resonance spectra observed at this laboratory on a suitably prepared Mn-ferrite and Cu-ferrite, as well as other results.[26] While the interpretations proposed here may even apply to magnetic semiconductors other than ferrites, it must be anticipated that, in substances possessing a small M_s value, the role of Kittel's ferri-magnetic effects[27] may have to be considered in the resonance problem. A more detailed understanding of magnetic spectra will probably depend on additional measurements of the magnetic constants (K, M_s, λ, etc.) of various materials, and on further studies of relaxation processes and magnetic interactions.

On the basis of the above discussion it appears that high μ_1 values will be difficult to obtain at microwave frequencies. To obtain even $\mu_1=2$ (with $\mu_2 \ll 2$) at 10^4 Mc/sec, for example, Eqs. (6) to (8) show that a substance characterized by $M_s \gg 430$ (and hence $K \gg 7.5 \times 10^5$ ergs/cc) would be required. Nevertheless, $\mu_1=2$ is clearly more useful than $\mu_1=1$, and, in addition, interesting wave propagation effects can be achieved by operating within a (narrow) resonance region. It is also noteworthy that, contrary to Snoek's theory, the total low frequency μ_1 may still be large even if the microwave μ_1 is small (see Eq. (11)). Furthermore, materials with a low Curie point, such as mixed ferrites containing a large amount of Zn-ferrite, are clearly not satisfactory for ordinary microwave use, but may sometimes be suitable for obtaining low insertion loss in devices based on the Faraday effect.

In conclusion, the writer wishes to thank R. W. Wright, W. H. Emerson, A. Terris, and M. Maloof for their invaluable contributions to the experiments discussed in this paper.

[26] Welch, Nicks, Fairweather, and Roberts, Phys. Rev. 77, 403 (1950).
[27] C. Kittel, Phys. Rev. 82, 565 (1951).

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Resonance Phenomena in Ferrites

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ABOVE a certain frequency, of the order of 5–100 Mc/sec, losses of ferrites in an alternating magnetic field are very high. Snoek[1] has ascribed this absorption to rotational resonance of the spins in the internal anisotropy fields, and has related the resonance frequency f_0 with the static initial permeability μ_0 by means of the equation

$$f_0(\mu_0-1)=(4/3)\gamma M, \tag{1}$$

with γ the gyromagnetic ratio and M the saturation magnetization. Experimentally considerable losses are found at the predicted f_0, but the absorption region is very broad and extends to frequencies above 1000 Mc/sec. In this connection one of us[2] has pointed out that in the resonating unmagnetized material magnetic poles will be created and annihilated on a Bloch wall, if the alternating field has a component parallel to it. In some regular arrangements of Weiss domains this effect can, together with demagnetization at the grain boundaries, give rise to high resonance frequencies. This, and also the occurrence of losses near f_0, will be illustrated with the following model.

Consider an ellipsoid divided into thin Weiss domains separated by 180° walls perpendicular to one of its principal axes. The ellipsoid is embedded in a medium with the average permeability $\mu(f)$ of the material. For ac fields perpendicular to the walls only the external demagnetization in the field direction plays a role (Fig. 1). The effect is reduced by the presence of the medium by a factor of the order of μ, which is large at relatively low frequencies. The influence of demagnetization and the formation of poles on the walls

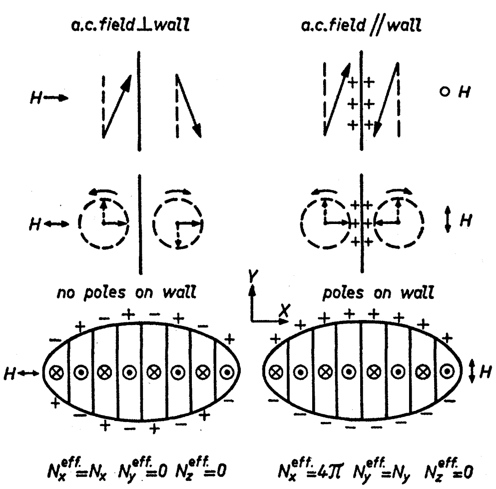

FIG. 1. Effect of Weiss domain structure on ferromagnetic resonance conditions.

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[1] J. L. Snoek, Nature 160, 60 (1947) and Physica 14, 207 (1948).
[2] D. Polder, J. phys. et radium 12, 337 (1951).

can be shown to be small also for less regular configurations. From this it may be inferred that a considerable part of the resonances in the actual material occurs at frequencies mainly determined by the internal anisotropy fields giving an absorption peak at f_0 from Eq. (1).

For ac fields parallel to the walls we have, besides the external demagnetization of the ellipsoid, the poles at the walls. The resonance frequency is now given by

$$2\pi f = \gamma M(4\pi N)^{\frac{1}{2}},$$

N being the demagnetization coefficient in the field direction (Fig. 1). Here we ignore anisotropy and the effect of the medium because of the low μ at this high high f. The maximum resonance frequency is accordingly given by $2\pi f_{\max} = \gamma 0.4\pi M$, as to be compared with $\gamma 0.2\pi M$ for an isolated homogeneously magnetized ellipsoid. With this mechanism one can explain the high frequency losses in unmagnetized ferrites as observed by Beljers, v.d. Lindt, and Went.[3] In these experiments strong absorption occurred only if $\gamma 0.4\pi M$ exceeded $2\pi f$, as was found by temperature variation.

[3] Beljers, v. d. Lindt, and Went, J. Appl. Phys. **22**, 1506 (1951).

For the explanation of the losses near f_0 the ratio of the wall thickness and the domain thickness has been assumed to be small. The relative influence on the resonance frequency is then of the order of this ratio.

In grains of the ferrite materials with dimensions of 10^{-5} or 10^{-4} cm especially when they are isolated some type of flux closure configuration[4] will exist, or the whole grain will be one Bloch wall. It is seen that in these cases losses near f_0 will be far less pronounced, since the resonance condition will largely be determined by demagnetization effects giving a peak at some thousands Mc/sec this being a fraction of $\gamma/2\pi 0.4\pi M$. We believe that these effects apply to the resonance phenomena observed by Wijn and van der Burgt,[5] and may contribute to the two dispersion mechanisms found by Rado, Wright, and Emerson.[6]

[4] C. Kittel, Revs. Modern Phys. **21**, 541 (1949).
[5] H. P. J. Wijn and C. M. v. d. Burgt (to be published).
[6] Rado, Wright, and Emerson, Phys. Rev. **80**, 273 (1950).

DISCUSSION

G. T. RADO, *Naval Research Laboratory, Washington, D. C.*: As stated in my paper, as well as in previous publications, the experimental evidence obtained by our group indicates clearly that internal demagnetizing fields have an important effect on wall resonance frequencies and on rotational resonance frequencies. The model suggested by Polder and Smit describes some detailed manifestations of such demagnetizing effects in particular situations.