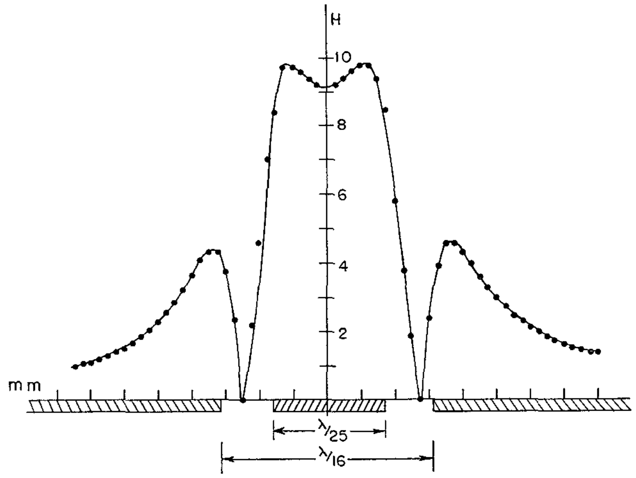


Fig. 7. Graph of normalized magnetic field H as a function of position measured close to slot line transmission.

tially a hybrid three-wire line with current directed down in the center conductor and up along the sides forming the outer edges of the slots. Alternatively, it may be considered as a four-wire line with two downward currents concentrated near the edges of the inner conductor and two return streams back along the outer conductors to the edges of the slot.

References

[1] Owyang, G. H., The slot transmission line and the slot antenna, Ph.D. dissertation, Harvard University, Cambridge, Mass., 1969.
[2] Booker, H. G., Slot aerials and their relation to complementary wire aerials, *J. Inst. Elec. Engrs.* (*London*), vol 93, pt IIIA, no 4, 1964, pp 620–626.
[3] King, R. W. P., and K. Tomiyasu, Terminal impedance and generalized two-wire-line theory, Tech Rept 74, Cruft Lab., Harvard University, Cambridge, Mass., Apr 1945; *Proc. IRE*, vol. 37, Oct 1949, pp 1134–1139; King, R. W. P., *Transmission-Line Theory.* New York: McGraw-Hill, 1955, pp 382–389.
[4] King, R. W. P., *Transmission-Line Theory.* New York: McGraw-Hill, 1955, pp 133–135.

Side-Wall-Coupled, Strip-Transmission-Line Magnetically Tunable Filters Employing Ferrimagnetic YIG Resonators

PHILIP S. CARTER, MEMBER, IEEE

***Abstract*—This paper describes a new type of band-pass filter configuration for multiple-coupled-resonator magnetically tunable microwave filters. For two or more resonators, this configuration, which employs a coupling slot in the common side wall between two strip-transmission lines, results in the smallest possible air gap and, therefore, the least amount of leakage or fringing flux, and the smallest ampere-turns requirement on the bias magnet.**

Response curves including pass band insertion-loss, bandwidth, stop-band rejection, spurious response levels and bandwidths, VSWR, and the effect of temperature on these characteristics are presented for a two-resonator band-pass filter of the type employing YIG resonators and making use of a ferrite core electromagnet to obtain the bias field. Performance data are also given for an experimental side-wall-coupled three-resonator filter.

Manuscript received March 2, 1964; revised January 18, 1965. Portions of this paper are based on work which was started while the author was employed at Stanford Research Institute and continued at Physical Electronics Labs. That part of the work which was performed at Stanford Research Institute was performed under Contract DA 36-039-SC-87398 for the US Army Signal R&D Lab., Ft. Monmouth, N. J. A shorter version of the contents of this paper was delivered at the 1963 IRE WESCON, San Francisco, Calif.

The author is with the Physical Electronics Labs., Menlo Park, Calif.

Introduction

PREVIOUSLY developed types [1]–[5] of magnetically tunable filters have employed one or more single-crystal YIG (yttrium-iron-garnet) resonators in overlapping transmission-line configurations similar to those shown in Fig. 1. Filters have been built using strip-transmission line, coaxial transmission line, and waveguide. The lines or guides may be oriented at right angles as in the single resonator filter shown in Fig. 1(a), or in parallel, as in the two-resonator filter shown in Fig. 1(b).

The band-pass filters shown in Fig. 1 have in common the geometrical arrangement of resonator centers in a line along the direction of the magnetic bias field H_0. The magnet air gap length required for this arrangement of resonators increases as the number of resonators is increased. The ampere turns required to furnish this bias field increases in nearly direct proportion to this air gap. Also, the percentage of leakage flux increases as the ratio of the gap to the pole face diameter is increased.

The magnetic flux energy can be reduced only to a certain extent by changing the lengths and proportions of the magnet core and the size and distribution of the winding on the core. The only way to further reduce the flux energy is to reduce the height of the filter itself.

An approach to the reduction of the height of the filter is to use the configuration of resonators shown in Fig. 2, with a coupling slot in the common side wall between the two transmission lines or waveguides. In the strip-transmission-line configuration shown in Fig. 2(a), a slot cut in the common side wall between the resonators produces magnetic coupling between the resonators due to the RF magnetic moments of the ferrimagnetic resonators which lie along the direction of the slot. At the same time, the slot causes very little coupling between the transmission lines since it is perpendicular to the magnetic fields produced by these lines.

The slot is made as narrow and as thick as possible, consistent with the amount of magnetic coupling that is needed, in order to minimize the direct coupling between the transmission lines.

In the three-resonator filter, shown in Fig. 2(b), the center resonator is mounted between the input and output resonators in the coupling iris or slot. One of the advantages of the three-resonator filter, aside from its increased selectivity, is its increased stop-band attenuation compared with that of the two-resonator filter. This increased stop-band attenuation is due to the thicker slot between the transmission lines.

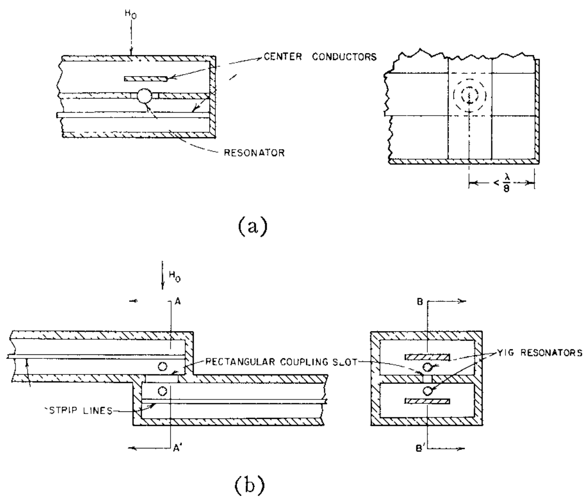


Fig. 1. Top- and bottom-wall-coupled magnetically tunable filter configurations.

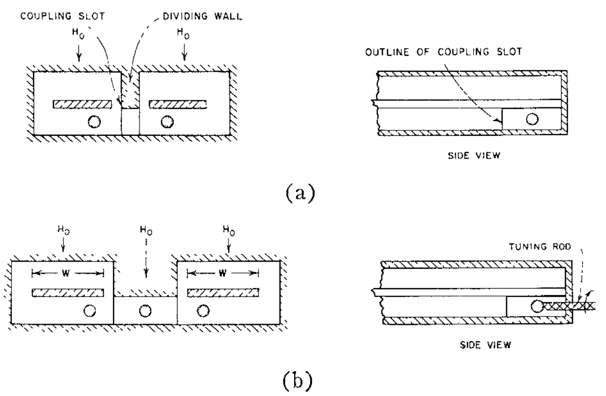


Fig. 2. Side-wall-coupled filter configurations.

Calculation of Filter Design Parameters

Figure 3 gives an approximation to the lumped-element circuit representation of the reciprocal multiple-ferrimagnetic-resonator band-pass filter. From this representation a systematic design procedure is carried out as follows, using previously developed formulas [6]–[9].

$$(Q_e)_A = \frac{\omega_1' g_1 g_0}{w} \tag{1}$$

$$(Q_e)_B = \frac{\omega_1' g_n g_{n+1}}{w} \tag{2}$$

$$k_{i,i+1} = \frac{w}{\omega_1' \sqrt{g_i g_{i+1}}} \tag{3}$$

where

$(Q_e)_A$, $(Q_e)_B$ = External Q's of input and output resonators.

$k_{i,i+1}$ = Coupling coefficient between ith and $(i+1)$th resonators.

$g_0, g_1, \cdots, g_n, g_{n+1}$ = Normalized low-pass prototype element values for desired response shape [9].

ω_1' = Cutoff frequency (radians/sec) of normalized low-pass prototype defined in Fig. 4.
= 1 for normalization chosen in Matthaei, et al. [9].

$w = (f_2 - f_1)/f_0$ = Fractional bandwidth, where f_1 and f_2 are defined in Fig. 4 and $f_0 = \sqrt{f_1 f_2}$.

n = Number of resonators.

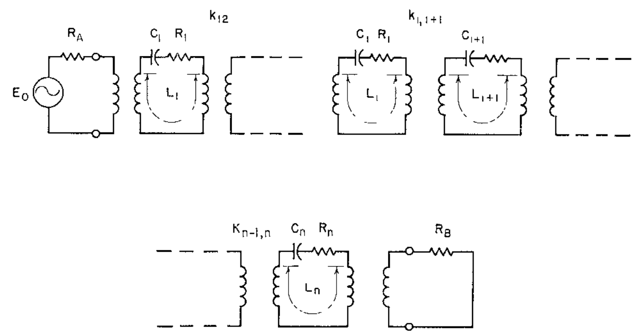


Fig. 3. Equivalent circuit of reciprocal multiple-coupled-resonator ferrimagnetic resonance filter.

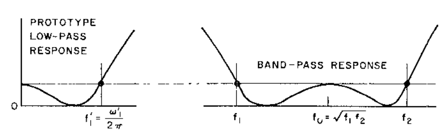


Fig. 4. Definition of low-pass-prototype and band-pass response nomenclature.

The center frequency dissipation loss L_d (not including reflection loss) is given approximately by [10]

$$L_d = 4.343 \frac{\omega_1'}{w} \sum_{i=1}^{n} \left(\frac{g_i}{Q_{ui}} \right) \text{dB}. \tag{4}$$

Here the prototype element values are assumed to be normalized so that $g_0 = 1$ and the Q_{ui} are the unloaded Q's of the resonators.

Dimensions of Coupling Structures

The dimensions of the coupling circuits for the input and output resonators are computed using previously developed theoretical formulas for the external Q's [2]. Figures 5 and 6 give curves of theoretical Q_e vs. resonator diameter for various combinations of line dimensions for 1) YIG resonators at the center of the short-circuited standard-height TE_{10} rectangular waveguide and 2) short-circuited symmetrical strip-transmission line. The curves in Fig. 5 can be used to obtain Q_e when TE_{10}-mode rectangular guides of other than standard height are used, by applying the following formula

$$Q_e' = Q_e \frac{b'}{b} \tag{5}$$

where

Q_e' = External Q in working guide.
Q_e = External Q of standard guide from Fig. 5.
b' = Height of working guide.
b = Height of standard guide.

The curves can also be used for all different shapes of ellipsoidal resonators by replacing D_m with D_m^e where

$$D_m^e = 2(abc)^{1/3} \tag{6}$$

in which a, b, and c are the semi-axes of the ellipsoid.

The curves of Figs. 5 and 6 can be used for materials other than YIG, e.g., Ga-YIG, by means of the following formula

$$Q_e^{\mathrm{OM}} = \frac{M_s^{\mathrm{YIG}}}{M_s^{\mathrm{OM}}} Q_e^{\mathrm{YIG}} \tag{7}$$

where

Q_e^{YIG} = External Q for YIG, from Fig. 5.
Q_e^{OM} = External Q for material other than YIG.
M_s^{YIG} = Saturation magnetization of YIG (1750 gauss at room temperature).
M_s^{OM} = Saturation magnetization of other material.

The dimensions of the coupling slot and the spacing between resonators are determined largely by experiment. Generally it is desirable to space the resonators as far apart as possible in order to minimize spurious responses due to magnetostatic modes [3]. This procedure, however, leads to a large coupling slot and consequently to a lower stop-band rejection. A trade-off, determined largely by experimental procedures, between high stop-band rejection and spurious response level is made.

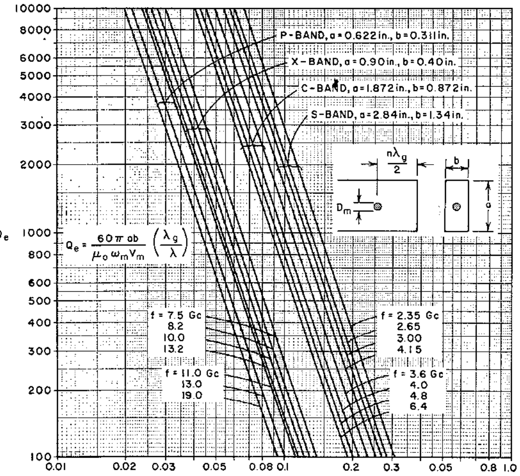


Fig. 5. Theoretical Q_e of YIG resonator in short-circuited TE_{10} rectangular waveguide.

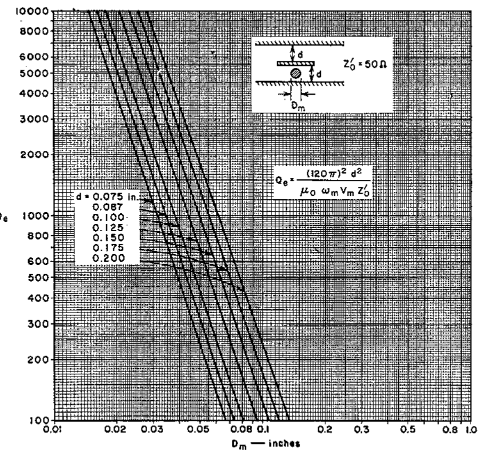


Fig. 6. Theoretical Q_e of YIG resonator in short-circuited strip-transmission line.

Two side effects of the presence of the coupling iris in the common wall between the two resonators are: 1) to cause the values of Q_e to be higher than those which are shown in Figs. 5 and 6, and 2) to cause Q_u to be higher than that which is measured when the coupling iris is not present. The practical consequence of the existence of these two side effects of the coupling slots is to require some additional experimental adjustment of the waveguide and resonator dimensions. Experience has shown that an approximate 25 per cent increase in the value of Q_e is obtained with typical coupling-slot configurations.

Properties of Ferrimagnetic Resonator Materials

Several different single-crystal materials are known to have possible application in magnetically tunable filter design including yttrium-iron-garnet (YIG), gallium-substituted yttrium-iron-garnet (Ga-YIG), lithium ferrite, and barium ferrite. The properties, including the unloaded $Q(Q_u)$ of these materials have been presented in previous publications [11]–[16].

TABLE I

PROPERTIES OF SINGLE-CRYSTAL FERRIMAGNETIC MATERIALS FOR MAGNETICALLY TUNABLE FILTERS AT ROOM TEMPERATURE

Material	$4\pi M_s$ (Gauss)	K_1/M_s (Oersteds)	ΔH* (Oersteds)	T_c (°C)
Yttrium-Iron-Garnet** YIG	1750	−43	0.22 (4Gc, [17])	292
Gallium-Substituted**	50–1750	—	—	—
Yttrium-Iron-Garnet	600	−55.8	—	160
	950±50	−41.7	0.7–2.0 (at 4.4 Gc)	206
Lithium Ferrite	3550±40 [13]	—	3*** (5 Gc)	—
"Planar" Ferrite "Zn_2Y" ($Ba_{12}Zn_2Fe_{12}O_{22}$)	2850 ([14])	4950 ([14])	10(X-band, ([14])	—

* These values of ΔH were measured in cavities. They may be considerably larger when measured in a filter structure.
** These materials were supplied by Microwave Chemicals Lab., 282 Seventh Ave., New York City, N. Y.
*** Private communication, J. W. Nielsen, Airtron Div. of Litton Industries, Morris Plains, N. J.

The physical constants of ferrimagnetic materials that affect the filter design are the saturation magnetization M_s, the anisotropy field constant K_1/M_s, the Curie temperature T_c, and the resonance linewidth ΔH.

Table I lists values of these physical constants measured at room temperature. The values of K_1/M_s, given in the table, were measured using two samples of Ga-YIG of different degrees of substitution of gallium. Values of the constants of the other materials in the table are taken from the given references.

The saturation magnetization M_s and the shape of the resonator determine the lowest resonant frequency f_0^{min}, which can be reached due to desaturation. Figure 7 shows f_0^{min} of spheroidal resonators as a function of $4\pi M_s$ in gauss with the ratio of principal axes as a parameter. The most commonly employed resonator shape is spherical, due to the ease with which it can be fabricated and polished to give resonators with very high values of Q_u. In principle it is possible to achieve lower resonant frequencies by the use of a thin disk-shaped resonator. Polished disks having low resonant frequencies and narrow linewidths are now available.[1]

The unloaded Q, Q_u, is usually given by the manufacturer in terms of an equivalent quantity, the linewidth ΔH.[2] To obtain Q_u from the linewidth, the following formula is used:

$$Q_u = \frac{f_0^{Mc}}{2.8\Delta H} \tag{8}$$

f_0^{Mc} = Resonant frequency, megacycles per second.
ΔH = Linewidth, oersteds.

The Q_u of YIG increases about linearly with increasing frequency in the 2-to-10 Gc frequency range. The values of Q_u obtained in a practical filter structure where the coupling is relatively tight, and consequently the conducting boundaries are near the resonator, are usually lower than the values specified for the material by the manufacturer. Figure 8 shows the values of Q_u that have been obtained with a 0.074-inch diameter YIG resonator in different coupling configurations, including a full-height S-band waveguide.

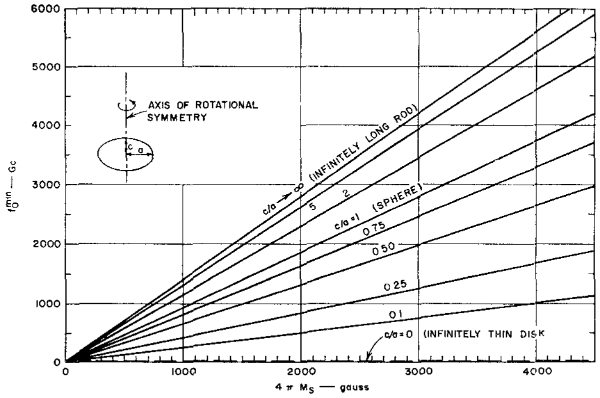


Fig. 7. Theoretical minimum resonant frequencies of spheroids.

The effect of magneto-crystalline anisotropy is that the biasing magnetic field required to produce resonance varies according to the orientation of the crystal axis with respect to the biasing magnetic field. Figure 9 shows the biasing field required to resonate a YIG sphere at room temperature. The resonator is rotated around a (110) crystal axis which is perpendicular to the biasing field. For crystals with cubic symmetry such as single-crystal YIG or gallium-substituted YIG [18],

$$H_0 = H_{eff} - \left(2 - \frac{5}{2}\sin^2\theta - \frac{15}{8}\sin^2 2\theta\right)\frac{K_1}{M_s}, \text{ oersted} \tag{9}$$

where

$$H_{eff} = \frac{f_0^{Mc}}{2.8}$$

θ = angle between H_0 and a [100] axis.

Formulas for the resonant frequency have been given for several other crystal structure types by Yager, et al. [18], Kittel [19], and Artman [20].

[1] Disks fabricated to specifications can be obtained from Litton Industries Airtron Div., Morris Plains, N. J., and from Microwave Chemicals Lab., New York City, N. Y.

[2] Linewidth is here defined as the difference between the two values of biasing field for which the imaginary part of the intrinsic susceptibility equals the real part, while frequency is held constant.

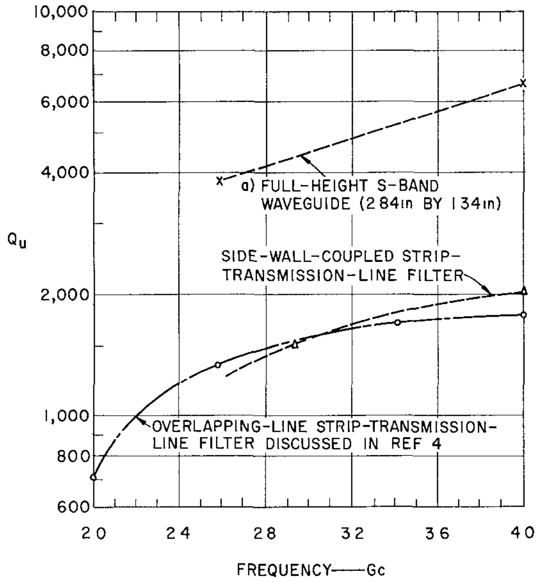


Fig. 8. Q_u of YIG resonator vs. frequency in waveguide and strip-transmission-line filter configurations.

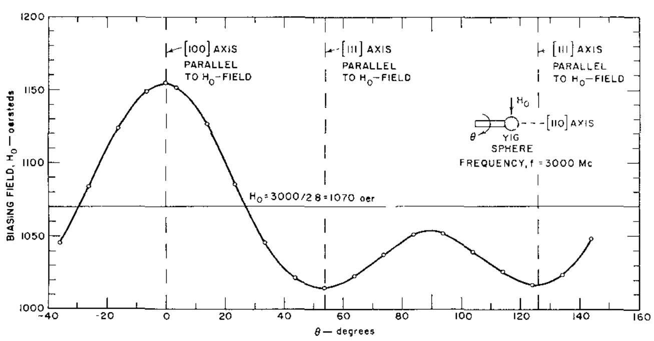


Fig. 9. Field strength for YIG sphere resonance at 3000 Mc as resonator is rotated about a [110] axis.

Design of Two-Resonator Side-Wall-Coupled Filter

The foregoing methods were used to design a two-resonator side-wall-coupled filter with the following characteristics:

Tuning Range	2–4 Gc
Bandwidth between 3-dB rejection frequencies	20 Mc

Type of response—maximally flat at center of tuning range.

From (1) and (2):

$$(Q_e)_A = (Q_e)_B = \frac{\omega_1' g_1 g_0}{w} = \frac{1 \times 1.414 \times 1}{0.0071} = 202$$

where

$$w = \frac{f_2 - f_1}{f_0} = \frac{20}{2820} = 0.0071.$$

$f_0 = 2820$ Mc is the geometric mean of the limits of the tuning range, i.e.,

$f_0 = \sqrt{2000 \times 4000}$. From (3)

$$k_{12} = \frac{w}{\omega_1' \sqrt{g_1 g_2}} = \frac{0.0071}{1 \times \sqrt{(1.414)^2}} = 0.00495.$$

k_{12} is realized experimentally by adjustment of the dimensions of the coupling iris.

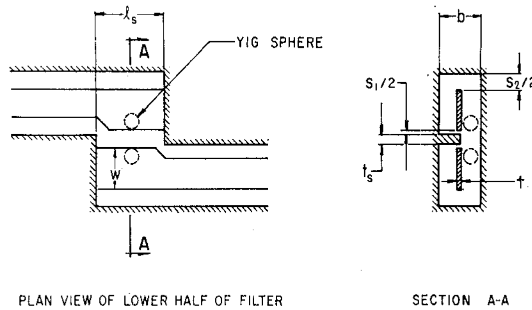
The resonator material is chosen using the requirement that the minimum center frequency is 2 Gc. From Fig. 7 a maximum $4\pi M_s$ of 2150 gauss for a spherical resonator is seen to be allowable. Yttrium-iron-garnet ($4\pi M_s = 1750$ gauss) satisfies this requirement; furthermore, its unloaded Q, Q_u, is still quite high at frequencies as low as 2 Gc (see Fig. 8). From Fig. 6 we then obtain the strip-transmission-line center-conductor-to-ground-plane spacing using $Q_e = 150$, rather than the value of 202 calculated above, in order to allow for a 33 per cent increase due to the decoupling effect of the iris. The resonator diameter $D_m = 0.074$ inch and center-conductor-to-ground-plane spacing $d = 0.110$ inch were chosen. The strip-transmission-line dimensions for the 50-ohm characteristic impedance line given in Fig. 10 were then obtained by conventional procedures.

Construction and Alignment of Filter

The body of the filter, which is shown in Fig. 11, was machined from LEXAN.[3] A thin shell, about 0.0005 inch thick, of copper was plated onto the LEXAN body. The purpose of this procedure was to avoid eddy currents in the filter body when using a rapidly swept bias field. The YIG resonators were mounted on Rexolite rods which could be rotated on an axis perpendicular to the direction of the biasing field. The YIG resonators were aligned with their [110] axes along the rod axis. This orientation was obtained using the ferromagnetic crystal orienter previously described in the literature [23]. The strip-transmission-line center conductor was supported by means of Rexolite slabs in the regions between the type N input and output connectors and the short section of transmission-line coupling to the YIG resonator. Split-block construction was used in fabricating the body of the filter.

The first step in aligning the filter was to adjust the spacing of the resonators to give the desired maximally flat response shape at 2.83 Gc. The next step was to orient the YIG crystal axes so that the variation of the resonant frequency with temperature was minimized. Examination of Fig. 9 or (9) shows that there is an angle θ at which the effect of the anisotropy field K_1/M_s is reduced to zero. With the sphere in this orientation, which is 29°45′ from a [100] axis, the variation of the resonant frequency due to a variation of K_1/M_s with

[3] Trade name, manufactured by General Electric Co. This material is a high-strength plastic dielectric material which retains its mechanical and electrical characteristics at high temperature.



t = 0.010 IN. t_s = 0.050 IN.
w = 0.231 IN. ℓ_s = 0.400 IN.
$S_1/2$ = 0.025 IN. b = 0.230 IN.
$S_2/2$ = 0.100 IN. DIA. OF YIG SPHERE = 0.074 IN.

Fig. 10. Dimensions of two-resonator filter.

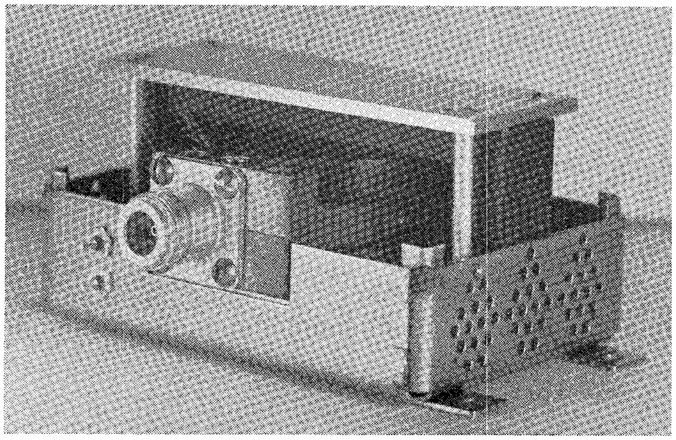


Fig. 11. Two-resonator filter with shield lid removed.

temperature is eliminated [23]. The resonator was mounted in the filter and rotated so that the desired zero-temperature-coefficient axis was obtained. This operation is conveniently carried out by operating the device with only one resonator in place, and measuring the small coupling to the output which is the result of leakage through the coupling slot in the sidewall. For YIG the zero-temperature-coefficient resonant frequency is 241 Mc above the minimum resonant frequency or 161 Mc below the maximum resonant frequency. The second resonator was then rotated to give the same resonant frequency.

In taking measurements on this type of filter using YIG resonators, it is important to operate the device below the saturation levels, which are as low as -10 dBm over part of the 2-to-4 Gc tuning range [4].

A highly uniform magnetic bias field is required for this filter since a nonuniform field causes the resonators to be tuned to different frequencies. Several references are available in which various aspects of electromagnet design are discussed [24], [25], and [26]. The magnet shown in Fig. 11 used two ferrite E-cores, the center legs of which had been shortened to provide the air gap. The pole-face dimensions were 0.685 inch by 0.685 inch and the air gap was 0.300 inch.

Filter Performance

Figure 13 summarizes the operating characteristics of the filter as it performed at room temperature. The quantities plotted in Fig. 13 refer to the filter response characteristics which are defined in Fig. 12.

The insertion loss at band center varies between a maximum value of $L_0 = 2.4$ dB at $f_0 = 2.0$ Gc and a minimum value of $L_0 = 1.2$ dB at $f_0 = 3.0$ Gc.

The center frequency loss could be reduced somewhat by using resonators with higher unloaded Q's. YIG resonators with unloaded Q's 25 to 50 per cent higher than those used in this filter can be obtained. The resonators used here are typical of those made of high-grade YIG material now available.[4]

The 3-dB and 30-dB bandwidths of the filter vary only slightly as the center frequency is tuned over the 2-to-4 Gc range. This constancy of the bandwidth is one of the features of the ferrimagnetic-resonance magnetically tunable filter which cannot easily be obtained with other types of mechanically and electronically tunable filters. This constant bandwidth characteristic results from the fact that the coupling coefficient k_{12} between magnetic resonators is inversely proportional to frequency while Q_e remains approximately constant [6]. An examination of the following expression for the insertion loss L shows why this results in a constant bandwidth.

$$L = 10\log\left\{\left[\frac{\left(1+\frac{Q_e}{Q_u}\right)^2}{2kQ_e} + \frac{kQ_e}{2}\right]^2 + 2\left[\frac{\left(1+\frac{Q_e}{Q_u}\right)^2}{k^2} - Q_e^2\right]\left(\frac{f-f_0}{f_0}\right)^2 + \frac{4Q_e^2}{k^4}\left(\frac{f-f_0}{f_0}\right)^4\right\}. \tag{10}$$

For a maximally-flat response $Q_e = k^{-1}$. Thus the variation of L with frequency is predominantly due to the third term on the right in (10). If $k \propto (f_0)^{-1}$ and Q_e = constant, then this term is proportional to $(f-f_0)$,[4] resulting in an approximately constant pass-band bandwidth.

A minimum stop-band rejection $L_R^{\min} = 40$ dB is obtained in this filter. It is probable that a somewhat greater value of stop-band rejection could be obtained with an elliptical coupling slot geometry.

The maximum amplitude of the spurious response at 730 Mc below the main response of this filter was at least 30 dB below the main response, as shown in Fig. 13. The three spurious responses shown here are at

[4] These YIG resonators were supplied to us by Microwave Chemicals Lab., Inc., New York, N. Y.

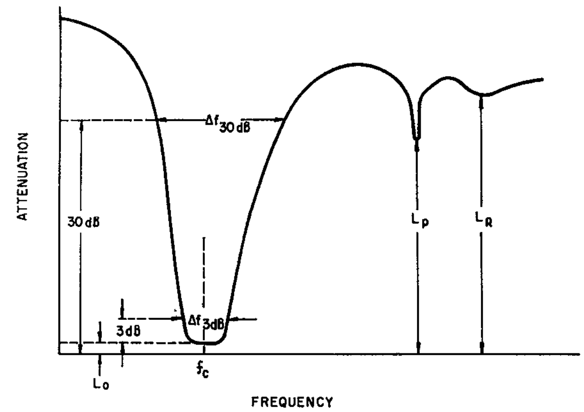


Fig. 12. Filter response nomenclature.

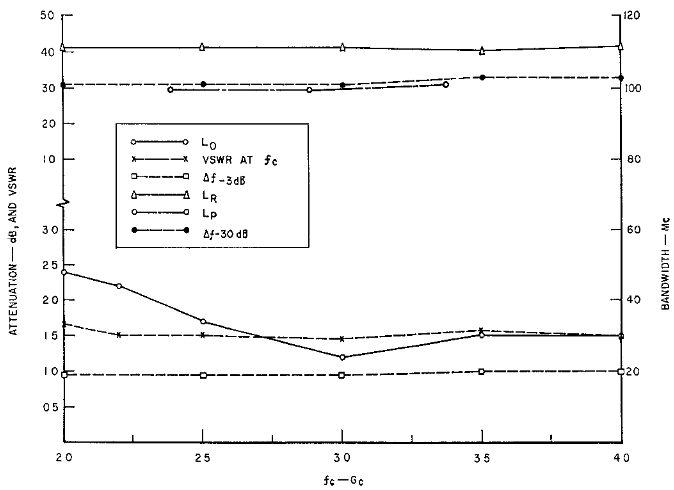


Fig. 13. Characteristics of two-resonator filter at room temperature.

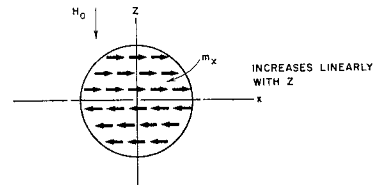


Fig. 14. Distribution of the RF magnetization in the (210) magnetostatic mode.

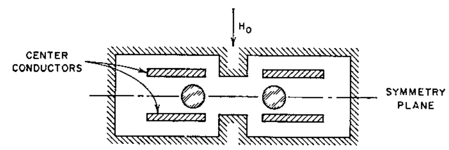


Fig. 15. A possible structure to eliminate the (210) magnetostatic mode spurious response.

2.270, 2.770, and 3.270 Gc, corresponding to main responses at 3.000, 3.500, and 4.000 Gc. The level of the spurious response depends on the uniformity of the biasing magnetic fields as well as the uniformity of the RF magnetic fields. A uniform bias field is needed to minimize the level of the spurious responses as well as to maintain synchronous tuning of the resonators.

The spurious response which occurs at a frequency approximately 730 Mc below the main response is caused by the excitation of the (210) magnetostatic mode. The distribution of the m_x component of RF magnetization of this mode is shown in Fig. 14. It is seen from this figure that this mode may be excited by the component of the RF magnetic field which has odd symmetry around the equator of the sphere. This odd-symmetrical component of RF field could be minimized by the use of a balanced symmetrical strip-transmission-line coupling structure such as the one shown in Fig. 15.

Figure 16 shows the effect of varying the temperature of the filter, which was tuned to a center frequency of 3.0 Gc at room temperature. The ambient temperature was varied between $-30°C$ and $+50°C$. It is seen that the operating characteristics, including the center frequency, remain very nearly constant over this tempera-

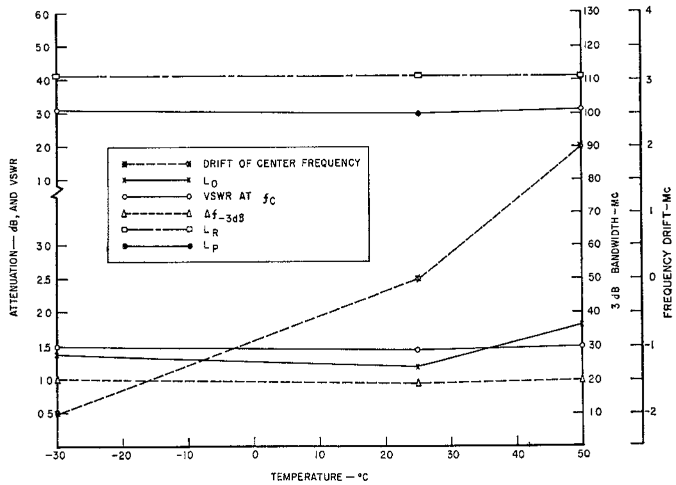


Fig. 16. Characteristics of two-resonator filter as a function of temperature at 3 Gc.

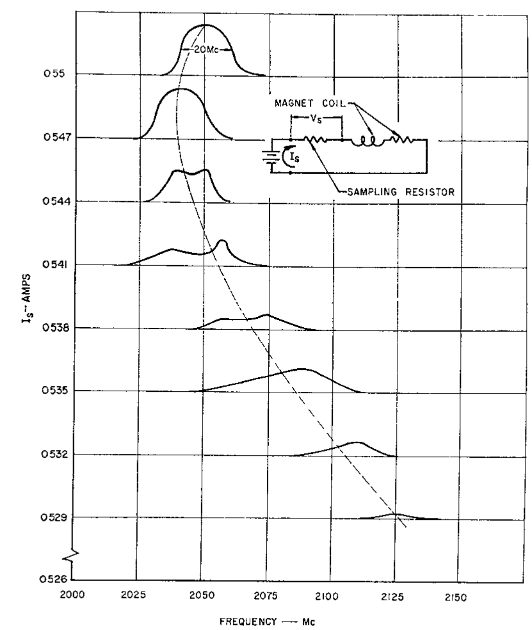


Fig. 17. Pass band response around 2 Gc vs. magnet current at $-40°C$.

ture range. The center frequency remained nearly constant—a total drift of 4 Mc was measured. Similar results were obtained when the filter was tuned to 2 Gc and to 4 Gc.

Above about 50°C the filter response shape deteriorated, broadening considerably as the temperature was increased. This behavior was believed to be due to saturation of the ferrite magnet core material. Filters using silicon steel magnet cores have been operated at ambient temperatures of up to 100°C with very little deterioration of performance.

A change of the response shape and the tuning characteristic occurs at the low end of the tuning range at low temperatures.[5] Figure 17 shows the responses which were obtained by varying the coil current at an ambient temperature of -40°C. As can be seen from Fig. 17, there is a "turnaround" point after which, when the magnet coil current is decreased, the center frequency begins to increase. Below this point the insertion loss also increases.

Three-Resonator Filter

A prototype three-resonator, side-wall-coupled filter was also constructed using the principles outlined previously. One of the main purposes for building this filter was to ascertain whether or not three resonators could be synchronously tuned over a wide range of frequencies. Before the filter was built, this point was somewhat in doubt, since the center resonator of a three-resonator filter is exposed to different field conditions than the two end resonators. As it turned out, differences in the resonant frequency of the center resonator could be compensated by rotating the crystal axis of the center resonator with respect to the bias field.

The dimensions and configuration of the input and output coupling lines and resonators were made exactly the same as those which were used in the two-resonator filter previously described. The only part of the two-resonator filter structure which was changed was the coupling iris, which was made wider, i.e., thicker, to accommodate the center resonator. A 0.230-inch-thick iris was used. The assembled experimental filter is shown in Fig. 18, without the biasing magnet.

The measured performance of the three-resonator filter is shown in Figs. 19 and 20. A laboratory-type electromagnet was used to supply the magnetic field. The output of the filter is shown as the magnetic field was varied through resonance while keeping the frequency f_c into the filter constant. These plots are closely related to the frequency-response properties of the filter since the RF impedance of the ferrite is a function of the quantity $\omega-\gamma H_0$. A change in H_0 thus is equivalent to an equal but opposite change in ω. Thus, the high field side of the field-response curve resembles the low-frequency side of the frequency-response curve and vice versa. The only approximation is that the frequency variations of the coupling circuit are not simulated. However, over the narrow pass band of the filter, this variation of the filter structure properties should be small.

Figure 19 shows the pass band responses of the filter when it was tuned to various center frequencies between 2.0 Gc and 7.0 Gc. The synchronism of the resonators is maintained over a very large tuning range as was hoped. Figure 19 shows that synchronous tuning is still obtained at a center frequency of 7.0 Gc. It is evident that at this highest frequency the response has become somewhat undercoupled as would be expected from the theory of coupled magnetic resonators [6].

Figure 20 shows the stop band and spurious mode responses of the filter as it was tuned to different frequencies between 2.0 and 5.0 Gc. As can be seen from these curves the rejection in the stop band is considerably better than that of the two-resonator filter. It is likely that the actual stop-band rejection (excluding spurious mode responses) is better than the -66 dB, shown for $f_c=5.0$ Gc, which was the limit of detection of the measurement set up.

The spurious, (210) mode, response which occurs at about 740 Mc below the center frequency is completely absent in Fig. 20. Its position, if it were present in these response patterns, would be at about 265 oersteds higher than the center of the main response. This increased insertion loss of the (210) mode response is due to the very weak coupling between (210) modes in the three resonators.

A spurious response appears at $f_c=2.0$ Gc as the field is decreased below the value required for the main response. This spurious response appears about 100 oersteds below the main resonance, a value of field at which no spurious response would be expected with an undoped YIG resonator. It is probable that this spurious response is actually the "turnaround" effect which was shown in Fig. 17 for the two-resonator filter at a low temperature. In application of this filter, this response would be avoided by keeping the bias field above the value at which this secondary response appears.

Table II lists some of the properties of this filter. Included here are frequency bandwidths, which were measured directly. The VSWR was low except at $f_c=2.0$ Gc where, it was suspected, the resonators were slightly detuned. The 30-dB bandwidth stays nearly constant over the tuning range. The ratio of the 30-dB bandwidth to the 3-dB bandwidth runs around 2.8 for the three-resonator filter design. Although the cutoff rate was considerably sharper for the three-resonator design, the performance of the three-resonator filter probably was not optimum because of a small amount of mistuning and because no effort was made to optimize the shape of the

[5] This phenomenon was first pointed out to us by Thomas Miles, Applied Electronics Lab., Stanford University, Calif.

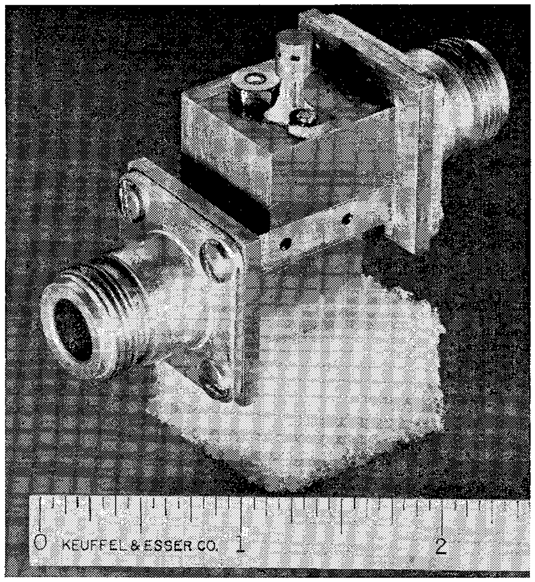


Fig. 18. Three-resonator filter shown assembled, without magnet.

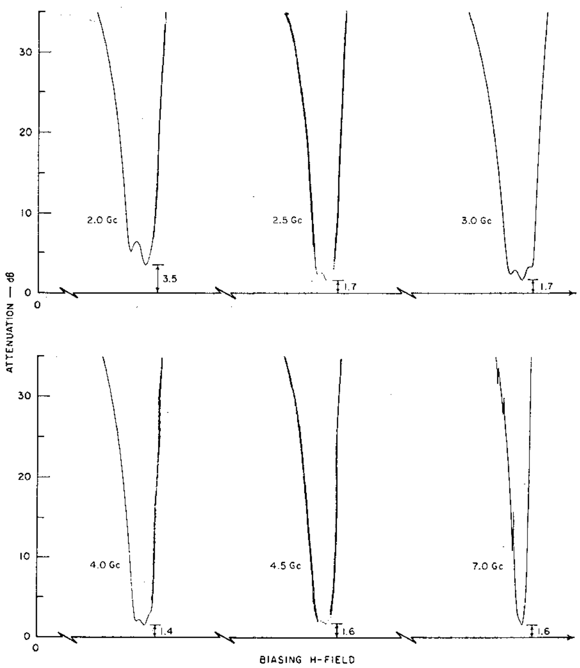


Fig. 19. Pass band responses of three-resonator filter.

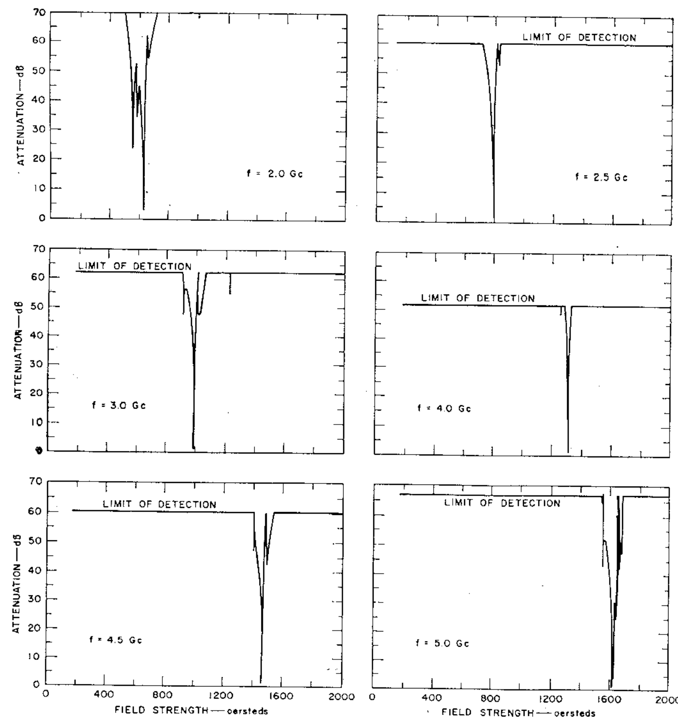


Fig. 20. Stop band responses of three-resonator filter.

TABLE II

MEASURED CHARACTERISTICS OF THREE-RESONATOR YIG FILTER

f_c (Gc)	L_0 (dB)	Δf^*-3dB (Mc)	$\Delta f-30$dB (Mc)	VSWR	H_0 (oersteds)
2.0	3.5	32.9*	91.4	2.50	610.0
2.5	1.7	34.2	90.1	—	867.1
3.0	1.7	33.6	90.6	1.23	990.0
4.0	1.4	30.9	87.2	1.10	1310.0
4.5	1.6	24.0	89.1	—	1586.8
7.0	1.6	29.6	—	—	—

* The bandwidths given are measured between points which are 3 dB and 30 dB below L_0.

pass band response. Filters designed to correspond to equal-element prototypes would probably be desirable for most tunable filter applications. Such filters would result in minimum midband dissipation loss for a given specified 30 dB (or other specified level) stop-band bandwidth [28].

Signal Limiting with the Magnetically Tunable Filter

An important property of filters employing ferrimagnetic resonators is their ability to suppress undesired high-level signals without affecting the response to the desired low-level signal. This limiting property occurs as a result of the parametric coupling between the main (uniform precession) resonance and the higher order "spin-waves," and causes signals in the pass band of the filter to be limited to output levels of the order of 0 dBm to −10 dBm in certain frequency ranges and +20 to +30 dBm in others. Several ferrimagnetic limiters having low limiting levels in the 2-to-10 Gc frequency range have been built [29]–[31].

Summary and Conclusions

A new type of coupling structure has been demonstrated which is applicable to YIG band-pass filters having two or more resonators, which minimizes the air gap between the pole faces of the bias magnet. It has been demonstrated, by constructing two- and three-resonator models of this filter, that at least an octave tuning range can be obtained while maintaining useful insertion loss and selectivity characteristics. It has also been shown that the two-resonator filter can be temperature stabilized to a degree which allows it to be operated over approximately a −30°C to 50°C range. Finally, a technique using a copper-plated dielectric filter body was demonstrated which allows the filter to be swept at high speeds.

Acknowledgment

Dr. G. Matthaei of Stanford Research Institute made many suggestions during the course of the work. Y. Sato conducted the testing with great skill at Stanford Research Institute.

Acknowledgment is made to the entire staff of Physical Electronics Laboratories for suggestions and assistance in completing the development of the two-resonator filter. E. Sheehan's efforts in the assembly and testing of this unit are also gratefully acknowledged.

References

[1] Carter, P. S., Jr., G. L. Matthaei, and W. J. Getsinger, Design criteria for microwave filters and coupling structures, Tech Rept 8, Project 2326, Contract DA 36-039 SC-74862, Stanford Research Inst., Menlo Park, Calif., Sep 1959.[6]

[6] Report submitted under referenced contract. Copies of this and other reports listed are available to qualified requestors from the Armed Services Technical Information Agency, or by writing to the U. S. Army Electronics Research and Development Lab., Ft. Monmouth, N. J., Attention: W. Dattilo.

[2] Carter, P. S., Jr., Magnetically-tunable microwave filters using single-crystal yttrium-iron-garnet resonators, *IRE Trans. on Microwave Theory and Techniques*, vol MTT-9, May 1961, pp 252–260.

[3] Matthaei, G. L., Carter, P. S., Jr., et al., Design criteria for microwave filters and coupling structures, final rept, SRI Project 2326, Contract DA 36-039 SC-74862, Stanford Research Inst., Menlo Park, Calif., Jan 1961, ch 28, pp 475–512.

[4] Carter, P. S., Jr., et al., Microwave filters and coupling structures, Rept 3, SRI Project 2326, Contract DA 36-039 SC-87398, Stanford Research Inst., Menlo Park, Calif., Oct 1961, pp 3–35.

[5] Kotzebue, K. L., Broadband electronically-tuned microwave filters, *1960 WESCON Conv. Rec.*, vol 4 pt 1, pp 21–27.

[6] Matthaei, G. L., L. Young, and E. M. T. Jones, Design of microwave filters, impedance-matching networks, and coupling structures, Stanford Research Inst., Menlo Park, Calif., vol 2, Jan 1963, ch 17, pp 993–1077. (To be published by McGraw-Hill.)

[7] Carter, P. S., Jr., et al., Microwave filters and coupling structures, Rept 7, SRI Project 3527, Contract DA 36-039 SC-87298, Stanford Research Inst., Menlo Park, Calif., Oct 1961, pp 31–70.

[8] Cohn, S. B., et al., Research on design criteria for microwave filters, final rept, SRI Project 1331, Contract DA 36-039 SC-74862, Stanford Research Inst., Menlo Park, Calif., Jan 1961.

[9] Matthaei, G. L., L. Young, and E. M. T. Jones, Design of microwave filters, impedance-matching networks, and coupling structures, SRI Project 3527, Contract DA 36-039 SC 87398, Stanford Research Inst., Menlo Park, Calif., vol I, Jan 1963, ch 4, pp 83–157.

[10] Cohn, S. B., Dissipation loss in multiple-coupled-resonator filters, *Proc. IRE*, vol 47, Aug 1959, pp 1342–1348.

[11] Carter, P. S., Jr., and C. Flammer, Unloaded *Q* of single crystal yttrium-iron-garnet resonator as a function of frequency, *IRE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol MTT-8, Sep 1960, pp 570–571.

[12] Spencer, E. G., and R. C. LeGraw, Line width narrowing in gallium substituted yttrium-iron-garnet, *Bull. Am. Phys. Soc.*, vol 5, pt 1, Jan 1960, p 58.

[13] Nielsen, J. W., D. A. Lepore, J. Zneimer, and G. B. Townsend, Effect of mechanical, thermal, and chemical treatment of the ferrimagnetic resonance linewidth on lithium ferrite crystals, *J. Appl. Phys.*, vol 33S, Mar 1962, pp 1379–1380.

[14] Buffler, C. P., Resonance properties of single-crystal hexagonal ferrites, *J. Appl. Phys.*, vol 33, Mar 1962, pp 1360–1362.

[15] Dixon, S., High-power characteristics of single-crystal ferrites with planar anisotropy. *J. Appl. Phys.*, vol 33S, Mar 1962, pp 1368–1369.

[16] Tauber, A., R. O. Savage, R. J. Gambino, and C. G. Whimfrey, Growth of single-crystal hexagonal ferrites containing Zn, *J. Appl. Phys.*, vol 33S, Mar 1962, pp 1381–1382.

[17] Matthaei, G. L., P. S. Carter, Jr., et al., *op. cit.*, pp 490–491.

[18] Yager, W. A., J. K. Galt, F. R. Merritt, and E. A. Wood, Ferromagnetic resonance in nickel ferrite, *Phys. Rev.*, vol 80, Nov 1950.

[19] Kittel, C., On the theory of ferromagnetic resonance absorption, *Phys. Rev.*, vol 73, 1948, pp 155–161.

[20] Artman, J. O., Microwave resonance relations in anisotropic single-crystal ferrites, *Proc. IRE*, vol 44, Oct 1956, pp 1284–1293.

[21] Matthaei, G. L., L. Young, and P. S. Carter, Jr., Microwave filters and coupling structures, Rept 5, SRI Project 3527, Contract DA 35-039 SC-87398, Stanford Research Inst., Menlo Park, Calif., May 1962.

[22] Reference Data for Radio Engineers, 4th ed. Internat'l Telephone and Telegraph Corp., New York, N. Y., 1959, pp 190–198.

[23] Sato, Y., and P. S. Carter, A device for rapidly aligning and mounting ferromagnetic single crystals along any desired axis, *IRE Trans. on Microwave Theory and Techniques* (*Correspondence*), vol MTT-10, Nov 1962, pp 611–612.

[24] Brailsford, F., *Magnetic Materials*, 3rd ed. London: Methuen, 1960.

[25] Rotors, H. C., *Electromagnetic Devices*, 1st ed. New York: Wiley, 1941.

[26] Livingston, M. S., and J. P. Blewett, *Particle Accelerators*, 1st ed. New York: McGraw-Hill, 1962, ch 8.

[27] Lax, B., and K. S. Button, *Microwave Ferrites and Ferrimagnetics*, sec 5-5, 1st ed. New York: McGraw-Hill, 1962, pp 227–231.

[28] Taub, J. J., Design of minimum loss band-pass filters, *Microwave J.*, vol 6, Nov 1963, pp 67–76.

[29] Lax, B., and K. J. Button, *op. cit.*, sec 12-13.

[30] Brown, J., Ferrimagnetic limiters, *Microwave J.*, vol 4, Nov 1963, pp 74–79.

[31] Kotzebue, K. L., Frequency-selective limiting in YIG filters, *J. Appl. Phys.*, vol 33, Feb 1962, p 747.