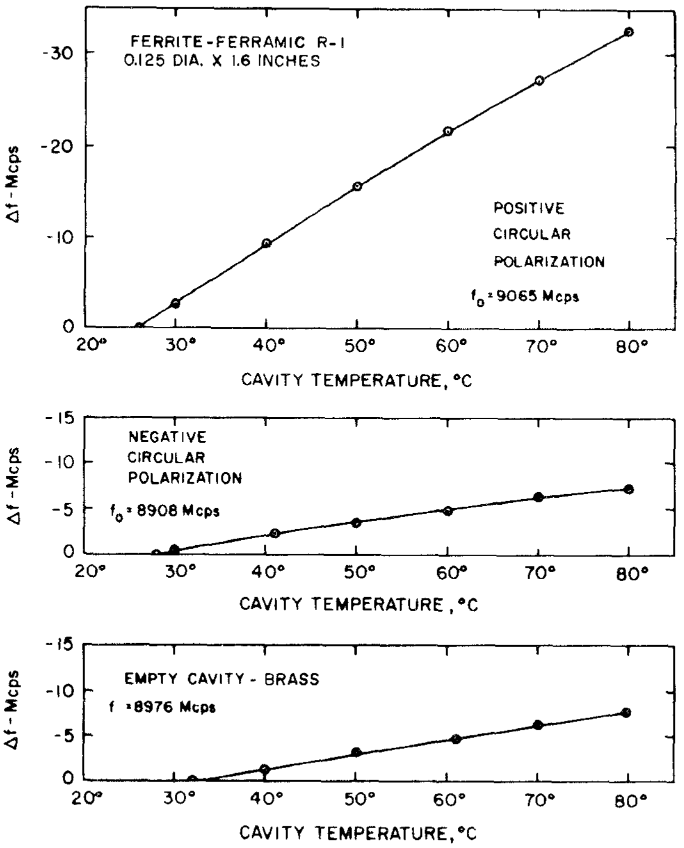

Fig. 1(h)—Frequency drift vs temperature.

Fig. 1(h) shows the variation in cavity resonant frequency vs temperature with the small Alnico 5 permanent magnet in place. As would be expected, for transmission on negative circular polarization, the frequency drift was slightly less than that for the brass cavity without ferrite. For positive circular polarization at this field the drift for the ferrite-loaded cavity was approximately four times larger. By proper choice of cavity mode and magnet configuration, low-expansion ferromagnetic alloys, such as invar, can be used to reduce this drift as in normal cavity design. Electrical temperature compensation is also possible.

Many variations of this filter are possible by using top- or side-wall couplers and other cavity modes. For example, Fig. 2 shows one version using only two apertures. In this arrangement, energy is reflected from the cavity near resonance and emerges from port *B*. Off resonance, the rf energy does not see the cavity and adds at port *C*.

Three-Port Ferrite-Loaded Filters

For duplexer operation, the previous four-port filters have an unused arm which must be terminated in a load. In lossless nonreciprocal devices it is possible to have three- as well as four-port networks which are theoretically matched looking into all ports, and the resulting three-port circulators have the proper characteristics for passive duplexer operation, again assuming a very well matched antenna. It does not appear possible to build a two-port, tunable, band-pass filter using a circularly polarized cavity which will have only one resonant, transmission frequency, unless nonreciprocal or nonlossless elements in the cavity-waveguide coupling system are allowed. A three-port filter should thus be the simplest configuration for this purpose. As will be seen, however, difficulty arises in trying to tune through the zero dc field condition. With these characteristics in mind, several three-port filters were investigated.

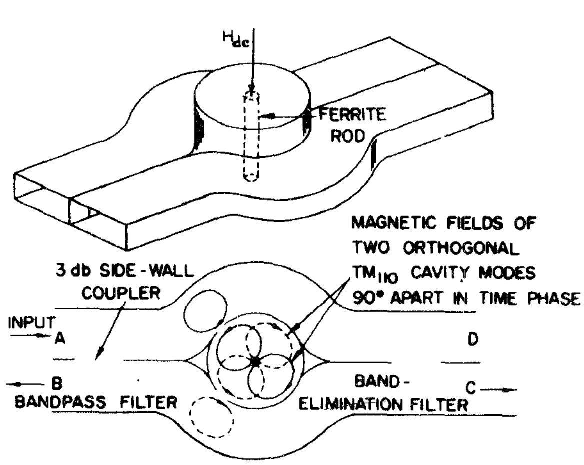

Fig. 2—Ferrite loaded, circularly polarized filter using two 3-db couplers, and two coupling apertures.

Fig. 3(a) illustrates a three-port filter which uses ferrite-loaded, degenerate, circular, TM_{110} cavity modes. The coupling aperture in waveguide *A–B* is placed at the point of circularly polarized magnetic field in the waveguide. Waveguide *C* is magnetically coupled to the TM_{110} cavity mode. Energy entering port *A* tends to excite a positive circularly polarized TM_{110} cavity mode and energy entering *B*, a negative circularly polarized mode for the dc magnetic field shown. Port *C* couples energy out of the linearly polarized component of these fields shown by the solid lines in the top view in Fig. 3(a). Port *C* thus has equal coupling to either positive or negative sense of cavity field rotation. The magnetic field at the wall of the cavity is, of course, linearly polarized in either case. The position of arm *C* around the cavity does not alter the operation of the filter.

The filter has nonreciprocal directional properties similar to those of the four-port filter previously described. The filter is band-pass at one frequency from *A* to *C* or from *C* to *B* and band elimination from *A* to *B*. The filter is band-pass at another frequency from *B* to *C* or from *C* to *A* and band elimination from *B* to *A*. These are the directional properties of a three-port circulator which circulates the energy between ports in one direction at or near f_+ and in the opposite direction at or near f_-. Far from resonance, ports *A* and *B* are directly connected and port *C* is decoupled.

For an experimental, *X*-band model, the resonant frequency for maximum transmission through the band-pass filter from port *A* to port *C* as a function of dc magnetic field is shown in Fig. 3(b). It is seen in Figs. 3(c) and 3(d) that losses are a minimum for transmis-

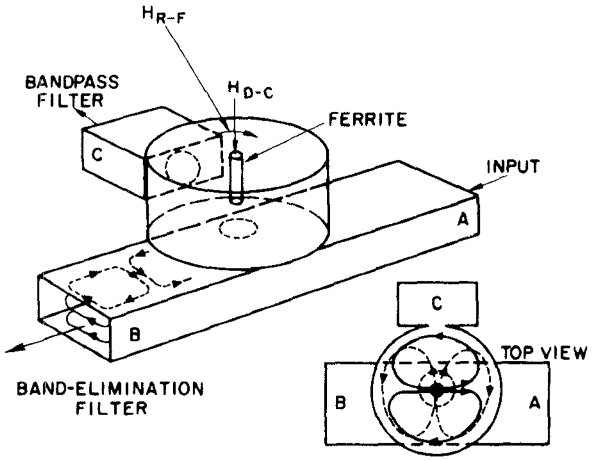

Fig. 3(a)—Ferrite loaded, three-port, circularly polarized filter using two TM_{110} cavity nodes.

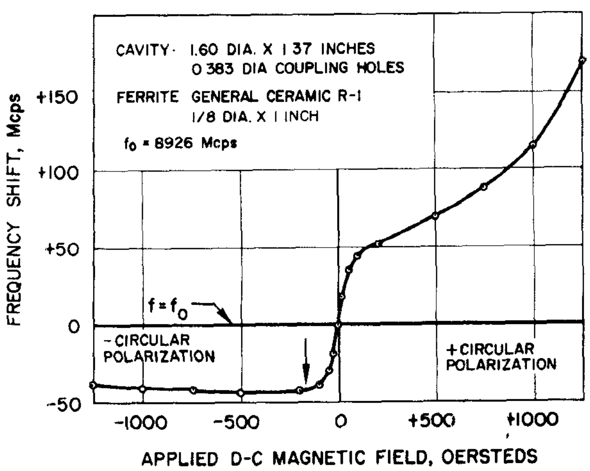

Fig. 3(b)—Resonant frequency, port A to port C, vs dc magnetic field.

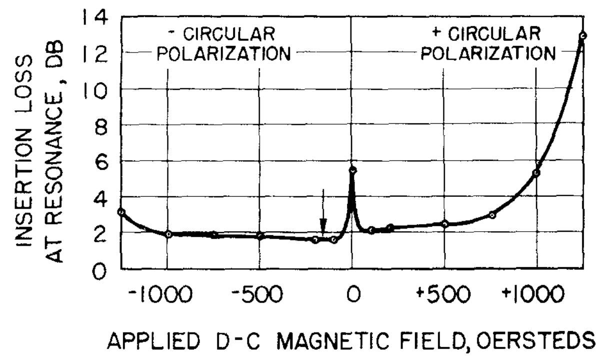

Fig. 3(c)—Insertion loss, port A to port C, vs dc magnetic field.

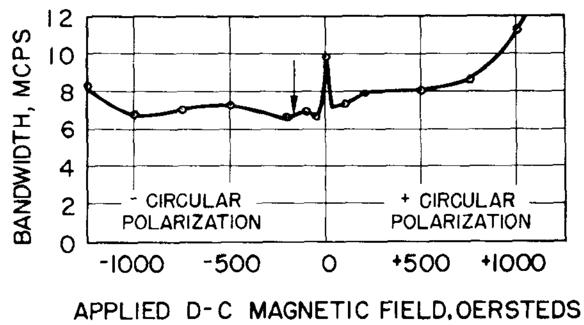

Fig. 3(d)—Bandwidth, port A to port C, vs dc magnetic field.

sion via negative circular polarization and rise rapidly with appreciable positive dc fields. As before, for transmission via negative circular polarization the resonant frequency is nearly independent of applied field below about -100 oersteds, while the insertion loss remains low between -100 and -1000 oersteds. With transmission by positive circular polarization a limited tuning range is possible before the insertion loss begins to rise because of ferrite resonance losses.

This filter might also be used as a selective duplexer. The transmitter would be connected to port B, the antenna to port A, and the receiver to port C. The frequency curve in Fig. 3(b) gives the operating frequency for a given dc field from a permanent magnet. The insertion loss and bandwidth curves in Figs. 3(c) and (d) are then the loss and bandwidth between the antenna and receiver. Energy from the transmitter sees a cavity off resonance and passes to the antenna with negligible loss. Energy from the antenna sees the cavity on resonance and is passed to the receiver.

It can be seen from Figs. 3(c)–3(d) that an effective magnetic field of -175 oersteds again gives nearly minimum losses and a reasonable frequency separation between f_+ and f_-.

When a small permanent magnet is used, energy entering arm B from the transmitter sees a cavity that is 100 mc off resonance, and any energy reaching the receiver in arm C by this path is attenuated over 30 db. This isolation of receiver from transmitter is shown as a function of frequency in Fig. 3(e). The curve closely follows the calculated coupling through a cavity off resonance except for the peak near the frequency of maximum A to C transmission. This cancellation is probably caused by stray coupling due to asymmetries in the cavity and coupling holes.

The vswr looking into arm B is less than 1.10 over a 10 per cent bandwidth at X band, including both resonances.

A theoretical analysis of the filter shows that there is a definite relation between coupling-hole diameters for minimum insertion loss, as would be expected. The holes in the filter just presented were near to the optimum size. A small adjustment in hole diameter did reduce the insertion loss from 1.6 to 1.2 db, but it raised the bandwidth from 6.7 to 8.6 mc.

It is interesting to consider the characteristics of the filter looking from the receiver into arm C. Energy entering this port can couple into the cavity at either of the two resonant frequencies of the circularly polarized cavity modes. The side-coupling hole has the proper symmetry for coupling into the linearly polarized TM_{110} mode shown by the solid lines in Fig. 3(a). The ferrite then couples energy from this mode into the orthogonal mode which lags or leads by 90° in time. Consequently,

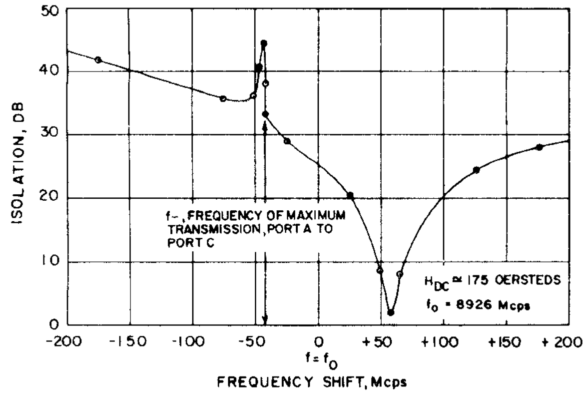

Fig. 3(e)—Isolation, port B to port C, vs frequency.

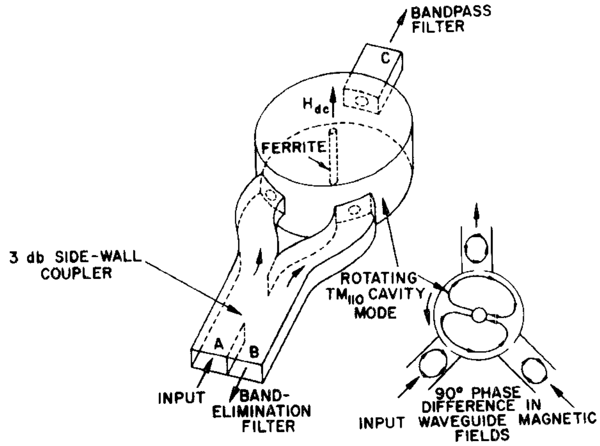

Fig. 4—Ferrite loaded, three-port filter using one 3-db coupler.

a nearly pure circularly polarized cavity field results at each resonant frequency when they are well separated. Off resonance, the excited cavity field is small, and essentially all energy entering C is reflected. With zero dc field, there is no coupling through the ferrite; hence, only the single linearly polarized mode is excited which couples equally out ports A and B. This single mode could also be decomposed into oppositely rotating fields which would then couple equally out of ports A and B. This division accounts for the increased loss and bandwidth seen in Fig. 3(c) at zero field. It should also be noted that the vswr looking into ports A and B rises at zero field because the two linear cavity modes are not loaded equally and consequently their reflections do not cancel in the main guide.

The input vswr looking into port C at resonance for the negative circularly polarized fields is 1.3. This value could theoretically be made 1.0 with only a negligible increase in loss with the same bandwidth by a slight increase in coupling-hole size at port C and a slight reduction in the other coupling-hole size.

Fig. 4 shows a three-port filter using one 3-db side-wall coupler. The over-all characteristics with respect to ports A, B, and C are similar to those of the previous three-port filter. The power-handling capacity is probably slightly higher, and a closed magnetic circuit can be more easily used. As with the other three-port filter, the isolation is dependent upon the off-resonance characteristic of the cavity and is not aided by the added directivity of a second 3-db coupler.

Conclusion

By exciting circularly polarized modes in microwave cavities, a new group of compact filters is made available. By ferrite-loading cavities, these filters become tunable and nonreciprocal. This paper has presented preliminary experimental data on these ferrite-loaded filters to indicate some of their general properties. For the ferrite sizes used, the ferrite losses in the filters are less than the cavity-wall losses when operating away from ferromagnetic resonance; therefore, these losses should not restrict the use of ferrites in microwave cavity filters.