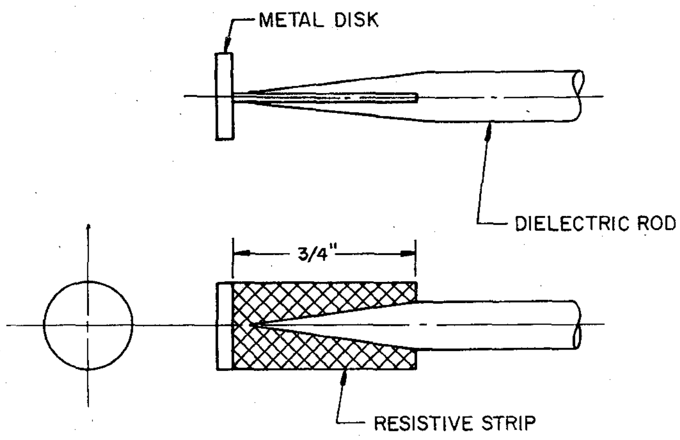

Fig. 6—Short strip and reflecting disk.

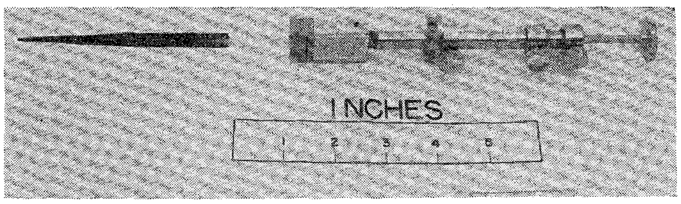

Fig. 7—Mechanical controls permitting independent adjustment of rotation and sliding, with control locking.

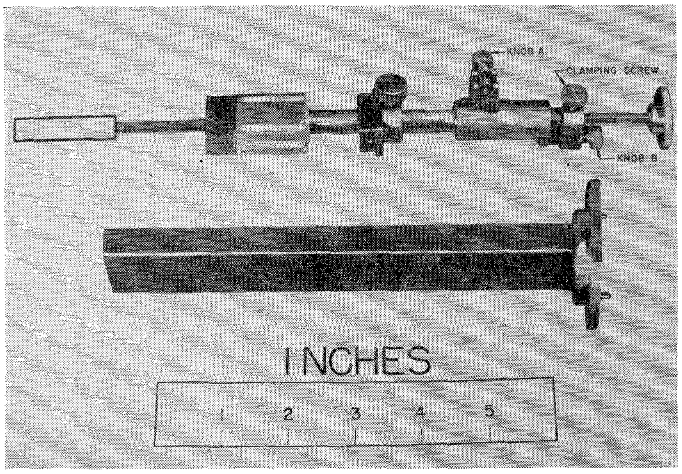

Fig. 8—Mechanical controls permitting coarse manual adjustment and locking, followed by fine independent adjustments of rotation and sliding.

ACKNOWLEDGMENT

The writer is indebted to J. Lowenbach, W. Foote, and W. Clore of the Instrument Shop, who made experimental models and contributed to the mechanical design, to E. Niesen, who made the measurements upon which Figs. 3 and 5 are based, and to Dr. D. M. Kerns and Dr. D. G. Burkhard, who reviewed the paper.

Field Displacement Isolators at 4, 6, 11, and 24 KMC*

S. WEISBAUM† AND H. BOYET‡

***Summary*—Performance of ferrite field displacement isolators at various frequency bands is described. Single and double-slab isolators have been constructed in rectangular waveguide. Four single-slab isolators are reported in the following frequency bands: 3700–4200 mc; 5925–6425 mc; 10,700–11,700 mc and 23,500–24,470 mc; one double-slab isolator is described in the frequency range 10,700–11,700 mc.**

INTRODUCTION

THE field displacement isolator consists of a rectangular slab of ferrite partially filling a rectangular waveguide.[1] The ferrite slab is transversely magnetized and has resistance material appropriately disposed on one of its sidefaces (see Fig. 1, opposite). Basically, this device produces isolation for the following reasons: When a microwave travels through the device in a given direction, the polarization of the rf magnetic field in the plane perpendicular to the biasing magnetic field is opposite in sense to that which it would be for the reverse direction of propagation. As a result, the rf magnetic field interacts differently with the spin precessions of the electronic magnetic moments for the two directions of propagation, and this leads to different electric field distributions across the waveguide for the two directions of propagation[2] (see Fig. 2). If this difference in electric field strengths at one face of the ferrite can be made large, resistance material, suitably placed on the ferrite, will attenuate reverse traveling waves to a much larger degree than forward traveling waves, and isolation is thereby effected.

The above principles have been applied with success to an isolator at 6 kmc (0.2-db forward loss, 30-db reverse loss, 1.06 vswr over the band 5925–6425 mc). The

* Manuscript received by the PGMTT, December 5, 1956.
† RCA, New York, N. Y. Formerly with Bell Telephone Labs., Murray Hill, N. J.
‡ Bell Telephone Labs., Murray Hill, N. J.
[1] A. G. Fox, S. E. Miller, and M. T. Weiss, "Behavior and applications of ferrites in the microwave region," *Bell Sys. Tech. J.*, vol. 34, pp. 5–103; January, 1955.

[2] B. Lax, H. J. Button, and L. M. Roth, "Ferrite phase shifters in rectangular waveguide," *J. Appl. Phys.*, vol. 25, pp. 1413–1419; November, 1954.

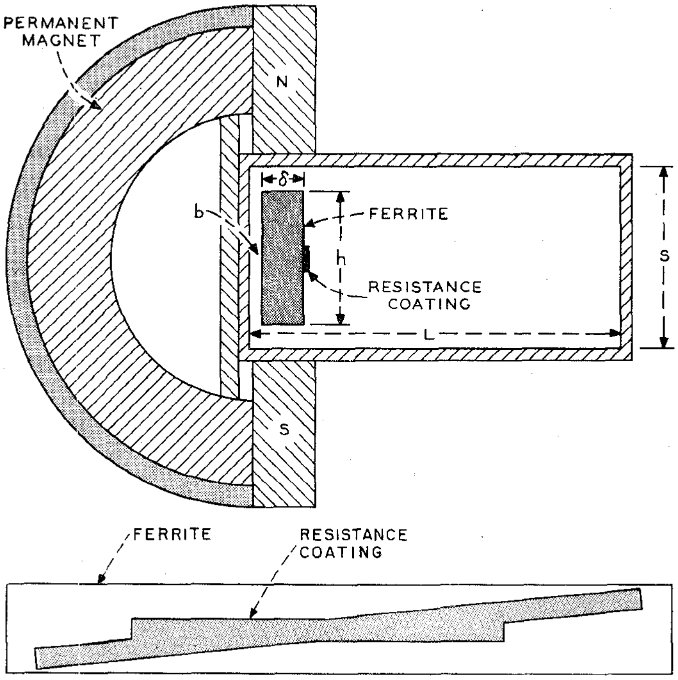

Fig. 1—Assembly of ferrite, resistance material, magnet, and waveguide in single-slab ferrite field displacement isolator and disposition of resistance material on ferrite slab.

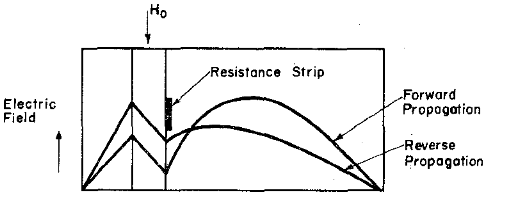

Fig. 2—Theoretical transverse electric field distribution in single-slab isolator, full height ferrite.

experimental, theoretical, and design details for this device have been elaborated upon elsewhere.[3] Subsequent work with the field displacement isolator has met with success at other frequency bands: 3700–4200 mc; 10,700–11,700 mc; and 23,500–24,470 mc. The purpose of this paper is to summarize the performance of field displacement isolators developed to date in the various frequency bands at Bell Telephone Laboratories.

Before doing so, it is desirable to discuss briefly two important features of the field displacement isolator: the partial height ferrite geometry used, and the disposition of the resistance material. Less than full height ferrite slabs are used to insure good match into the isolator. With such partial height slabs the boundary requirements on the top and bottom faces of the ferrite are less stringent and a smaller portion of the incident wave needs to be converted into a reflected wave to satisfy the boundary conditions. This results in considerably smaller vswr for the partial height ferrite than for the full height ferrite.

A disposition of the resistance material was conceived which makes use of the nonreciprocal nature of the longitudinal components of electric field set up by the partial height ferrite.[3] Resistance material is placed in a region where both the fundamental transverse component and longitudinal component of electric field are small for the forward direction but, as a result of the nonreciprocity of both components, both may be large at the resistance material for the backward direction of propagation. This configuration of resistance material is shown in Fig. 1. The actual resistance material is a baked resistance coating of graphite and resin covered by a baked clear coating, similar to that used in attenuator vanes. The length of the resistance strips is critical in determining the forward and reverse attenuations. Experiments indicate that the attenuation is not a linear function of length of resistance strip.

As an aid in the design of isolators at various frequency bands, we have relied to a first approximation on a scaling[3] of transverse geometric quantities and magnetic quantities. Thus starting from a frequency ω, we may scale to a new frequency $f\omega$ (f any number) by changing all waveguide and ferrite geometries and spacings by a factor $1/f$ and all magnetic quantities by a factor f (see Appendix).

Performance

In Figs. 3, 4, 5, and 6, next page, we show graphically the performance of the field displacement isolator at 4 kmc, 6 kmc, 11 kmc, and 24 kmc, respectively, together with the values of the operating parameters. $4\pi M_s$ denotes the saturation magnetization of the ferrite. The other symbols are defined in Fig. 1. The length of ferrite is 5 inches in each isolator, but shorter lengths are currently being investigated.

In the 24-kmc case the largest $4\pi M_s$ ferrite available was 4900 Gauss.

A double-slab field displacement isolator[4] was constructed at 11 kmc. In this construction the two slabs are located symmetrically with respect to the center line of the rectangular waveguide. The two slabs are magnetized by equal but oppositely directed magnetic fields so that the spin precessions in each interact equally with the rf magnetic fields at each slab. Each slab has a resistance strip configuration identical with that shown in Fig. 1. The length of ferrite slabs is 5 inches. Performance and operating conditions are shown in Fig. 7.

Table I, p. 197, summarizes performance of most recent isolator models. All isolators are single slab except where noted.

[3] S. Weisbaum and H. Seidel, "The field displacement isolator," *Bell Sys. Tech. J.*, vol. 35, pp. 877–898; July, 1956.

[4] S. Weisbaum and H. Boyet, "A double slab ferrite field displacement isolator at 11 kmc," Proc. IRE, vol. 44, pp. 554–555; April, 1956.

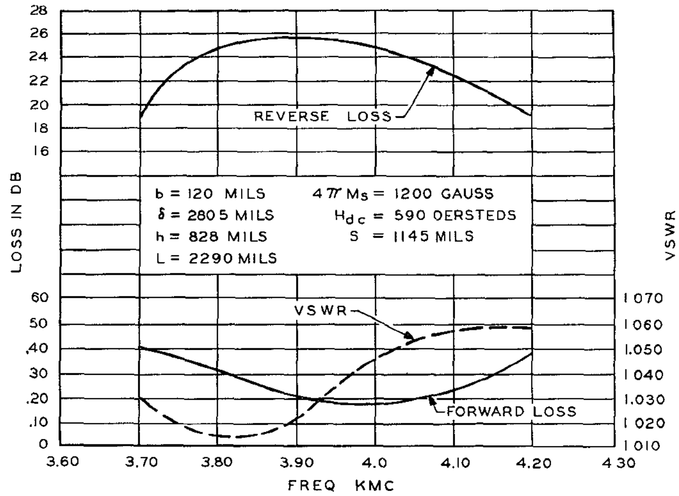

Fig. 3—Performance of single-slab field displacement isolator at 4 kmc.

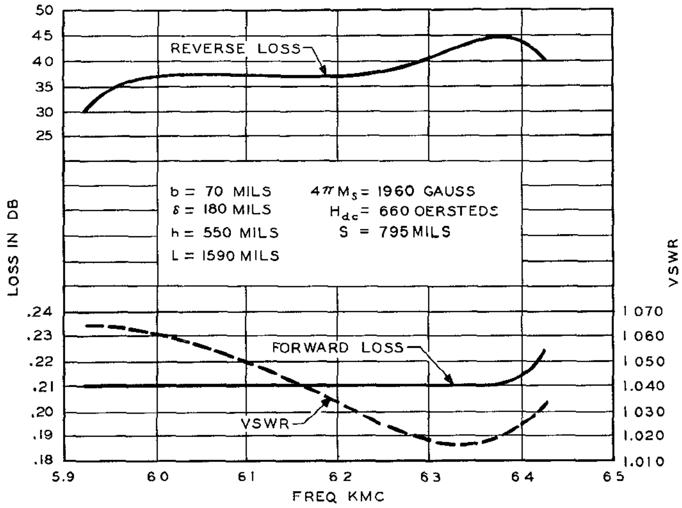

Fig. 4—Performance of single-slab field displacement isolator at 6 kmc.

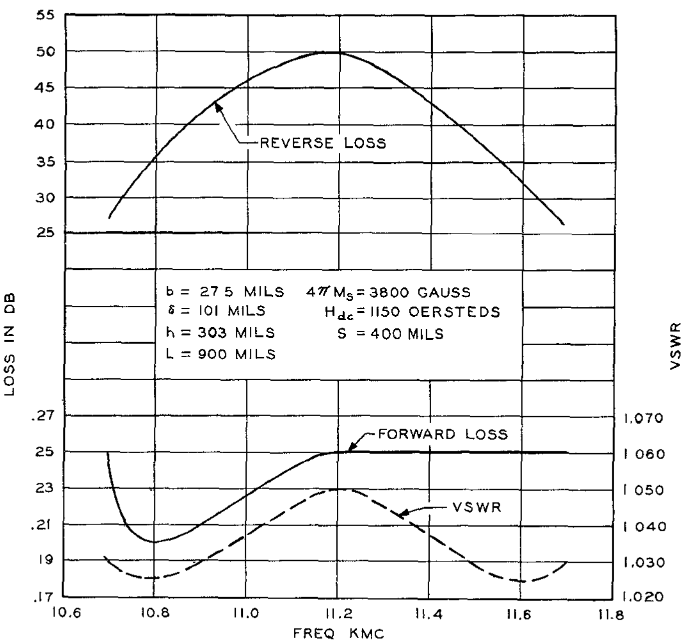

Fig. 5—Performance of single-slab field displacement isolator at 11 kmc.

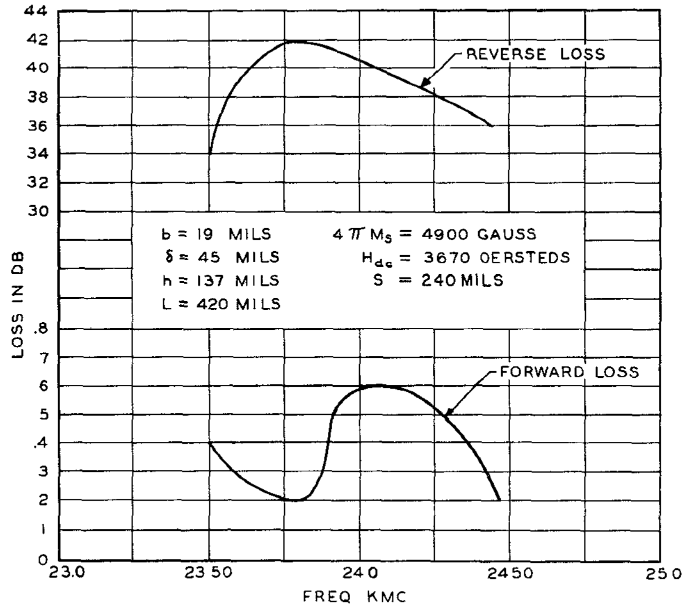

Fig. 6—Performance of single-slab displacement isolator at 24 kmc. VSWR was not measured in this case.

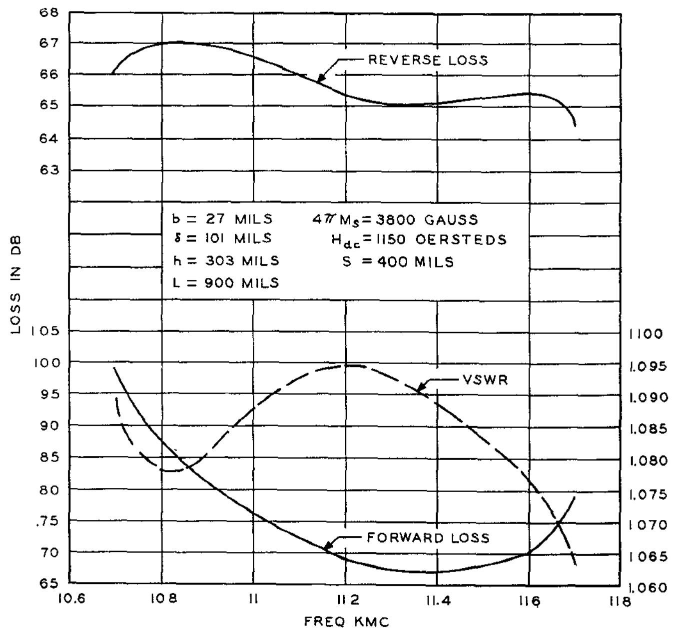

Fig. 7—Performance of double-slab field displacement isolator at 11 kmc.

Discussion

The theoretical basis of scaling to other frequencies is presented in the Appendix. Table II opposite presents the geometrical and magnetic operating conditions to be expected in the various frequency band isolators, using the 6-kmc isolator as a basis and scaling the parameters up (or down) to the other frequency band isolators (4 kmc, 11 kmc, 24 kmc). The values in parentheses are the values expected from scaling, the others are the values used in the actual device.

In all cases, the cross sections of the waveguides available at the various frequencies did not scale exactly from the 6-kmc case. In addition, for convenience the length of ferrite in the various isolators were exactly the same (5 inches) so as to make use of the same magnet

TABLE I

PERFORMANCE OF FIELD DISPLACEMENT ISOLATORS

Frequency range (mc)	Maximum forward loss (db)	Minimum reverse loss (db)	Minimum return loss (db)	Ferrite description		Applied dc magnetic field (oersteds)
				Composition	Magnetization (Gauss)	
3700–4200	0.41	19.2	30	$Mg_{.9}Cu_{.1}Al_{.35}Fe_{1.4}Mn_{.04}$	1200	590
5925–6425	0.22	30	30	$Mg_{.9}Mn_{.1}Fe_{1.2}$	1960	660
10,700–11,700 single slab	0.25	28	32	$Ni_{.8}Cu_{.1}Zn_{.1}Fe_{1.9}Mn_{.02}$	3800	1150
double slab	0.99	65	27		3800	1150
23,500–24,470	0.60	34	—	$Ni_{.6}Zn_{.4}Fe_{1.9}Mn_{.02}$	4900	3670

TABLE II

SCALED AND ACTUAL VALUES OF GEOMETRIC AND MAGNETIC PARAMETERS IN ISOLATORS AT VARIOUS FREQUENCY BANDS; 6-KMC ISOLATOR IS USED AS BASIS. QUANTITIES IN PARENTHESES ARE SCALED VALUES

Frequency mc	δ mils	b mils	h mils	L mils	$4\pi M_s$ Gauss	H applied oersteds
5925–6425	180	70	550	1590	1960	660
3700–4200	280.5, (288)	120, (112)	828, (880)	2290, (2544)	1200, (1225)	590, (412)
10,700–11,700	101, (100)	27.5, (39)	303, (305)	900, (883)	3800, (3528)	1150, (1188)
23,500–24,470	45, (45)	19, (17)	137, (137)	420, (397)	4900, (7840)	3670, (2640)

assembly in all cases. Naturally, as a result of starting out with these two nonscaled quantities, we had to compensate the other geometric and magnetic quantities so as to bring performance at all frequency bands into line. This partly accounts for the discrepancies between scaled and actual operating conditions shown in Table II.

In addition, the bandwidth over which the 4-kmc isolator was tested was considerably greater (on a scaled basis) than that for the 6-kmc isolator. Thus to obtain good performance over the relatively greater band, the geometric quantities had to be altered somewhat from their scaled values.

In the 11-kmc isolator, the best ferrite available at the time was one with a saturation magnetization approximately 300 Gauss away from the scaled value. We see from Table II that the position of the slab, b, was quite different from the scaled value to compensate for this.

The largest $4\pi M_s$ ferrite available at 24 kmc was 4900 Gauss, considerably away from the 7840 Gauss required by scaling. While we used approximate scaled values for the transverse geometric parameters, we note the applied magnetic field is quite far from the required scaled value. Indeed, Table I shows the forward loss for this isolator to be quite out of line with forward losses obtained in the other cases. We may understand this on the basis of the theory of the electric field null developed[3] for the case of a full height ferrite. There it is shown that an electric field null is obtained at the ferrite face for the forward direction of propagation if the geometric and magnetic quantities satisfy

$$\frac{\frac{\pi}{b}(\mu^2 - k^2)\tan k_m\delta}{\mu k_m - k\beta \tan k_m\delta} + \tan k_a(L - b - \delta) = 0$$

where all quantities are defined in the Appendix. Clearly if the geometric quantities are scaled in going from 6 kmc to 24 kmc (*i.e.*, k_a, k_m, $\beta \rightarrow fk_a$, fk_m, $f\beta$ and L, b, $\delta \rightarrow (L/f)$, b/f, δ/f, f being the scaling factor), while the magnetic quantities are not, so that μ and k are different at 24 kmc than at 6 kmc, then the equation is not preserved and the electric field null is destroyed. Hence the higher forward loss in the 24-kmc isolator.

Finally, the applied fields would not be expected to scale if the internal anisotropy fields are different from their scaled values in the various ferrites used. While we have no data on the anisotropy fields in the various ferrites employed, it is unlikely that they scale according to frequency.

We have made use of scaling only as a guide in obtaining isolators at other frequency bands. It is highly likely, however, that if all geometric and magnetic parameters were perfectly scaled, comparable performance could be obtained in each scaled frequency band.

APPENDIX

Scaling for a rectangular waveguide containing a full height ferrite slab may be seen from the following considerations: the phase constant β satisfies the transcendental equation[2]

$$\frac{1}{2}\left(\frac{k_a^2}{\rho^2} + \frac{\beta^2}{\theta^2} - k_m^2\right)\cos k_a(L - \delta - 2b) + \frac{j\beta k_a}{\rho\theta}\sin k_a(L - \delta - 2b)$$

$$+ \frac{1}{2}\left(\frac{k_a^2}{\rho^2} - \frac{\beta^2}{\theta^2} + k_m^2\right)\cos k_a(L - \delta) + \frac{k_a k_m}{\rho}\cot(k_m\delta)\sin k_a(L - \delta) = 0$$

where

$$\rho = \frac{\mu}{\mu^2 - k^2}$$

$$\theta = \frac{\mu}{jk}$$

$$\mu = 1 + \frac{4\pi M_s \gamma \omega_0}{\omega_0^2 - \omega^2}$$

$$k = -\frac{4\pi M_s \gamma \omega}{\omega_0^2 - \omega^2}$$

$$E_z = A \sin k_a x e^{-j\beta y}$$

$$A = \frac{\left[\left(1 - \frac{\beta}{k_m\theta}\right) \sin k_a(L - b - \delta) + \frac{jk_a}{k_m\rho} \cos k_a(L - b - \delta)\right] e^{-jk_m\delta}}{\left(1 - \frac{\beta}{k_m\theta}\right) \sin k_a b - j\frac{k_a}{k_m\rho} \cos k_a b},$$

$4\pi M_s$ = saturation magnetization of ferrite
γ = gyromagnetic ratio of electron
ω = angular frequency of wave
$\omega_0 = \gamma H_0$
H_0 = internal dc magnetic field
$k_a^2 = \omega^2\epsilon_0\mu_0 - \beta^2$
$k_m^2 = \frac{\omega^2\epsilon\mu_0}{\rho} - \beta^2$
ϵ_0, μ_0 = dielectric constant and permeability of free space
ϵ = dielectric constant of ferrite.

Suppose the loaded waveguide produces a phase constant β at the frequency ω. We assert that the phase constant at a new frequency $f\omega$ (f any number) is $f\beta$ provided the geometric and magnetic quantities are changed from their old values b, δ, L, $4\pi M_s$, H_0 to the new values b/f, δ/f, L/f, $f4\pi M_s$, and fH_0 at the new frequency $f\omega$. For then, μ, k, ρ, and θ remain unchanged while k_a and k_m become fk_a and fk_m provided β becomes $f\beta$ at the new frequency. Indeed, with these changes, $f\beta$ satisfies the transcendental equation at the new frequency, as is readily observed. A typical component of field is given by[2]

and thus the fields are unchanged in value and distribution at the new frequency, phase constant, and operating conditions provided the geometry x, y is scaled down (or up) to x/f, y/f.

Acknowledgment

We should like to thank F. J. Sansalone, J. J. Kostelnik, and J. D. Apgar for aid in the measurement program.

We are greatly indebted to L. G. Van Uitert for the development of the suitable ferrites in each of the various frequency ranges.