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YIG filters

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Introduction

A new group of microwave ferrite components have attracted a good deal of attention in recent years because of their unique and very nearly ideal characteristics. These components, known as "YIG" devices, are now employed in various applications. Small polished samples of single-crystal yttrium iron garnet (YIG, $Y_3Fe_5O_{12}$), operated at the ferrimagnetic resonance, are used as resonators for tunable filters [1], for tuning oscillators and for low-level limiters. Single-crystal YIG has an extremely small ferrimagnetic resonance linewidth, which gives high unloaded Q-factors (up to 10 000).

Fig. 1 shows the principle of operation of a YIG resonator in a typical coupling configuration giving a band-pass-filter response. The electron spins in the YIG crystal that are unpaired and are the origin of its ferrimagnetism are aligned by a static or quasistatic magnetic field H_0. An r.f. signal at the input coupling loop builds up an r.f. magnetic field $\boldsymbol{H}_{\rm rf}$ perpendicular to the static field. Because of the gyroscopic property of the electron spins the resultant magnetization $\boldsymbol{M}$ in the YIG crystal will precess around $\boldsymbol{H}_0$; the precession increases in amplitude if the signal frequency coincides with the precession frequency, which is also known as the ferrimagnetic resonance frequency, and is determined solely by the fundamental constants of the electron and by the applied magnetic field H_0 [2]. As a result of the precession an r.f. magnetic-field component arises perpendicular to the plane of $\boldsymbol{H}_0$ and $\boldsymbol{H}_{\rm rf}$ (fig. 1); this perpendicular component can be coupled out by means of the second half-loop. It follows that only signals at the precession frequency are coupled from the input loop to the output loop by the precessing magnetization in the YIG sphere. Signals at other frequencies are unaffected by the YIG sphere and no r.f. power is transferred by the YIG filter because there is no coupling between the two orthogonal loops. Thus a YIG filter will give a single unambiguous response, which can be tuned over a range of more than ten to one in frequency simply by varying the applied static magnetic field. The electrical behaviour of YIG filters is in many aspects the same as that of conventional microwave filters with transmission-line resonators or cavities, but YIG resonators do have some unique features (including certain limitations) which will be described in the following section. Several completely assembled YIG devices are shown in *fig. 2*. Their size is mainly determined by the electromagnet used for tuning.

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Resonance; lower cut-off frequency

In applications of single-crystal YIG samples as ferrimagnetic resonators for microwave filters the uniform-precession resonance mode (UPR mode) is utilized. This is the fundamental resonance mode in which all electron spins in the YIG sample precess with the same amplitude and phase angle about the static magnetic field. Higher-order resonance modes also exist in which the amplitude and phase of the precession are not the same all over the YIG sample (usually a sphere) and vary in a regular geometrical pattern. The

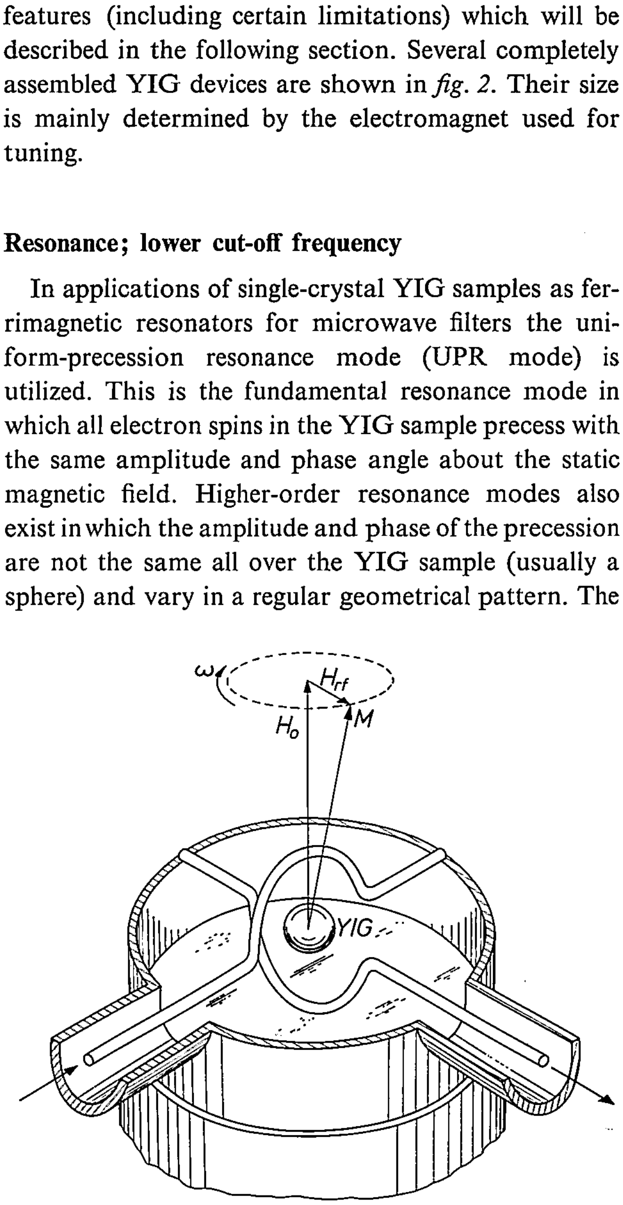

Fig. 1. Band-pass filter with YIG resonator. Input and output are coupled to the YIG sphere *YIG* by two orthogonal half-loops. The sphere is magnetized by a static external field $\boldsymbol{H}_0$; if an r.f. magnetic field $\boldsymbol{H}_{\rm rf}$ is coupled in, the resulting magnetization $\boldsymbol{M}$ precesses about the direction of $\boldsymbol{H}_0$ because of the gyroscopic property of the electron spins in the material. The precession introduces magnetic-field components that can be coupled out by the output semiloop. The precession angular frequency ω increases linearly with the magnetic field strength H_0, which is adjusted to tune the filter to the frequency required. Other frequencies do not excite the precession and are therefore not transmitted by the filter.

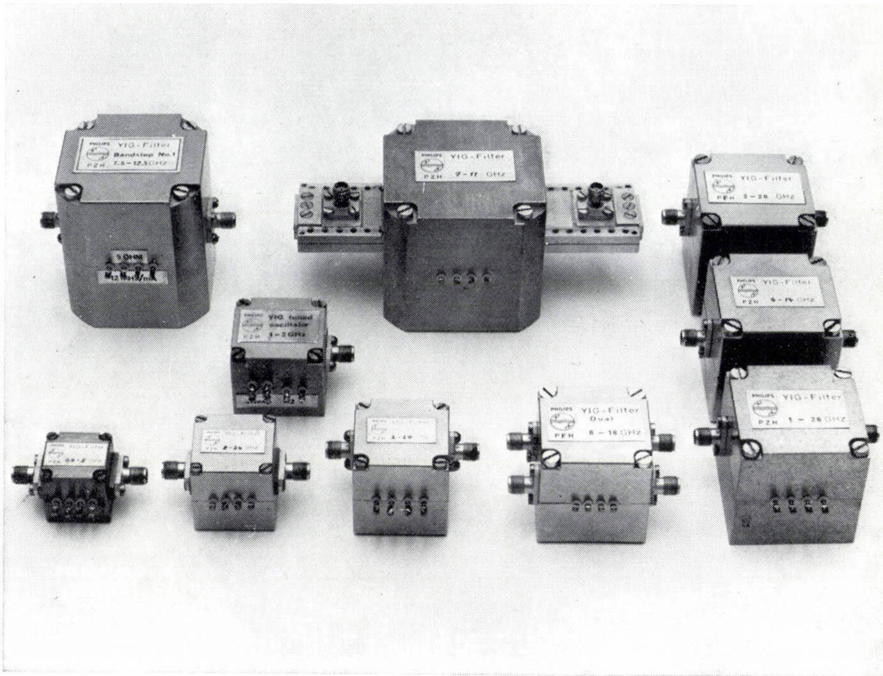

Fig. 2. Several tunable YIG devices. The electromagnets, whose connections can be seen on the front of the housings, determine the size of the devices.

resonance modes of YIG samples sufficiently small compared with the wavelength for the effects of wave propagation through the sample to be neglected have been calculated by L. R. Walker [3]; these are called magnetostatic modes or Walker modes.

The resonant frequency of the UPR mode for axially magnetized spheroids with circular symmetry about $\boldsymbol{H}_0$ is given by:

$$f_0 = \gamma \{H_0 + H_a + (N_t - N_z)M_s\}, \qquad (1)$$

where γ is the gyromagnetic ratio, which is equal to 35.2 kHz/(A/m) (2.8 MHz/Oe). In the relation (1) H_0 is the external static or quasistatic magnetic field and H_a is the crystal-anisotropy field, which may be regarded as an additional external field whose magnitude and sign depend on the crystallographic orientation of the YIG resonator with respect to $\boldsymbol{H}_0$. The quantities N_t and N_z are the demagnetizing factors for the YIG sample in the transverse and axial directions respectively. Both vary with its geometric shape; for a sphere N_t is equal to N_z, which means that the last term in (1) vanishes. Consequently the UPR resonant frequency of a sphere does not depend on the saturation magnetization M_s, which is a constant of the material and has a value of 1.42×10^5 A/m (1780 Oe) for YIG.

In some applications the YIG resonator cannot be made very small compared with the wavelength and wave-propagation effects have to be taken into account. For a sphere in which N_t is equal to N_z, the resonant frequency is given by [4]:

$$f_0 = \gamma \left\{H_0 + H_a - \frac{4\pi^2}{90} M_s(\varepsilon_r + 5) \left(\frac{d}{\lambda_0}\right)^2\right\}, \qquad (2)$$

where ε_r is the relative dielectric constant ($\varepsilon_r = 16$ for YIG) d the sphere diameter and λ_0 the free-space wavelength at resonance. Unlike that of the UPR mode, the resonant frequency is not independent of the dimensions of the sample. The propagation term remains smaller than 50 MHz if the ratio of the diameter of the sphere to the wavelength is less than 1 : 30. This ratio is exceeded, for typical YIG resonators with a diameter of 0.3 mm, at frequencies above 30 GHz.

The resonant frequencies f_n of the higher-order magnetostatic modes are located in a frequency band around the resonant frequency f_0 of the UPR mode:

$$f_0 - \gamma N_t M_s < f_n < f_0 + \gamma\,(0.5 - N_t)M_s. \qquad (3)$$

Fortunately only a few of the higher-order modes are excited in a homogeneous r.f. magnetic field, and only weakly. In multistage filters the level of interfering higher-order modes can be suppressed further by using spheres with a slightly different M_s. This will not change the resonant frequency of the UPR mode but the higher-order modes will have slightly different resonant frequencies owing to their dependence on M_s. Thus the main response remains unchanged whereas the interstage coupling of the unwanted higher-order modes is considerably reduced.

It also follows from eqs. (1) and (2) that there are no resonances at higher harmonics of the frequency f_0; this means that a YIG resonator gives only a single response between d.c. and millimetre wavelengths, which can be tuned linearly through a frequency band of more than a decade by an external static or quasistatic magnetic field.

[1] See for example: G. L. Matthaei, L. Young and E. M. T. Jones, Microwave filters, impedance-matching networks, and coupling structures, McGraw-Hill, New York 1964.
[2] See also: M. Lemke and W. Schilz, Microwave integrated circuits on a ferrite substrate; this issue, page 315.
[3] L. R. Walker, Resonant modes of ferromagnetic spheroids, J. appl. Phys. 29, 318-323, 1958.
[4] J. E. Mercereau, Ferromagnetic resonance g factor to order $(kR_0)^2$, J. appl. Phys. 30, 184S-185S, 1959.

Single-crystal YIG has the smallest known ferrimagnetic resonance linewidth (of the order of 1 MHz [5]). Imperfections in the surface and impurities in the crystal give losses because of scattering of r.f. energy into the crystal lattice; a highly polished surface and a high degree of purity and homogeneity of the YIG crystal are therefore required to obtain the high Q_0 (quality factor) which is possible with YIG resonators. Curves showing the measured Q_0 plotted against frequency for YIG and YGaIG (a gallium-substituted YIG) spheres and for a YIG disc are shown in *fig. 3* [6]. The Q_0 decreases rapidly to zero at the lower frequencies. This occurs when the static magnetic field H_0 corresponding to low frequencies becomes so weak that the YIG resonator is no longer magnetically saturated and the internal magnetic field approaches zero, because the spins are then no longer aligned parallel and r.f. energy couples from the UPR mode to the crystal lattice.

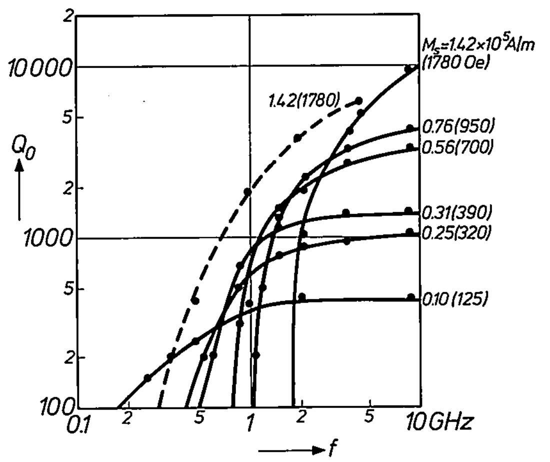

Fig. 3. Unloaded Q_0 (quality factor) plotted against frequency f, measured for YIG and YGaIG spheres (*solid lines*) and a YIG disc (*dashed*) [6].

The cut-off frequency f_c of a YIG resonator that is obtained when the internal magnetic field H_{iz} approaches zero can be found from (1) when we neglect H_a and put $H_{iz} = H_0 - N_z M_s = 0$:

$$f_c = \gamma N_t M_s. \qquad (4)$$

For spheres, with $N_t = 1/3$, the cut-off frequency given by (4) is 1660 MHz; measured values are somewhat higher (around 1800 MHz) because not all the electron spins are aligned as soon as H_{iz} becomes greater than zero (this can be seen from the rounded corners of the hysteresis loop).

The cut-off frequency of a ferrimagnetic resonator can be lowered by using thin axially magnetized discs which have an N_t close to zero, or by reducing the saturation magnetization of the resonator material. The saturation magnetization can be reduced either by substituting gallium at iron sites in the YIG system ($Y_3Ga_xFe_{5-x}O_{12}$, with typical x-values between 0.05 and 0.9) or by heating the YIG resonator and making use of the natural decrease of M_s with increasing temperature. All these methods can of course be combined to extend the application of YIG resonators to lower frequencies; owing to poor Q_0 and weak coupling, applications are not feasible below 200 or 100 MHz. The upper limit of the useful frequency range is only determined by the high tuning fields required; a practical limit lies at about 56 GHz, requiring a field of 1.6 MA/m (20 kOe).

Temperature dependence

YIG resonators can be operated from liquid-helium temperatures up to a little below the Curie temperature, which is at about 280 °C. In the usual temperature range for applications, −40 °C to +80 °C, the effect of the temperature on Q_0 and f_0 can be entirely accounted for by the temperature dependence of M_s and H_a. It has been found experimentally that at frequencies well above f_c the quality factor Q_0 is approximately proportional to M_s; the resulting variation in Q_0 with temperature is not large, of the order of ± 10% between −40 °C and +80 °C.

The requirements for the temperature stability of the resonant frequency are quite strict since YIG filters are narrow-bandwidth devices. Optimum performance is obtained with spherical resonators, because N_t is equal to N_z and eqs. (1) or (2) show that H_a is the chief temperature-sensitive parameter. Depending on the crystallographic orientation with respect to the tuning field, the temperature coefficient of the resonant frequency may be adjusted between a positive or a negative value of about 1 MHz/°C, and a very low value (20 kHz/°C) can be obtained with a carefully adjusted sphere.

In other shapes of resonator M_s has a direct effect on the resonant frequency. Thin discs, which are sometimes used because of their low f_c and high Q_0, have a temperature coefficient of the order of 10 MHz/°C.

Non-linearity; power limiting

Depending on the applied r.f. power level YIG resonators have either a linear or a non-linear response. Marked non-linearity appears suddenly above a sharply defined r.f. power level which is different for different materials and for different signal frequencies. This power level is very low (about 10 μW) if an r.f. signal at the UPR-mode frequency f_0 can parametrically excite spin waves at a frequency $f_0/2$. This is possible in a frequency band whose upper limit can be shown to be $2\gamma N_t M_s$ [7]. This happens to be twice the cut-off frequency f_c, so that these spin waves can occur when the resonant frequency of the filter lies between f_c and $2f_c$.

Signals at frequencies above $2f_c$ mainly couple to degenerate spin waves and the threshold for non-linearity is of the order of 10 mW to 100 mW. The non-linearity can be utilized for making passive r.f. power limiters, but it also reduces the range of application of linear YIG devices to systems operating at r.f. power levels below 100 mW.

Coupling; practical examples

The r.f. magnetic field, which couples the r.f. signals to a YIG resonator, should be perpendicular to the tuning field to achieve the maximum coupling. The coupling is proportional to M_s and the volume of the YIG resonator and it also depends on the dimensions and impedance of the transmission line. Unlike transmission-line resonators YIG resonators will only give a relatively weak coupling, which means that these resonators will not be heavily damped by the transmission lines coupled to them. As a consequence the bandwidth of a YIG filter remains small; the maximum achievable bandwidth (between the −3 dB points) is of the order of 1 or 2 per cent of the resonant frequency.

A coupling section that is frequently used is the orthogonal-semiloop arrangement shown in fig. 1, which will give a single-stage *band-pass* filter. Multistage filters, which are often required for increased selectivity, are obtained by cascading such coupling sections. A two-stage band-pass filter using this principle is shown in *fig. 4*; the upper half of the tuning magnet has been removed. This particular filter can be continuously tuned from 1 GHz to 20 GHz and has a 3 dB bandwidth varying from 20 to 45 MHz and passband losses between 1.5 dB and 3 dB. *Fig. 5* shows a typical response for a filter of this type tuned to 9 GHz; a spurious response due to coupling of higher-order magnetostatic modes can also be seen; at other frequencies the rejection is more than 50 dB.

Band-stop filters are obtained by inserting YIG resonators into a transmission line at approximately a quarter-wavelength spacing; a symmetrical stripline is usually chosen, so that the tuning magnet can be brought close to the stripline conductor without disturbing the r.f. field (*fig. 6a*). This configuration may be represented by an equivalent circuit with lumped elements. Let us first consider the case in which there is only one YIG sphere. This may be represented by a parallel-resonant circuit coupled to a coupling winding in the transmission line (fig. 6*b*). In the same way as the magnetically coupled parallel circuit at resonance considerably reinforces the magnetic field inside the

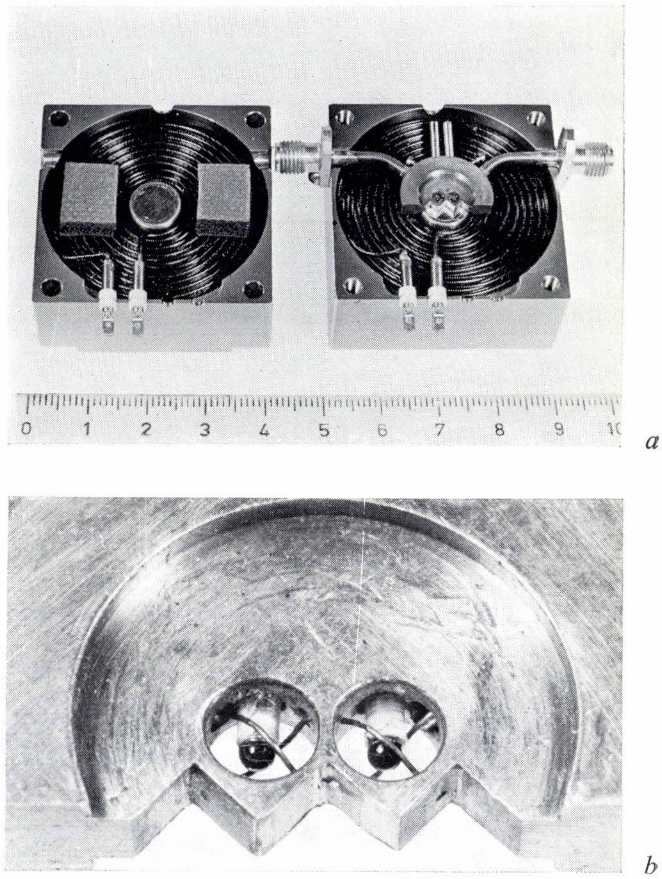

Fig. 4. *a*) Two-stage band-pass filter designed on the principle outlined in fig. 1. The upper half of the electromagnet has been taken off and is shown on the left. This filter can be tuned from 1 GHz to 20 GHz, the 3 dB bandwidth increasing from 20 MHz to 45 MHz. *b*) The two YIG resonators with coupling loops.

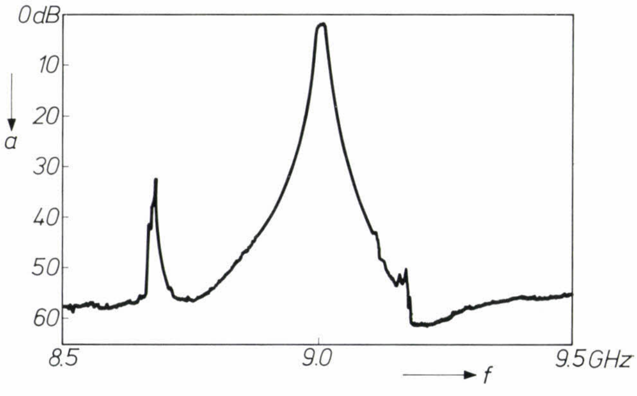

Fig. 5. Attenuation *a* of the filter shown in fig. 4 as a function of frequency. The filter is tuned to 9 GHz. Apart from a spurious response due to a higher-order magnetostatic resonance the rejection is greater than 50 dB outside the passband.

[5] Since the resonance measurements are usually performed at a fixed frequency while subjecting the YIG sample to a varying magnetic field, linewidths are generally given in magnetic units in the literature; 1 MHz corresponds to 28.4 A/m or 0.357 Oe.

[6] The single crystals were grown from a solution of YIG (or YGaIG) in molten lead oxide and lead fluoride, in a process described in W. Tolksdorf, Growth of yttrium iron garnet single crystals, J. Crystal Growth **3/4**, 463-466, 1968.

[7] H. Suhl, The nonlinear behavior of ferrites at high microwave signal levels, Proc. IRE **44**, 1270-1284, 1956.

coupling winding, the precession field of the resonant YIG sphere locally reinforces the magnetic field of the stripline. The resultant effect is that the line has a high impedance at the location of the resonator.

Owing to the distributed nature of the stripline a second YIG sphere spaced a quarter-wavelength from the first presents a low impedance at the reference plane of the first sphere; this may be represented in the equivalent circuit by a series-resonant circuit connected in parallel. If the coupled parallel-resonant circuit of fig. 6*b* is replaced by an equivalent parallel circuit connected into the line, the equivalent circuit represented in fig. 6*c* is obtained for the two-stage band-stop filter of fig. 6*a*. The corresponding band-stop-filter response is given in fig. 6*d*; this figure also shows the voltage standing-wave ratio *S*. The tuning range is limited to about one or two octaves because of the $\lambda/4$ separation of the resonators.

A *nonreciprocal-attenuation* response is most effectively obtained by coupling the YIG resonator to circularly polarized r.f. magnetic fields. These are present in a waveguide and can be set up in a coaxial or microstrip line by using special techniques. Nonreciprocal YIG filters may be applied as narrow-band tunable isolators, circulators or directional filters. We should note here that a nonreciprocal phase shift is given by the orthogonal semiloops shown in fig. 1, although the r.f. field is linearly polarized here. Since the precession of the magnetization in the YIG resonator has a fixed sense of rotation the direction of wave propagation determines whether the phase shift will be $+90°$ or $-90°$.

It has been stated above that the size of YIG devices is mainly given by the required tuning magnet. Since the highest required tuning field is determined by the highest frequency to be tuned, tuning power and magnet size can only be kept small by paying careful attention to the height required for the air gap when designing the r.f. section. Typical air-gap dimensions given by different designs are 1 mm to 2 mm for the orthogonal half-loop, 1.5 mm to 3 mm for symmetrical stripline and 2 mm to 4 mm for waveguides. The diameter of the pole faces should be at least five times the height of the air gap to provide a homogeneous tuning field.

Fixed-tuned YIG filters with permanent magnets are much smaller than filters in waveguide or coaxial line,

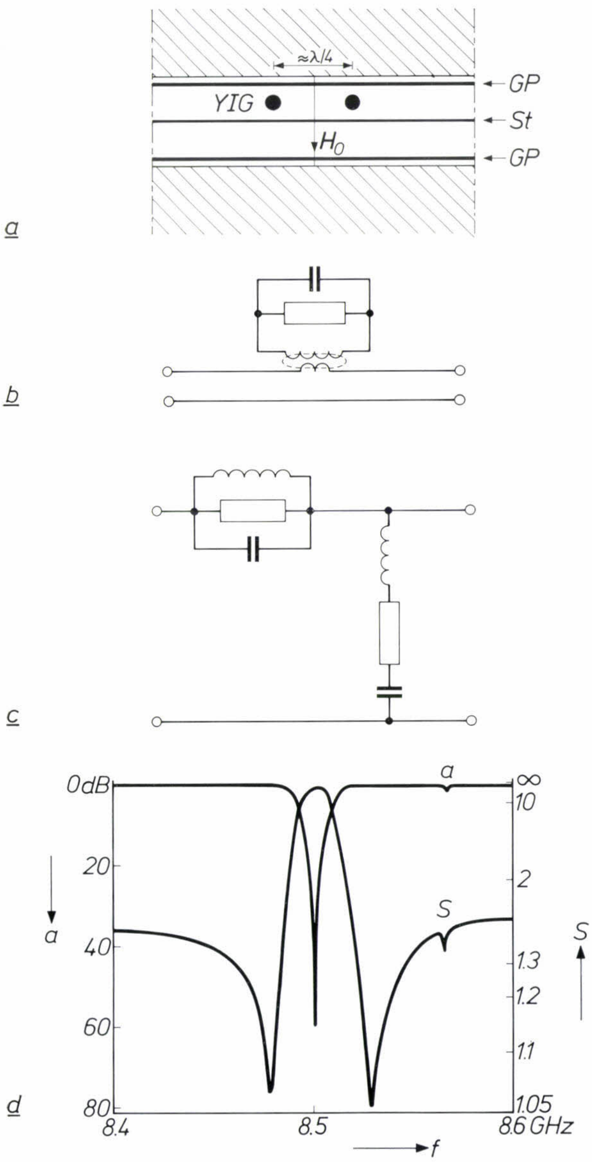

Fig. 6. Two-stage YIG band-stop filter. *a*) Cross-section. Two YIG spheres (*YIG*) are embedded in the dielectric of a symmetrical stripline (*St* strip conductor, *GP* ground planes) at approximately a quarter-wavelength spacing. The whole arrangement is placed between the poles of a magnet giving a static magnetic field H_0. *b*) A single YIG resonator behaves like a parallel-resonant circuit coupled to the line (or appropriately transformed and inserted into the line). *c*) Equivalent circuit of filter containing two resonators at $\lambda/4$ spacing. *d*) Attenuation *a* and voltage standing-wave ratio *S* in the frequency band including the resonance.

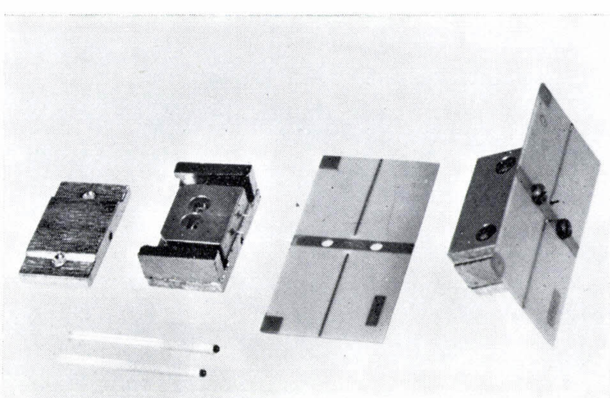

Fig. 7. Fixed-frequency two-stage YIG band-pass filter with permanent magnets, to be inserted into a microstrip line. *From left to right:* upper pole piece, coupling structure for YIG resonators with lower pole piece and two permanent magnets, microstrip substrate and assembled filter. The narrow strip on the substrate is the microstrip line; the filter is connected to it by two contact pins. *Foreground:* two YIG resonators glued to tiny rods for manipulating them and mounting them in position.

particularly for the lower microwave frequencies, where transmission-line resonators become increasingly large. YIG resonators are indeed small enough to be

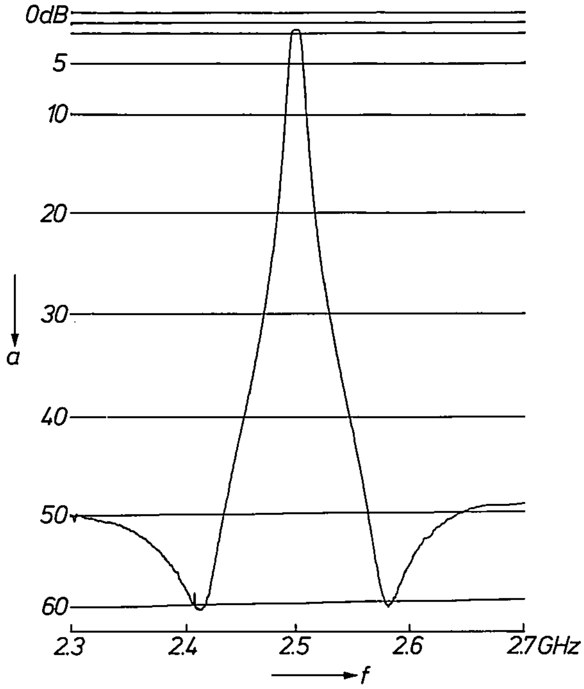

Fig. 8. Measured frequency response of the fixed-frequency YIG band-pass filter shown in fig. 7.

used in microstrip circuits as high-Q resonators. An experimental two-stage YIG band-pass filter with permanent tuning magnet for microstrip application is shown in *fig. 7*; it can be fixed to the substrate of an integrated microstrip circuit by screws. *Fig. 8* shows the performance of this filter. Band-pass or band-stop filters of this kind are feasible for frequencies from about 1 GHz to more than 12 GHz.

Many other devices can be made with YIG resonators, e.g. fast switchable filters, tunable frequency discriminators, frequency meters, magnetic-field measuring probes, tunable transistor and Gunn oscillators and tunable harmonic generators with varactor multipliers.

Summary. Single crystals of the ferrite material yttrium iron garnet (YIG) give the smallest known ferrimagnetic-resonance linewidth. Since microwave signals are efficiently coupled to the ferrimagnetic resonance, single-crystal YIG samples can be used as magnetically tunable microwave resonators with unloaded Q-factors up to 10 000 and a linear tuning range of more than ten times in frequency. YIG resonators are used in devices such as tunable band-pass or band-stop filters. The resonators can be used for signal frequencies from about 100 MHz up to 60 GHz, depending on material characteristics and shape. Spheres of YIG will give a low temperature coefficient for the resonant frequency (about 20 kHz/°C). The resonance effect is non-linear above an r.f. power level of between 10 and 100 mW (above 10 μW at the lowest frequencies); this is of use in power limiters.