A 500-to-1000 MHz Magnetically Tunable Bandpass Filter Using Two YIG-Disk Resonators

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Abstract—**A magnetically tunable UHF bandpass filter designed in strip transmission line and with two disk-shaped resonators of yttrium-iron-garnet (YIG) is described. Single crystals of both pure YIG and gallium-substituted YIG were used.**

The properties of the disk resonators were first investigated by testing them in a bandstop filter configuration. Linewidths were measured as a function of both frequency and temperature over the band 500 to 1000 MHz and sometimes beyond. The effect of metal boundaries near the ferrimagnetic resonator on its linewidth and resonant magnetic field was determined. Magneto-static modes were examined. Methods for adjusting the resonant frequency of a disk are discussed.

A description is given of the filter coupling structure, which includes two 50-to-5-ohm transformers in strip line. The experimental tuning procedure is outlined. Tests of the filter with gallium-YIG disks revealed a midband insertion loss of less than 3.3 dB from 500 to 1200 MHz and less than 2 dB from 600 to 1100 MHz; the filter with pure YIG disks had a midband insertion loss of less than 3.2 dB from 450 to 1100 MHz and had fewer spurious responses than the gallium-YIG filter. Response curves, limiting characteristics, and other experimental results are also presented.

I. Introduction

A UHF magnetically tunable bandpass filter was designed in strip line. The filter uses single-crystal yttrium-iron-garnet (YIG) resonators, both undoped and doped with gallium. Such filters have been described extensively before in the technical literature [1]–[3]. The filters described in this report differ from the earlier filters mainly in that relatively low-frequency operation was obtained with disk-shaped pure-YIG crystals and slightly doped GaYIG crystals, whereas the usual method of obtaining low-frequency operation with such filters is to use spherical, heavily doped crystals.

Section II describes the basic considerations and measurements made prior to the design of the bandpass filter. Perhaps the most basic problem was how to achieve tight coupling between the external circuit and the ferrimagnetic resonator. This usually involves constricting the mechanical dimensions around the resonator which, in turn, may bring on two adverse effects: the excitation of spurious modes, and increased dissipation losses due to wall currents in the metal boundaries.

A particular problem with disk resonators is the difficulty of synchronously tuning two or more resonators used in one filter. Spherical resonators can be tuned by mounting them on a dielectric rod that permits rotation of the spherical crystals about their (110) axes. This does not alter the geometric orientation of the sphere. With disks, however, this tuning procedure is only of limited utility, because only a few megacycles tuning can be achieved before the dissipation losses increase catastrophically. Pure-YIG crystals differ little in magnetic properties from sample to sample, but gallium-doped YIG crystals vary considerably in their saturation magnetization.

Extensive measurements were made to determine the linewidth ΔH as a function of doping, frequency, and temperature. These measurements were made by placing the disk resonator in a bandstop filter configuration and measuring the maximum attenuation at resonance and the 3-dB bandwidth in a manner similar to that used in Matthaei [3]. The physical and magnetic characteristics of the ferrimagnetic resonators used in these experiments are summarized in Appendix A.

Section III describes the development of the bandpass filter, including the design technique and development of the coupling structure, the experimental tuning procedure, and the performance of the two filters, one with GaYIG disks and the other with pure-YIG disks. The passband insertion loss of the GaYIG filter was slightly better (less than 2 dB from 600 to 1100 MHz), but the spurious mode activity of the pure YIG was considerably less.

II. Basic Considerations

A. Spherical and Disk-Shaped Resonators

The current range of operation of magnetically tunable filters extends from at least 250 MHz to 40 GHz. Several design alternatives exist, depending to some extent on the frequency band. The important parameters to be considered for the resonator are its shape, the material saturation magnetization ($4\pi M_s$), and the resonant mode of operation. Standard filter designs incorporate spherical ferrimagnetic resonators operating in the uniform precessional mode, the (110) mode; with this approach a material with low saturation magnetization is required for filter operation at the relatively low frequencies of 500 to 1000 MHz. With presently available materials the required low $4\pi M_s$ can be obtained by doping YIG with gallium, or by heating the ferrimagnetic resonator to a temperature approaching the Curie point of the material [4]. The present approach is to use a disk-shaped resonator operating in the (110) mode.

To understand why it is possible to operate at lower frequencies with disk-shaped resonators than with spherical resonators, consider the effect of the shape demagnetizing factors on the internal field, H_i. This field is given by

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$$H_i = H_{dc} - N_z(4\pi M_s), \quad (1)$$

where H_{dc} is the applied static magnetic field, N_z is the longitudinal demagnetizing factor [1], [5], and $4\pi M_s$ is the saturation magnetization measured in Gaussian units. The resonant frequency f_0 in megacycles is given in terms of the magnetic field in oersteds by

$$f_0 = 2.8[H_{dc} - (N_z - N_t)(4\pi M_s)] \quad (2)$$

for a resonator with circular symmetry, where N_t is the transverse demagnetizing factor. The two demagnetizing factors for a body with circular symmetry are related by

$$N_z + 2N_t = 1. \quad (3)$$

For low-loss resonance, the ferrimagnetic sample must be saturated and the internal magnetic field H_i must be positive. Hence, from (1)–(3),

$$f_0 > 1.4(1 - N_z)(4\pi M_s). \quad (4)$$

For a sphere, N_z is equal to $\frac{1}{3}$, and hence,

$$f_0 > 0.93(4\pi M_s) \quad \text{[sphere]}. \quad (5)$$

For a disk (strictly for an ellipsoid) having a diameter of 30 times the thickness, N_z is approximately equal to 0.95, and (4) reduces to

$$f_0 > 0.07(4\pi M_z) \quad \text{[30-to-1 disk]}. \quad (6)$$

Thus, it can be seen that with the disks used (those having a diameter-to-thickness ratio of 30:1), the lower-frequency limit of operation can be extended downwards by a factor of approximately 13, for the same ferrimagnetic material. For pure YIG crystals, the lower frequency limit is thereby extended from about 1700 MHz to about 125 MHz. This does not mean that satisfactory low-loss resonance can be achieved all the way down to those frequencies; in practice, the sample will gradually cease to be saturated as the lower frequency limit is approached, and satisfactory operation will cease before the lower limit is reached. With the pure YIG disks in our possession and with the filter structure to be described in Section III, satisfactory filter operation can be obtained down to frequencies of at least 450 MHz.

B. Ferrimagnetic Resonator-to-Circuit Coupling

1) *Circuit Design for Strong Coupling:* When the resonator characteristics (for instance, resonator unloaded Q, or ferrimagnetic material linewidths) are fixed, the dissipation loss in the filter passband can be reduced by stronger coupling into and between the resonators. Increasing the coupling also increases the filter bandwidth (thus making the filter less selective), but in most practical magnetically tunable filters the bandwidth is not a limitation, since it is difficult to obtain strong coupling into the small samples that constitute the RF resonators. The coupling to the ferrimagnetic resonator can be increased by increasing its saturation magnetization ($4\pi M_s$), by increasing its total volume, or by increasing the RF magnetic-field intensity generated by the circuit in the location where the small ferrimagnetic resonator is placed. The value of $4\pi M_s$ is limited by the available materials and by the frequency of operation. The physical size of the resonator is limited by the crystal growth process and the machining costs. The local RF magnetic field can be intensified by constraining the field into a small cross section containing the ferrimagnetic resonator, and by making that cross section a low-impedance point.

The resonators that were used in the filters described in this report were disks of diameter 0.150 inch and thickness 0.005 inch. Two materials were used, pure YIG (with a saturation magnetization of approximately 1780 Oe)[1] and GaYIG (with a saturation magnetization of approximately 1000 Oe). The physical and magnetic characteristics of the disks that were available to us are described in more detail in Appendix A.

To enhance the coupling to the resonator by controlling the circuit parameters, the strip line is transformed down to a low impedance, thus increasing the total current flow. The center conductor is then necked down sharply over the resonator to increase the current *density* and thereby the local RF magnetic field intensity through the resonator. This technique is suitable for both bandstop filters and bandpass filters. The basic experiments were all made on single disks in bandstop filter configurations for greater simplicity. The general arrangement is indicated in Fig. 1. The disk is mounted parallel to the center strip which is notched, to a width on the same order as the disk diameter, just above the disk. The strip width leading both into and out of this region is wider to present a lower impedance and therefore stronger magnetic-field intensity at the disk.

Off resonance, the disk disturbs the transmission line very little, and almost all the incident power is transmitted. However, at resonance, energy is coupled into the resonator, which reflects it. By measuring the peak attenuation and the 3-dB bandwidth, both the external $Q(Q_e)$ and the unloaded $Q(Q_u)$ can be determined [3]. The dissipation loss of the bandpass filter will be determined by the ratio of Q_u to Q_e; this ratio is a function of only the peak attenuation (and not the 3-dB bandwidth) measured with the bandstop filter. The peak attenuation was measured and the ratio Q_u/Q_e was calculated over a wide frequency band for various notched center conductor widths. The results are plotted in Fig. 2. It is seen that the dissipation loss in the passband of the bandpass filter will decrease the more the center conductor is notched in the vicinity of the disk. The external $Q(Q_e)$ was calculated, and the result is plotted in Fig. 3. It is seen that Q_e decreases, that is, the coupling increases, even as the center conductor is notched to a width less than the disk diameter.

The effect of notching on the excitation of spurious modes is also of considerable interest. The magnetic field was swept and the attenuation recorded as shown in Fig. 4. In addition to the main attenuation peak, the two adjoining and most prominent spurious mode responses were recorded. This experiment was repeated at several frequencies, and it was found that the same two spurious modes were being

[1] A brief note on the unit of magnetization, oersted (Oe) rather than gauss, will be found in Appendix B and Young [12].

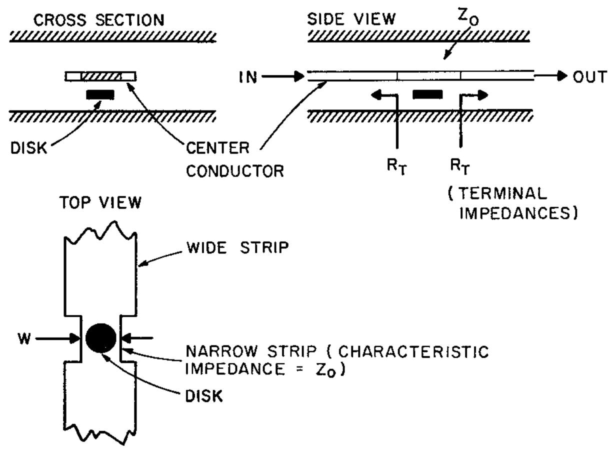

Fig. 1. Schematic of bandstop filter, showing notched center strip and notation for impedances.

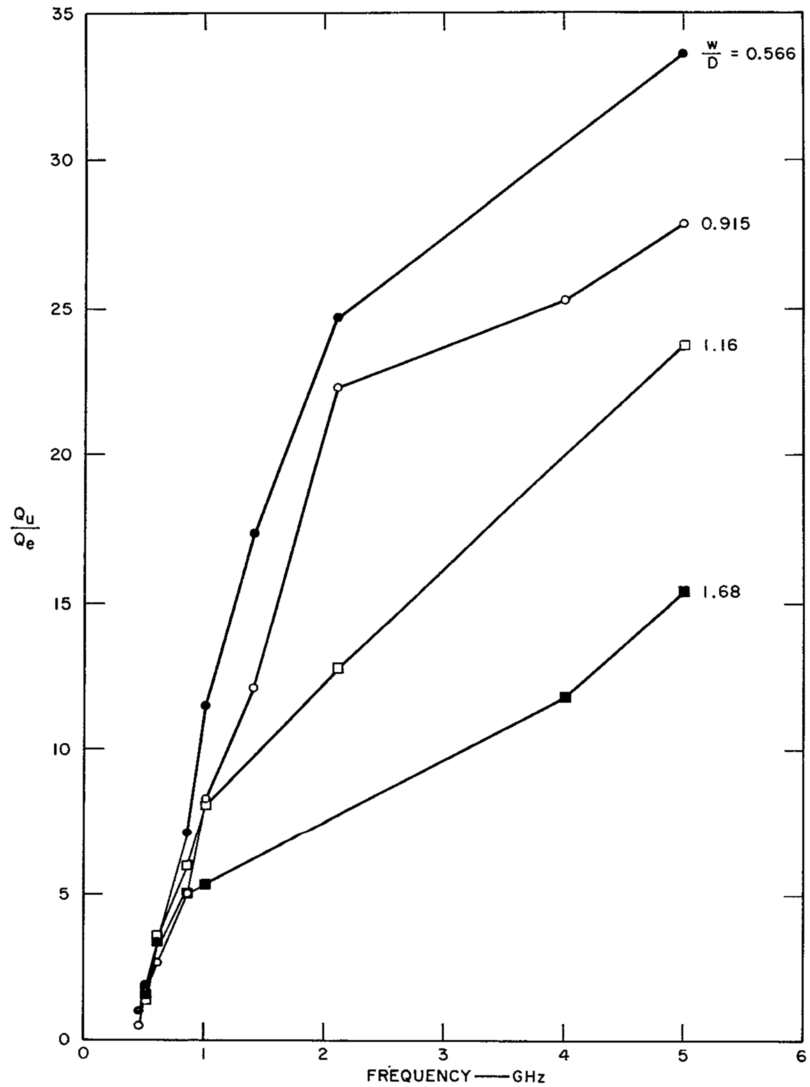

Fig. 2. Variation in Q_u/Q_e as a function of frequency for several center conductor widths (w=width of notched strip, D=diameter of disk=0.150 inch).

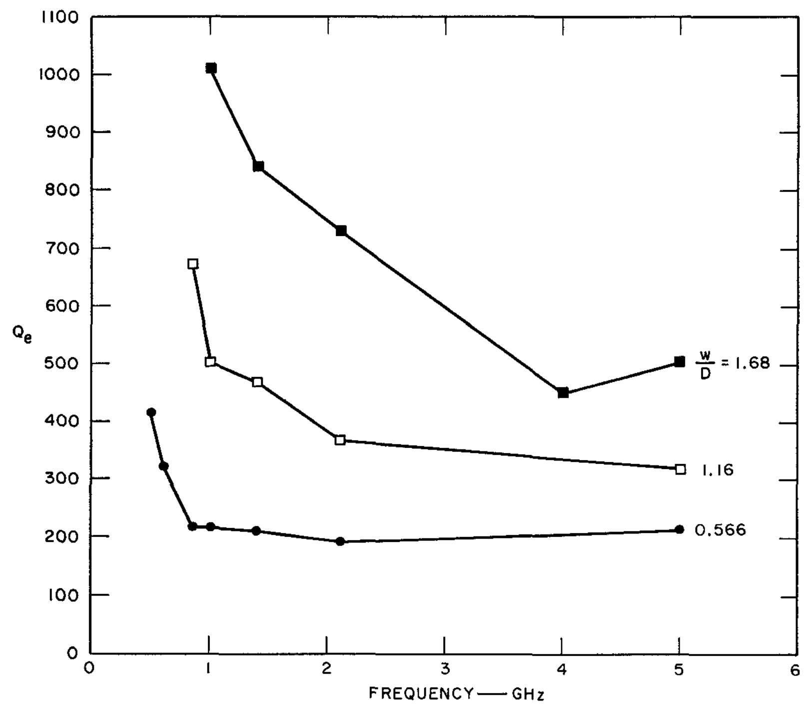

Fig. 3. Reduction in Q_e of a pure-YIG disk resonator as a result of reducing the width of the center conductor (w = width of notched strip, D = diameter of disk = 0.150 inch).

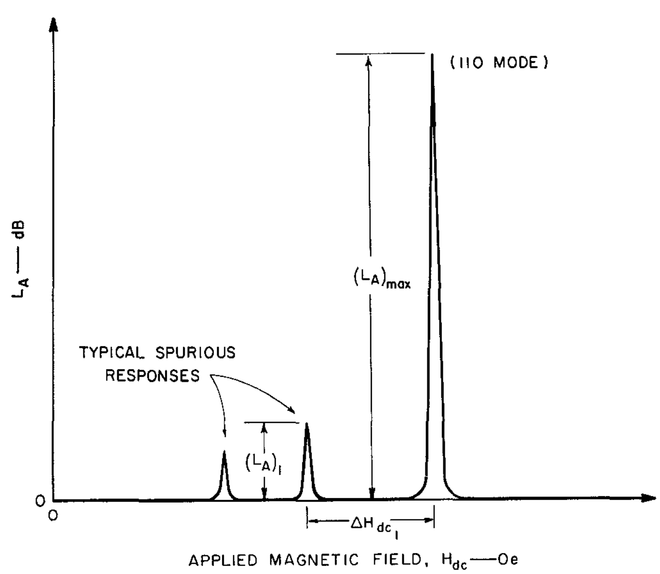

Fig. 4. Definition of spurious-response parameters.

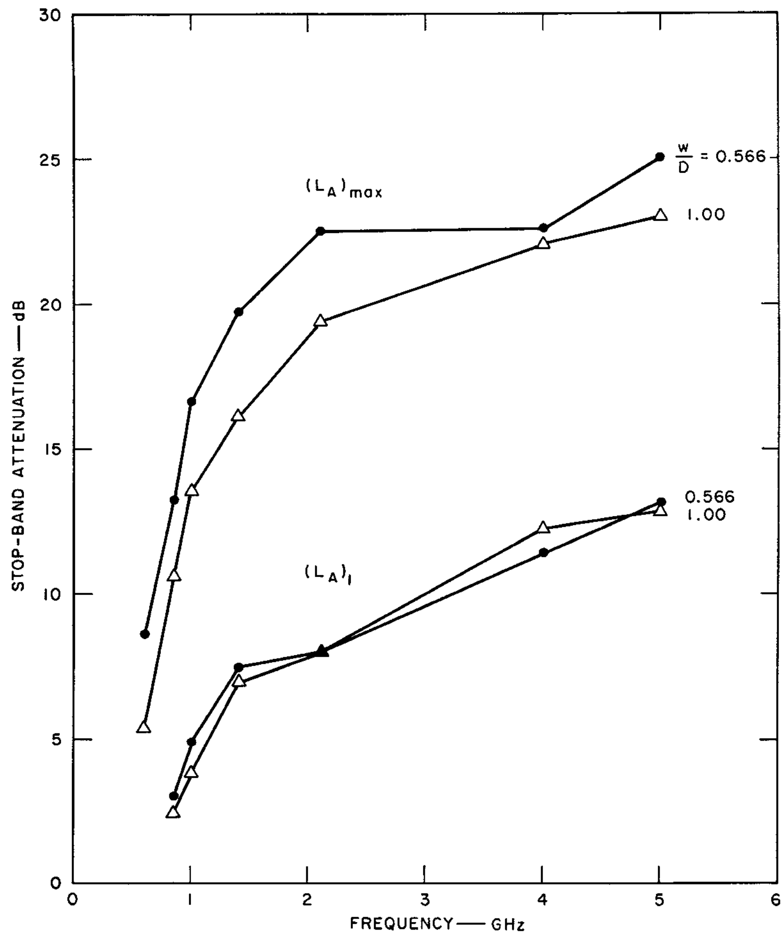

Fig. 5. Comparison of main-to-spurious responses for two center-conductor strip widths [$(L_A)_{max}$ and $(L_A)_l$ are defined in Fig. 4].

tracked in frequency. Figure 5 indicates that the most prominent spurious mode experiences approximately the same enhancement in coupling as is obtained for the desired, uniform precessional mode that corresponds to the peak response. Thus, notching the center conductor over the region of our experiment does not make the problem of spurious modes any worse, at least for pure-YIG crystals.

2) *Wall Effects:* In order to intensify the magnetic field in and around the ferrimagnetic resonator, it is necessary to bring all the metal boundaries in close to the resonator, as has been already pointed out. The presence of a conducting wall too close to the resonator results in currents that increase the dissipation loss as well as detune the resonator [6].

Figure 6 presents data taken at Stanford University [6]. Figure 6(a) shows the effect of the proximity of a metal wall on the effective linewidth. These experiments were made with a spherical ferrimagnetic resonator, and it is seen that the dissipation loss due to currents flowing in the metal wall increase the apparent linewidth of the material when the spacing between the center of the sphere and the metal wall becomes less than about one sphere diameter. For spacings greater than that, there is little noticeable line broadening. Figure 6(b) shows how the proximity of a metal wall tends to detune the ferrimagnetic resonator. This effect also becomes noticeable at about the same spacings that begin to affect linewidth. Table I shows the variation in stopband parameters (ratio of Q_u to Q_e, and resonance field H_{dc} at four frequencies) for various spacings of a disk resonator from the center conductor of a strip transmission line. In addition, strong spurious modes arise for both spheres and disks when they come too close to a conducting wall. This effect is likely to be worse when the nearby conductors disturb the symmetry of the RF fields.

To illustrate the "wall effect" of the center strip on a YIG disk (having different dimensions from those used in our filters), some measurements made by us are reproduced in Table I.

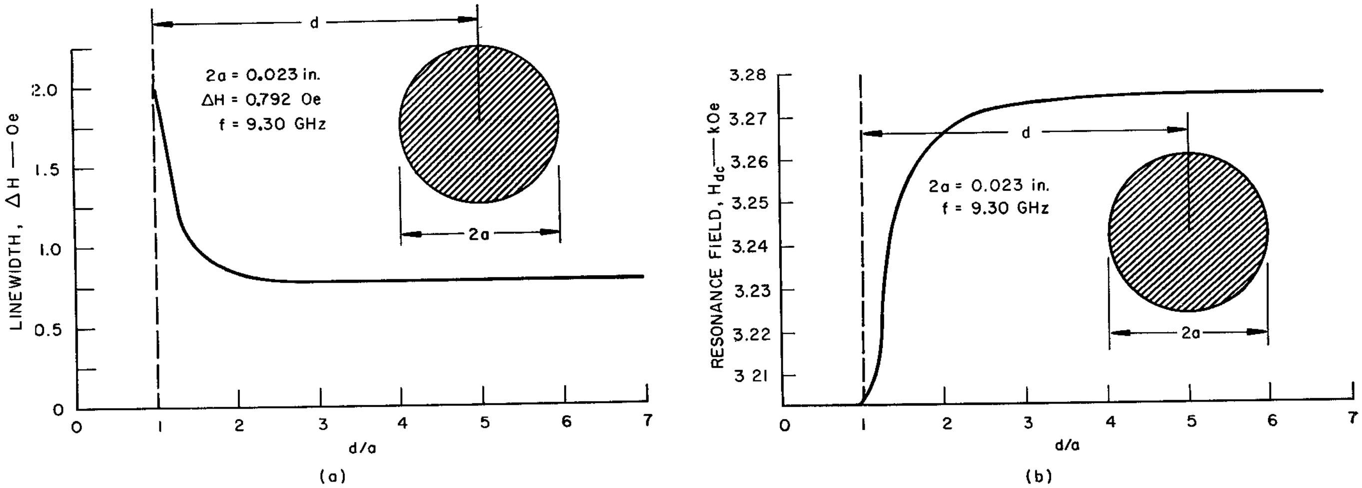

Fig. 6. Wall effect on a ferrimagnetic spherical resonator (after Anderson [6]): (a) showing change in linewidth, (b) showing shift in static magnetic field required for resonance.

TABLE I

VARIATIONS IN Q_u/Q_e AND IN RESONANT MAGNETIC FIELD H_{dc} OF A DISK RESONATOR DUE TO "WALL EFFECT"

	Frequency (GHz)	x =0.051 (inch)	x =0.038 (inch)	x =0.028 (inch)	x =0.0145 (inch)	x =0.008 (inch)
	5	11.40	11.40	10.08	6.34	3.50
Q_u/Q_e	4	8.04	7.16	6.94	4.18	3.70
	3	4.26	2.74	...	2.80	2.97
	2	1.03	0.888	...	0.30	0.38
	5	3.05	3.05	3.08	3.02	3.00
H_{dc}	4	2.70	2.69	2.69	2.60	2.67
(kOe)	3	2.32	2.31	2.31	2.29	2.28
	2	1.94	1.93	1.93	1.90	1.89

Conditions:

1) Data measured on pure-YIG disk, 0.098-inch diameter by 0.014-inch thick, in a 50-ohm air-strip transmission line.
2) Ground-plane spacing to center conductor = 0.110 inch.
3) x = disk-to-center-conductor spacing in inches.

C. Ferrimagnetic Resonator Characteristics

1) *Control of Resonant Frequency by Tilting:* The resonant frequencies of individual ferrimagnetic resonators that are used in a single filter cannot be allowed to differ from one another by more than a small fraction of the filter bandwidth. This criterion is generally not met by GaYIG resonators even when manufactured to nominally the same specifications. Spherical resonators used in the same filter can be synchronized conveniently by rotating the spheres about the (110)-mode crystalline axis. No similar convenient synchronizing technique exists for disks.

The resonant frequency of a disk resonator can be predicted quite well from (2) provided that the anisotropy field can be neglected. The applied static magnetic field H_{dc} is assumed to be in the z-direction, and N_z is the Cartesian demagnetizing factor in the z-direction.

We had previously found that a disk resonator could be rotated approximately $\pm 1\frac{1}{2}$ degrees relative to the applied magnetic field and still perform as an effective filter element. This rotation provides a manual frequency control useful in synchronizing multiresonator filters. Figure 7(a) illustrates the relative orientation of the RF and static magnetic fields to the disk for the axis of rotation used. In order to optimize filter performance while synchronizing the resonators, a second form of control was desirable. This was provided by rotating the static magnetic field relative to the entire filter. Figure 7(b) illustrates the rotation of the external static

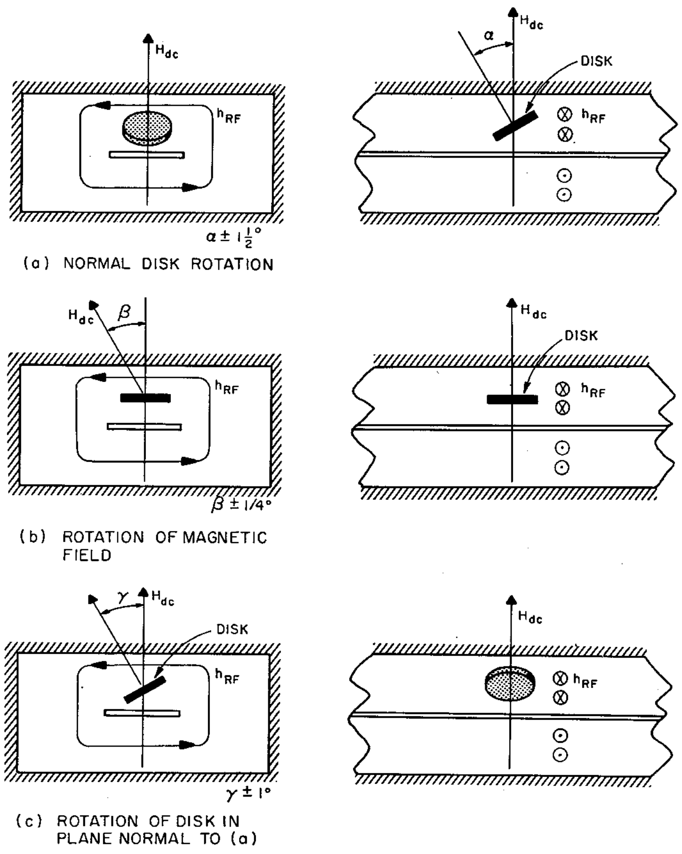

Fig. 7. Methods of rotating the disk resonator relative to its mount and to the static magnetic field.

magnetic field relative to a fixed disk inside the filter. It was found that a rotation of the static field H_{dc} in excess of $\pm\frac{1}{4}$ degree would degrade the resonator performance. It will be noted that in both rotations, Fig. 7(a) and (b), the RF magnetic field is always kept perpendicular to the static magnetic field. The only remaining independent rotation of the disk relative to the applied field is shown in Fig. 7(c). This possible adjustment was not made use of experimentally.

The use of disk resonators therefore requires fairly precise methods of obtaining the orthogonal RF-to-static magnetic field relationship, as well as effective controls for orienting the disk to obtain the highest unloaded Q.

An experimental series of recordings for a bandstop filter using pure-YIG disks is shown in Fig. 8. There are six plots in the figure taken at 100-MHz intervals from 500 to 1000 MHz. It is clear that a crossing mode occurs. This spurious mode can be seen in Fig. 8 as it rises on the right of the main resonance at 500 MHz and then crosses over and descends on the left of the main resonance as the frequency is increased.

The response curves in Fig. 8 do not have the ideal shape of the curve sketched in Fig. 4. There is a rounded minimum immediately to the left of each resonant curve. The explanation for this minimum is that a mismatch exists, arising from connectors and from notching the strip in the region of the disk, and this mismatch is compensated in part by the resonator for a particular applied field strength. (Maximum compensation occurs at the bottom of the minimum, where the insertion loss is minimum.) Figure 9 illustrates how the 3-dB bandwidth was measured. The 3-dB level was determined above the asymptotic value of the attenuation in the direction of increasing H_{dc}. The width of the curve was measured in oersteds, and this number was multiplied by 2.8 to obtain the bandwidth in megahertz.

2) *Linewidth Measurements:* The linewidth of a ferrimagnetic resonator is a function of both frequency and temperature. At any given frequency, the linewidth has a minimum for a particular temperature. The minimum is usually very flat and rises very steeply on the high-temperature side toward the Curie point. On the low-temperature side, the linewidth usually increases gradually as the temperature is lowered, corresponding to the onset of magnetic domain structure as the resonator material becomes unsaturated. An interesting set of curves is given by Yakovlev and Lebed [9] and is reproduced here in Fig. 10. The curves in Fig. 10 were obtained with spherical samples of YIG crystals. A curve of linewidth versus temperature for a pure-YIG disk is reproduced in Fig. 11 [10]. Lenzo has plotted linewidth against frequency for a 400-Oe gallium-doped YIG disk [11]; he found the linewidth to remain constant at 0.3 Oe from 500 to 1000 MHz, but rising sharply below 350 MHz.

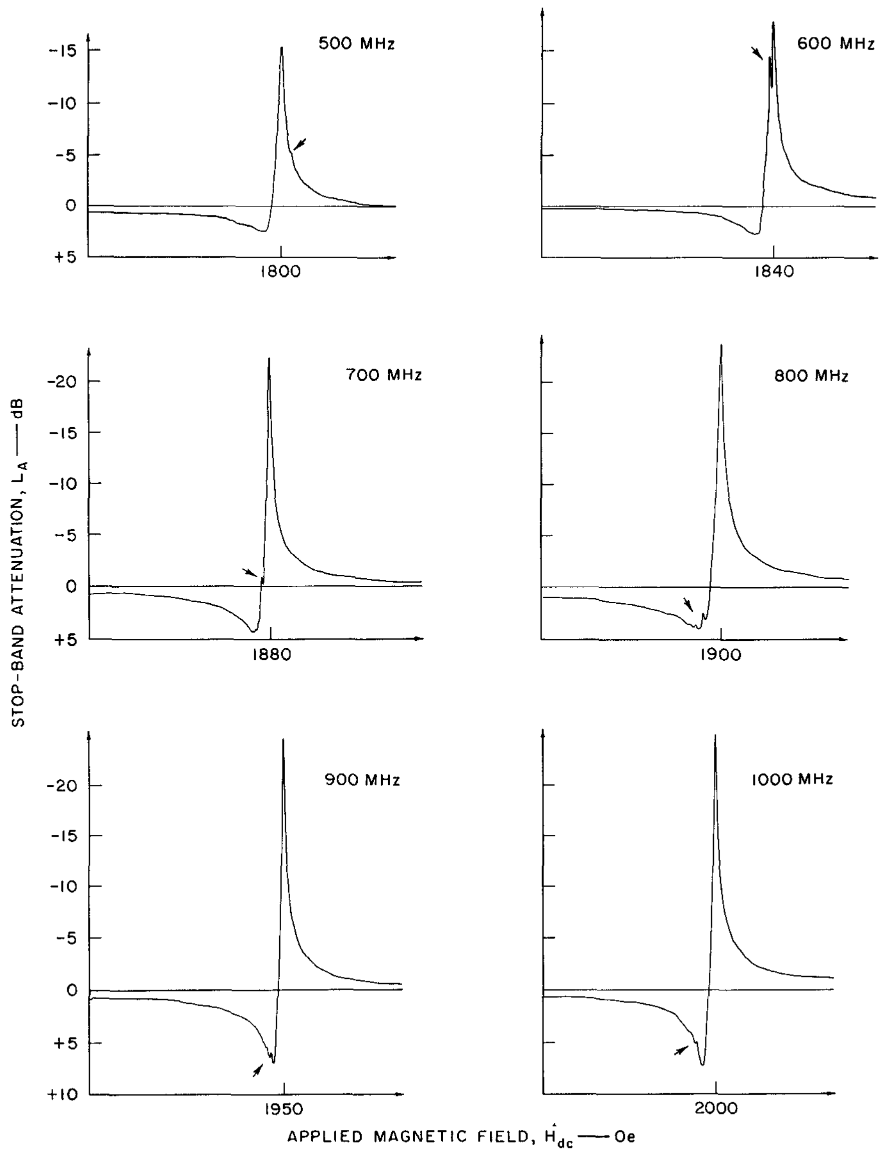

Fig. 8. Response of a single YIG-disk-resonator bandstop filter over the band 500 to 1000 MHz—showing a crossing mode (arrow).

Linewidth measurements on a pure-YIG disk were made by us using the bandstop filter method. The results of our measurements are shown in Fig. 12. There appears to be a distinct rise in the linewidth below about 700 MHz. The largest linewidth in the band of interest occurs at the low-frequency end (500 MHz) and is equal to about 0.8 Oe. Above 700 MHz the linewidth is less than 0.4 Oe. No experiments were performed on heated pure-YIG disks.

From the point of view of a filter application, the unloaded $Q(Q_u)$ is of more interest than the linewidth. The results corresponding to Fig. 12 are tabulated in Table II.

The linewidth of gallium-doped YIG disks was next investigated. (A different filter mount was used, however, so that the measured values for pure YIG and GaYIG are not exactly comparable because of different wall effects and degrees of coupling.) It was found that the linewidth increased sharply below 600 MHz at room temperature. If the filter were to operate successfully down to 500 MHz, it appeared necessary to heat the GaYIG disk. A series of measurements were then performed on the effect of both frequency and temperature on the resonant linewidth of a GaYIG disk. The results of these measurements are shown in Fig. 13. It is seen that even a moderate rise in temperature, for instance to 35°C, considerably improves the linewidth.

The unloaded Q can again be determined from the linewidth. The results corresponding to the room-temperature curve in Fig. 13 are tabulated below in Table III.

The change in $4\pi M_s$ with temperature was also measured. It was found that $4\pi M_s$ dropped almost linearly as the temperature was raised, descending from 1000 Oe at room temperature to 780 Oe at 100°C.

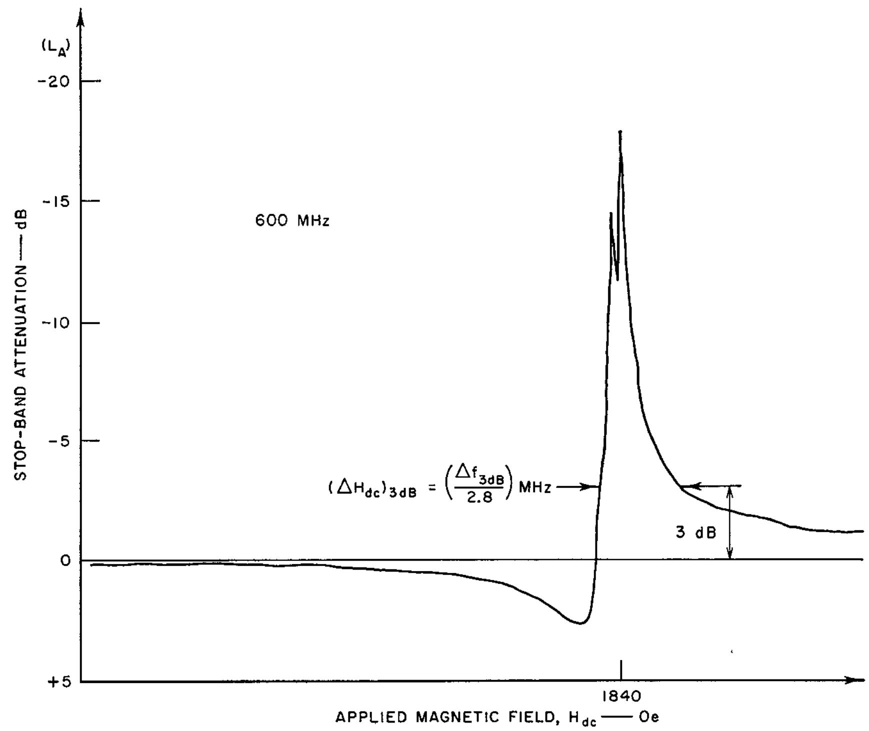

Fig. 9. Definition of parameters for Fig. 8.

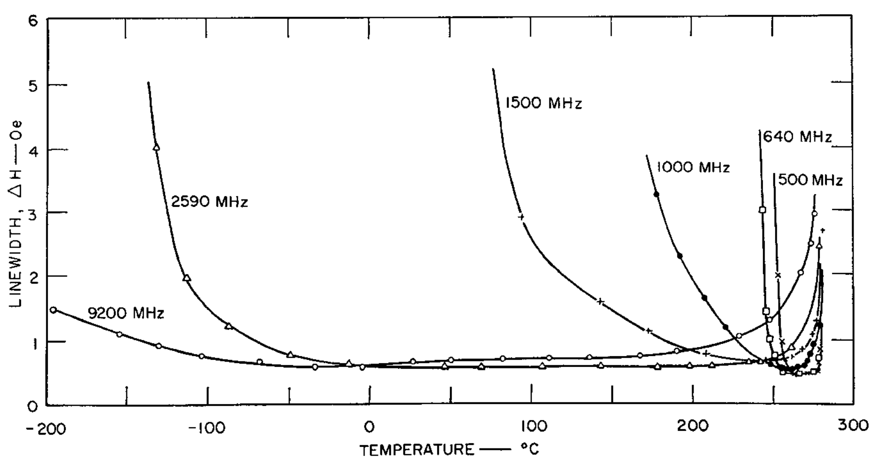

Fig. 10. Linewidth of pure-YIG spheres as a function of temperature at six frequencies (after Yakovlev and Lebed [9]).

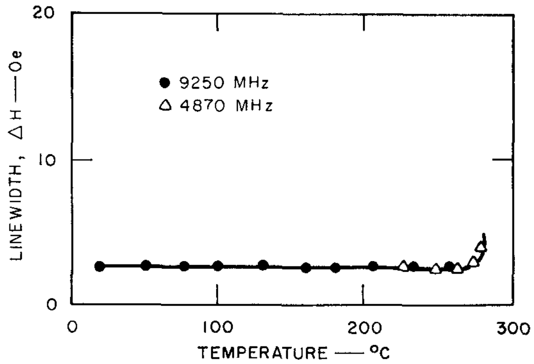

Fig. 11. Linewidth of a pure-YIG disk as a function of temperature at two frequencies (after Lebed and Shevlyagin [10]).

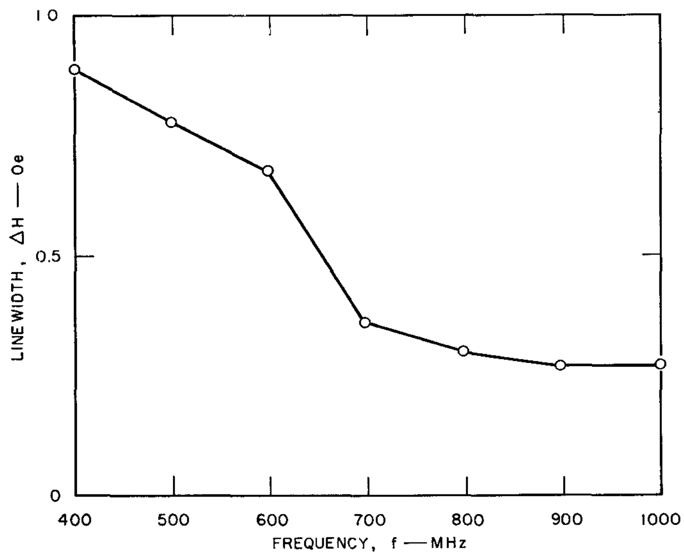

Fig. 12. Measured linewidth versus frequency for a pure-YIG disk at room temperature.

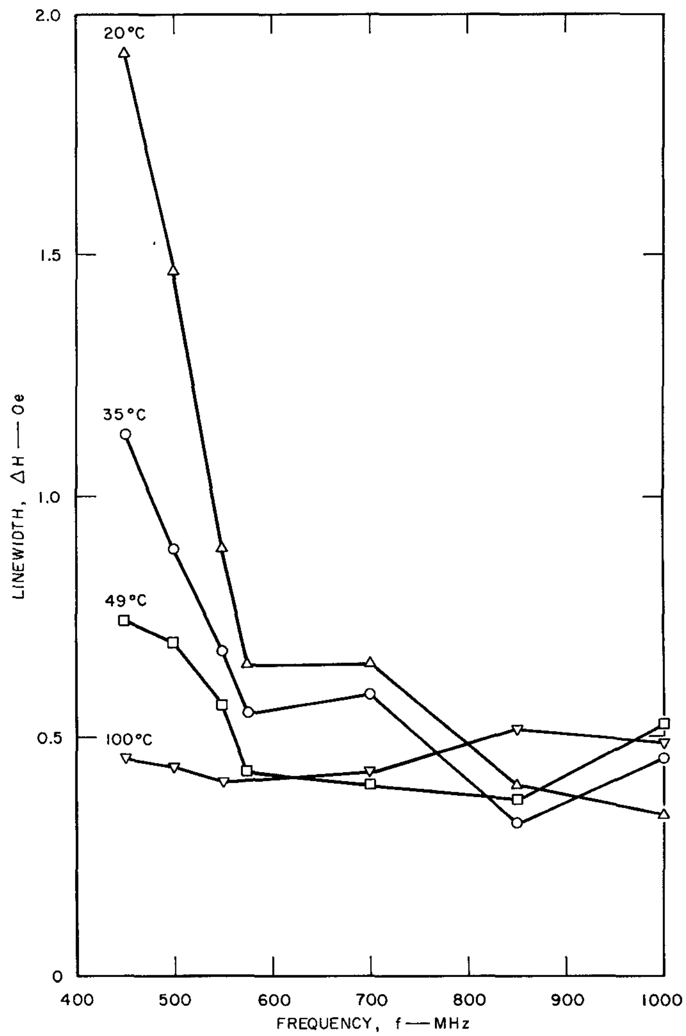

Fig. 13. Measured linewidth versus frequency for GaYIG disk ($4\pi M_s = 1000$ Oe), at four temperatures.

TABLE II

UNLOADED Q AS A FUNCTION OF FREQUENCY FOR PURE-YIG DISK

Frequency (MHz)	400	500	600	700	800	900	1000
Unloaded $Q(Q_u)$	210	276	366	747	1020	1250	1390

Conditions:

1) H_{dc} is perpendicular to plane of disk.
2) Plane of disk is perpendicular to (111) crystal axis.
3) Disk dimensions: 0.150-inch diameter by 0.005-inch thick.
4) Room temperature.

TABLE III

UNLOADED Q AS A FUNCTION OF FREQUENCY FOR GaYIG DISK

Frequency (MHz)	500	600	700	800	900	1000
Unloaded $Q(Q_u)$	122	329	384	697	846	1050

Conditions:

1) H_{dc} is perpendicular to plane of disk.
2) Plane of disk is perpendicular to (110) crystal axis.
3) Disk dimensions: 0.150-inch diameter by 0.005-inch thick.
4) Room temperature.

III. Development of Bandpass Filters

A. Design of Coupling Structure

It was decided to design a filter having an insertion loss in the passband of about 2 dB over the tuning range of 500 to 1000 MHz. Such a low insertion loss requires strong coupling into the resonators. For this reason, it was desired to present an external impedance of 5 ohms to each of the two disk resonators. Hence, the first order of business was the design of two transformers from 50 ohms down to 5 ohms. Although a number of more compact designs were considered, it was finally decided to use a quarter-wave transformer [1]. A four-section transformer was designed to have equal-ripple performance from nominally 400 to 1200 MHz, with a design VSWR of less than 1.2.

The two transformers can now be used to make up a bandpass filter by displacing them laterally and coupling each to a ferrimagnetic-disk resonator in such a way that the two disks are aligned axially and can be coupled through an iris plate. Two photographs of the filter are shown in Figs. 14(a) and (b). In Fig. 14(a) the top plate or ground plane has been removed on the left, thus exposing part of the stepped-impedance transformer. The tilted plate is the mount containing a rotatable paddle on which one YIG disk can be seen. The tuning knob projecting in the lower right of the picture rotates a second similar paddle on which the second disk (not visible in the picture) is mounted. Figure 14(b) is a top view of the filter opened up. The YIG disk is seen in the center of the upper part. The black slot in the lower part is the iris coupling hole. The critical dimensions of the resonator housing are shown in Fig. 15.

Two GaYIG disks were then selected from the five we had on hand; they had all been previously tested (Appendix A), and the two disks selected had almost the same values of $4\pi M_s$. The two disks were carefully aligned before measuring the filter performance.

B. Performance of Filter with GaYIG Disks

The filter designed, constructed, and tuned up, as previously described, was then ready for more detailed testing. The midband insertion loss, the 3-dB bandwidth, the passband response shape, and the spurious responses were all measured. The measurements were made at frequencies 100 MHz apart over at least the band 500 to 1000 MHz. (Sometimes a few additional frequencies were also selected for testing.)

Figure 16 shows the midband insertion loss of the GaYIG filter. Measurements were made first at room temperature (approximately 20°C). The insertion loss was 2 dB or less from 600 to 1100 MHz but rose steeply to 3.2 dB at 500 MHz. Referring to the linewidth plots in Fig. 13 one would expect that heating the disks would result in a considerable improvement at 500 MHz without any substantial increase in insertion loss at the other frequencies. The filter was accordingly heated to 30°C; the resulting insertion loss curve is shown in Fig. 16. The improvement obtained at 500 MHz was disappointingly small, while the insertion loss at all other frequencies increased. Although the maximum insertion loss in the band was then 0.2 dB better than before, the overall performance could hardly be said to have improved. No further heating experiments were therefore made.

The 3-dB bandwidths were also measured at the same frequencies, and are plotted in Fig. 17. The bandwidth remained less than 10 MHz throughout the band.

The shapes of the response curves at the same frequencies are recorded in Fig. 18. Here the attenuation is plotted against magnetic field which was swept through resonance at the six frequencies mentioned. It is seen that the filter is approximately maximally flat, being perhaps slightly undercoupled at the low end of the band and slightly overcoupled at the upper end of the band. It is interesting to note the spurious responses that progressively pass through the main resonance as the frequency is changed. (They are probably excited by the concentration gradient and inhomogeneties inside the gallium-doped YIG material.) A similar set of curves for a temperature of 30°C was taken. These curves are generally very similar in shape to those depicted in Fig. 18, but showed less evidence of spurious mode activity in the passband.

Spurious responses outside the main passband of the filter were also recorded separately. It was found that there are many strong spurious responses close to the main response on the low magnetic-field side. (This would correspond to the high-frequency side if the frequency were swept while the magnetic field remained constant.) The strongest spurious response outside the passband is between 5 and 20 dB down, depending on the frequency of operation.

In general, it may be stated that the design objectives for this filter have been met. Its greatest shortcoming is the large number of strong spurious responses outside the passband. This appears to be attributable not to the filter design or the choice of $4\pi M_s$, but to the problems inherent in the manufacture of doped materials.

C. Performance of Filter with Pure-YIG Disks

Theoretically, the GaYIG disks should give less spurious responses than pure YIG, and this was one of the principal reasons for selecting GaYIG rather than pure YIG. Since this expectation was not borne out by experiment for the reasons outlined above, two pure-YIG disks were substituted for the two GaYIG disks in the same filter structure. The midband insertion loss obtained over the frequency band 500–1200 MHz with pure-YIG disks in the same filter structure as was designed for the GaYIG disks was found to rise uniformly with frequency, going from 2.1 dB to 4.1 dB between 500 and 1000 MHz. An examination of the response curves showed that the filter was considerably overcoupled at 1000 MHz (having a 3-dB ripple in the center of the passband at the high end of the tuning band), and calculations showed that the external Q approximately tripled in going from 500 to 1000 MHz. The reason for this is not clear, since it did not occur with the GaYIG disks in the filter. Although the proper design procedure would have been to correct for this condition, it was simpler to reduce the iris coupling between the two disks. Accordingly, aluminum adhesive tape was used to cut down the iris size.

This had the effect of improving the midband insertion loss, particularly at the high end of the band. With the reduced-size iris, midband insertion loss of the filter was less than 3.2 dB from 450 to 1100 MHz. No effort was made to improve the performance any further.

The 3-dB bandwidths are approximately twice what they were for the GaYIG filter (Fig. 17). One would conclude from a comparison of the bandpass filter measurements with GaYIG and then pure-YIG disks that the unloaded Q and therefore linewidth of GaYIG disks at these frequencies are better than those of pure-YIG disks. This conclusion is not borne out by a comparison of Figs. 12 and 13. The discrepancy is too great to be attributed entirely to experimental error, and it seems likely that the explanation is "wall effect" (Sec. II-A-2), since the boundary conditions are different in the bandpass filter and in the two bandstop filter structures used; the strength of the wall effect might also be affected by the $4\pi M_s$ values of the disks.

The passband response curves were generally similar in shape to those shown in Fig. 18. They go from critically coupled at 500 MHz to overcoupled at 1000 MHz. Although some spurious responses were visible in the pass band, they are not strongly excited and are generally negligible.

Wideband recordings were also taken to show the spurious responses outside the passband. It was found that the spurious responses are greatly reduced, compared to those obtained with the GaYIG filter. They fall off sharply away from the passband. The strongest response is generally about 20 dB down. All spurious responses beyond the third or fourth were at least 40 dB down.

Finally, measurements were made on the limiting characteristics of the filter with pure-YIG disks. Two plots are shown in Fig. 19. It is seen that the onset of limiting occurs at an input power level of approximately -10 dBm at a frequency of 500 MHz, and at an input power level of approximately 0 dBm at a frequency of 1000 MHz.

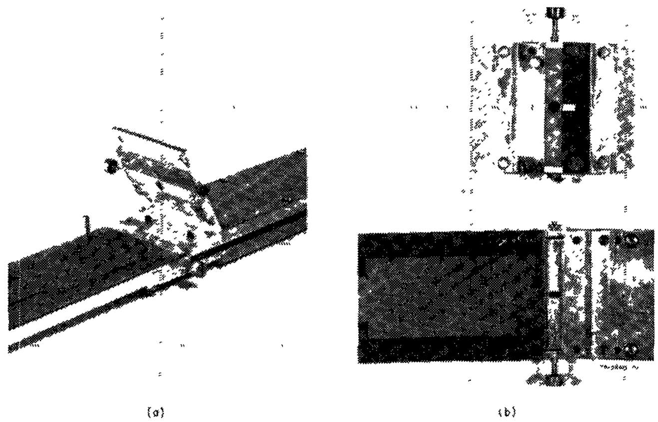

Fig. 14. Photograph of filter assembly.

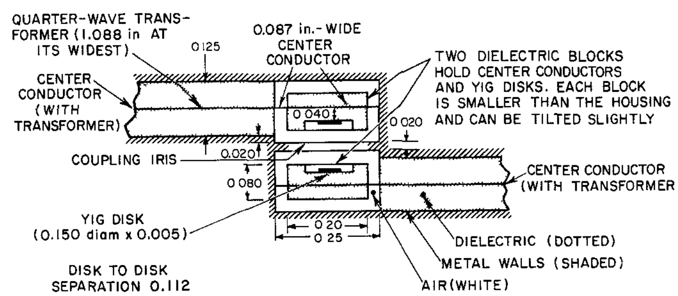

Fig. 15. Disk resonator housing (side view).

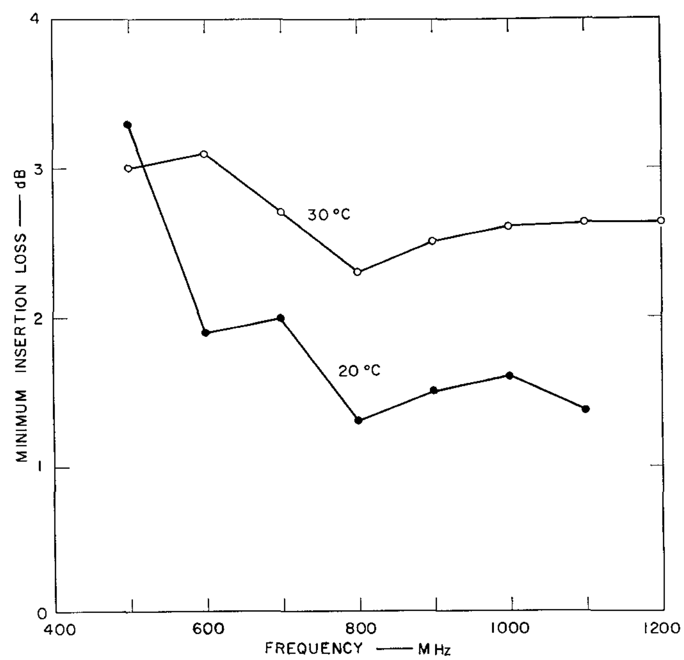

Fig. 16. Minimum insertion loss for GaYIG two-resonator bandpass filter versus frequency, at two temperatures.

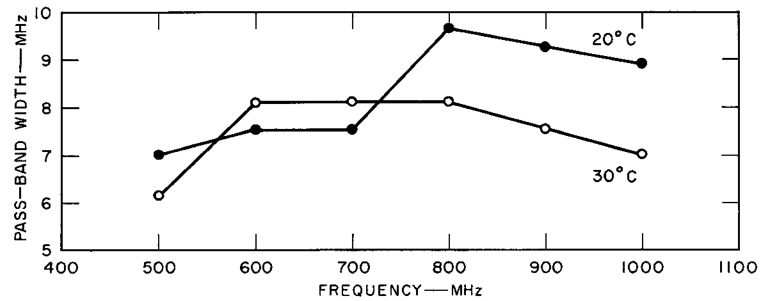

Fig. 17. Bandwidth (between 3-dB points) of GaYIG two-resonator bandpass filter versus frequency, at two temperatures.

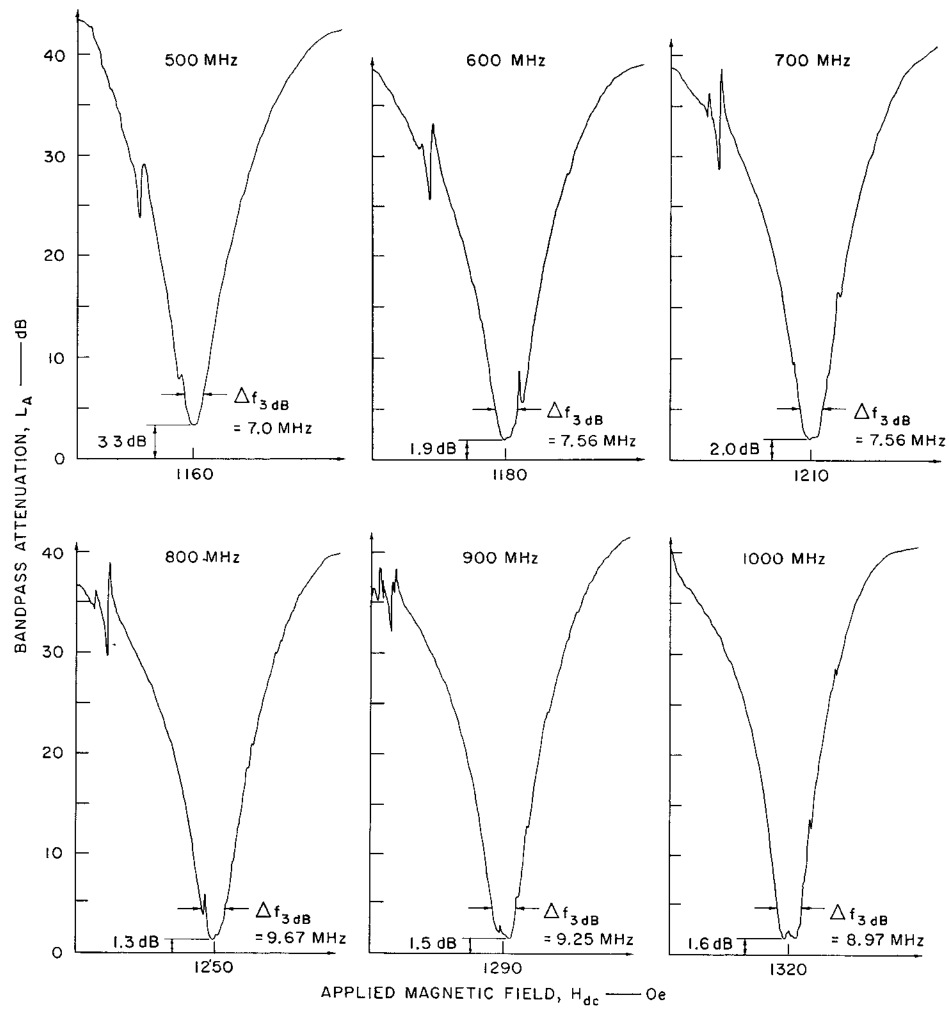

Fig. 18. Bandpass response of GaYIG two-resonator bandpass filter at room temperature, at six frequencies.

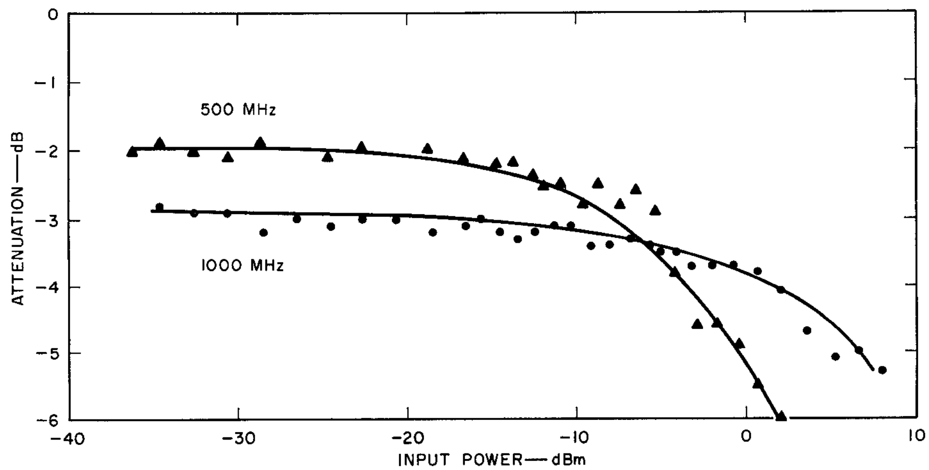

Fig. 19. Output power versus input power for pure-YIG two-resonator bandpass filter at 500 and 1000 MHz—showing limiting.

IV. Conclusion

The possibility of electronic tuning by other means, such as varactor-tuned resonators, also exists. A detailed comparison has not been made, and each problem should be evaluated on its own merits. In the present problem wide tuning range was the principal concern (at least one octave was desired, and almost two octaves were obtained), and YIG resonators were chosen for this reason.

Two magnetically tunable bandpass filters operating from 500 to 1000 MHz were constructed, one having GaYIG disks and the other pure-YIG 'disks. The former had a generally lower insertion loss and narrower bandwidht, while the latter had fewer spurious responses. The midband insertion loss of both filters could be made less than 3.2 dB, and that of the GaYIG could be made to average less than 2 dB over the band of interest (500 to 1000 MHz). The strongest spurious response of the pure-YIG filter in its stopband was generally about 20 dB down. Numerous experimental data have been presented, including measurements on linewidth, filter response curves, wall effect, tuning procedures, and limiting characteristics.

Appendix A

Summary of Physical and Magnetic Characteristics of Ferrimagnetic Resonators Used in These Experiments

An order for five GaYIG disks, placed with Airtron, specified nominal dimensions of 0.150-inch diameter × 0.005-inch thickness, and $4\pi M_s = 1000$ Oe with a variation of ± 10 gauss from one specimen to another. When received, the disks were inspected mechanically and electrically and accepted on the basis of the data shown in Table IV. In measuring relative resonant fields (with a differential gaussmeter) at a given frequency, the quantity $4\pi M_s N_z$ is involved, rather than $4\pi M_s$ alone, because of variation in disk shape and size. For a two-disk filter, it is actually $4\pi M_s N_z$ that matters, although it places a more severe criterion on similarity of one disk to another. Two of the disks came from a common crystal slice, hence should have been close in $4\pi M_s$. These disks were not identified in the shipment, but they might have been numbers DA-1 and DA-5, of which the second resonates at a field only 5 ± 3 Oe below that of the first (at 575 MHz), the ± 3 Oe accounting for experimental uncertainty. However, DA-5 was about 0.003-inch larger in diameter. These two disks were later used in the bandpass filter.

Linewidth data on one disk were presented in Fig. 13. All five disks were measured at 575 MHz, and their linewidths were compared. The disks all appeared comparable in performance here, even though DA-4 had a visible crack.

Additional specifications on the disks that were not checked out at SRI include the following: the two flat surfaces of each disk were specified to be parallel to within 0.0001 inch; the crystalline axis orientation of each disk was to be such that the plane of the disk should be a (110) plane, within ± 3 degrees; and each disk was to have an optically polished surface finish.

Disks are more fragile and therefore more difficult to handle than spheres. In our series of experiments the disks had to be repeatedly mounted and demounted from one filter to another and from one test to another. In the process of cementing the disk to its dielectric mount and then dissolving the adhesive, it is likely that the solutions penetrated into small cracks of the crystal, thereby gradually weakening the sample and forcing it apart. By the time all the experiments were finished, only two of the original five disks remained intact. On the other hand, in a production set-up the disks need to be mounted only once; therefore, the chance of losing a disk by breakage (always providing that it is handled carefully) is considerably less.

TABLE IV

INSPECTION OF FIVE GaYIG DISKS RECEIVED FROM AIRTRON IN SEPTEMBER, 1965
(Nominal $4\pi M_s = 1000$ Oe)

SRI Identification Number	Mechanical Data			Difference in Resonant Magnetic Field (Oersteds)
	Diameter (inch)	Thickness (inch)	Remarks	
DA-1	0.1495 −0.1505	0.0058	slight flat on edge	0 (reference)
DA-2	0.1495 −0.1510	0.0056	line scratches on one surface	-17.5 ± 2.5
DA-3	0.1504 −0.1516	0.0057	large flat on edge	-38.5 ± 2.5
DA-4	0.1495	0.0059	crack starting at edge	-8.5 ± 2.5
DA-5	0.1530 −0.1536	0.0057	—	-5 ± 3

APPENDIX B
UNIT OF MAGNETIZATION

The saturation magnetization $4\pi M_s$ is usually specified in gauss. However, the great majority of electrical engineering text books, as well as the International Electrotechnical Commission (IEC), favor a definition which makes $4\pi M_s$ dimensionally equivalent to magnetic field (measured in oersted) and not to magnetic flux density (measured in gauss). Hence, $4\pi M_s$ should be measured in oersted. In Gaussian units there are no numerical consequences, and either gauss or oersted may be interchangeably used, since the permeability of free space is unity in Gaussian units. However, when converting to MKSA units, oersted and not gauss should be the starting point. Since the IEEE has gone on record as favoring MKSA units, we have brought our terminology into line to the extent of presenting saturation magnetization in oersted rather than gauss. The reader who wants to take the final step can then substitute (for YIG) $M_s = 1.39\times10^5$ A/m instead of $4\pi M_s = 1750$ Oe. For a more detailed explanation, see Young and Barrow [12].

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