db for a 3-db measurement and 0.17 db for a 40-db measurement.

If the three similar attenuators are connected in cascade and inserted in the system, Fig. 8 shows that ϵ_1 is now 0.12 db for a 40-db measurement and 0.10 db for a 75-db measurement, and Fig. 12 shows that ϵ_2 is 0.13 db for both measurements. Addition of these yields the limits of mismatch error, ϵ_T, of 0.25 db for a 40-db measurement and 0.23 db for a 75-db measurement. These examples are felt to be representative of conditions met in typical rectangular waveguide systems.

Conclusion

It can be seen that if maximum possible error is assumed, the mismatch error increases for smaller relative attenuation measurements.

The limit of mismatch error estimated by this method is a conservative figure since it is based on the assumption that all values of the coefficients have phases at the initial and final settings which give the maximum possible error. Thus, in an actual application, the mismatch errors are very probably less than those estimated in the examples.

A Nonreciprocal, TEM-Mode Structure for Wide-Band Gyrator and Isolator Applications*

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Summary—**The theoretical and experimental operation of a novel form of TEM transmission-line network capable of operation over octave bandwidths is described. This network consists, basically, of a parallel arrangement of two conductors and a ferrite rod within a grounded outer shield. The conductors may be connected in a two-port configuration which provides, in the absence of the ferrite rod, complete isolation from zero frequency to the cut-off frequency of the first higher mode. With an unmagnetized ferrite rod properly inserted, the broad-band isolation is virtually unaffected. When the rod is magnetized by an axial magnetic field, coupling occurs between the two ports by a process analogous to Faraday rotation.**

The device may be used as a broad-band gyrator, switch, or modulator, and with the addition of a resistance load, as an isolator. The bandwidth of these components is inherently limited only by the bandwidth capability of the ferrite material itself.

I. Qualitative Description of Operation

Gyrator Network

THE form of the nonreciprocal TEM transmission-linenet work that functions as a wide-band gyrator, switch, or modulator is illustrated in Fig. 1.[1-3] It consists of a pair of shielded, coupled transmission lines and an axially oriented ferrite pencil. This circuit behaves, in the absence of the ferrite rod, as an all-stop filter; *i.e.*, infinite attenuation theoretically exists between the two ports at all frequencies.[4] For the network to be an all-stop filter, it is necessary that one of the coupled lines be open-circuited and the other short-circuited, in the manner shown in the figure, and that the phase velocity of the even and odd modes on the coupled lines be the same. Both these conditions are satisfied when the ferrite is properly oriented in the plane of symmetry between the coupled lines. The proper position of the rod is quite independent of frequency, so that the composite structure has high attenuation over a wide band of frequencies.

When an axial magnetic field is applied to the ferrite rod, it rotates the plane of polarization of the linearly polarized transverse RF magnetic field existing along the ferrite rod, and energy is coupled between the input and output ports. When the axial field is increased to the point where the RF magnetic field is rotated by 90 degrees, virtually all the energy is transferred. When the cross section of the ferrite rod is small in terms of wavelength, and the operating frequency is far removed from the ferromagnetic resonance frequency, the rotation of the plane of polarization per unit length by the ferrite is essentially independent of frequency. Therefore, low insertion loss is experienced over a wide frequency range. Because the plane of polarization of the RF magnetic field is rotated in the same sense with respect to the positive direction of the biasing magnetic field, independent of the direction of propagation through the

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1 E. M. T. Jones, S. B. Cohn, and J. K. Shimizu, "A wide-band nonreciprocal TEM-transmission-line network," 1958 WESCON Convention Record, pt. 1, pp. 131–135.

2 O. W. Fix, "A balanced-stripline isolator," IRE Convention Record, pp. 99–105; March, 1956.

3 H. Boyet and H. Seidel, "Analysis of nonreciprocal effects in an N-wire ferrite-loaded transmission line," Proc. IRE, vol. 45, pp. 491–495; April, 1957.

4 E. M. T. Jones and J. T. Bolljahn, "Coupled-strip-transmission-line filters and directional couplers," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 75–81; April, 1956.

device, it can be seen that the signal undergoes 180 degrees more phase shift while passing through in one direction that it does while passing through in the opposite direction. Thus, the device functions as a gyrator. It may also be used as a switch by abruptly changing the magnetizing field from zero to the strength that gives full transfer of energy, or it can be used as a modulator by continuously varying the field.

Isolator

The network configuration most suitable for use as an isolator is shown in Fig. 2. The diagrams at the bottom of the figure illustrate the manner in which the RF magnetic field at the axis of the ferrite rod is rotated in passing through the device in either direction. When a signal travels from left to right, the RF magnetic field is initially oriented at an angle ϕ_1, somewhat greater than 45 degrees to the horizontal. Since there is no voltage induced in the short-circuited line on the upper left, the resistive termination placed behind this line does not attenuate the signal. The RF magnetic field, on passing through the ferrite, is rotated through an angle ϕ_1 so that at the output it is horizontal. A signal entering

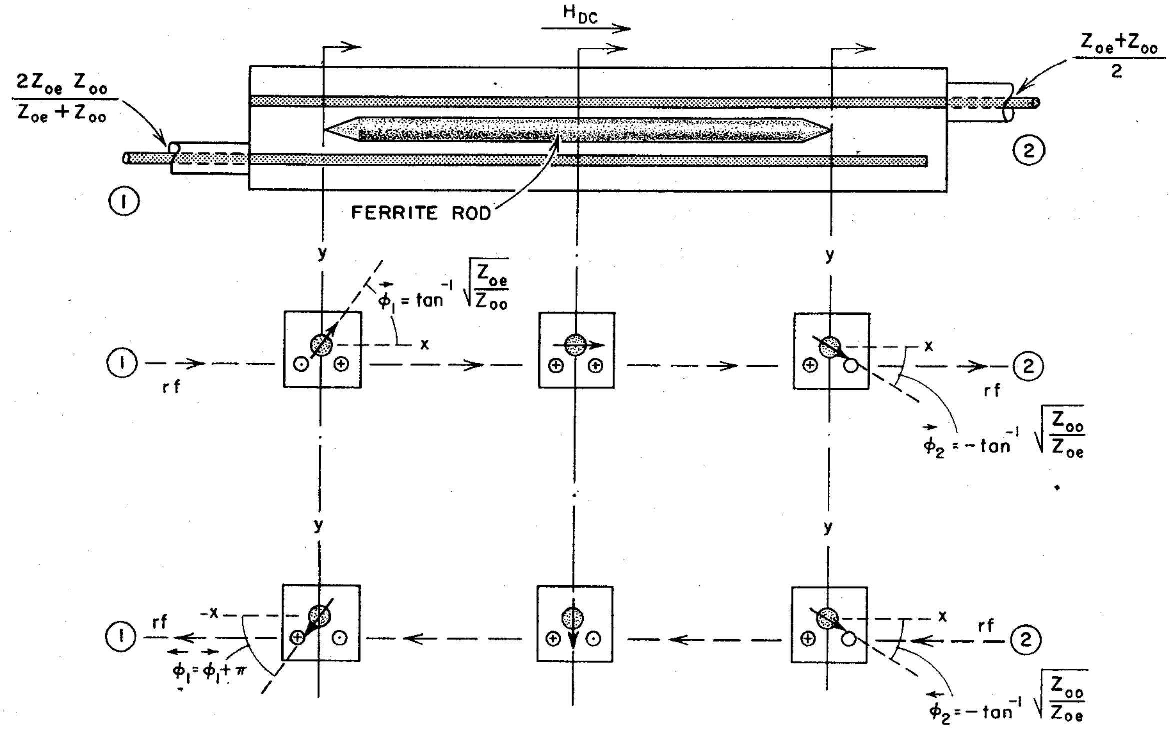

Fig. 1—Wide-band gyrator.

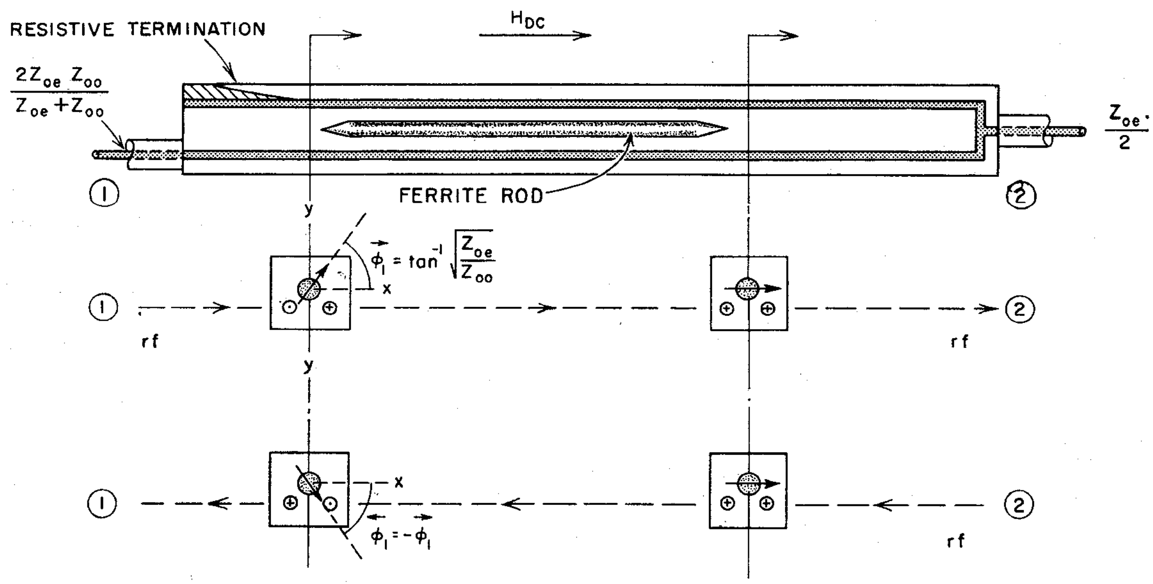

Fig. 2—Wide-band isolator.

from the right also has its RF magnetic field rotated ϕ_1 degrees as it passes through the ferrite so that all the power is transferred to the upper line where it is attenuated by the resistive termination at the left-hand end of the network.

II. Perturbation Analysis of Nonreciprocal Coupling Between a Pair of Shielded Conductors

A more detailed picture of the behavior of the various forms of the device may be obtained by analyzing the nonreciprocal coupling between shielded conductors using perturbation theory.[5] This theory is exact for ferrite rods having infinitesimal cross section areas, and is qualitatively correct for the ferrite rods used in practice. Application of this theory shows that with a lossless ferrite rod in position and unmagnetized, the propagation constant β_e' of the even mode is

$$\beta_e' - k_1 = \frac{\omega\mu_0 \Delta s H_e^2 \left[2\left(\frac{\epsilon - 1}{\epsilon + 1}\right) + 2\left(\frac{\mu - 1}{\mu + 1}\right)\right]}{4I_e^2 Z_{oe}} \quad (1)$$

while the propagation constant β_0' of the odd mode is

$$\beta_0' - k_1 = \frac{\omega\mu_0 \Delta s H_0^2 \left[2\left(\frac{\epsilon - 1}{\epsilon + 1}\right) + 2\left(\frac{\mu - 1}{\mu + 1}\right)\right]}{4I_o^2 Z_{oo}} \cdot \quad (2)$$

In these expressions,

- H_e = RF field existing at the axis of the ferrite, in the absence of the ferrite, when the device is excited in the even mode; *i.e.*, equal in-phase currents I_e flow on the conductors;
- H_0 = RF magnetic field existing at the axis of the ferrite, in the absence of the ferrite, when the device is excited in the odd mode; *i.e.*, equal out-of-phase currents I_0 flowing in the center conductors;
- Z_{oh} = characteristic impedance of one center conductor to ground with equal in-phase current I_e flowing in the center conductors;
- Z_{oh} = characteristic impedance of one center conductor to ground with equal out-of-phase currents I_{oh} flowing in the center conductors;
- k_1 = propagation constant of the unperturbed system, which is assumed lossless;
- μ = relative initial permeability of the ferrite;
- ϵ = relative dielectric constant of the ferrite;
- $\mu_0 = 4\pi \times 10^{-7}$ henries/meter;
- ω = angular operating frequency; and
- Δs = cross section area of ferrite rod, meter.[2]

In order that there be no reciprocal coupling between the conductors, the ferrite rod must be oriented so that the phase velocities of perturbed even and odd modes are equal. That is,

$$\beta_e' = \beta_o' = \beta. \quad (3)$$

Substitution of (1) and (2) into (3) yields the relation

$$\frac{H_e}{I_e\sqrt{Z_{oe}}} = \frac{H_o}{I_o\sqrt{Z_{oo}}} \cdot \quad (4)$$

Eq. (4) shows that when the even and odd modes carry equal power, they will produce equal RF magnetic fields at the axis of the ferrite rod. However, equal even- and odd-mode currents do not produce equal fields at the center of the rod.

When the rod is biased with an axial field, the amount of nonreciprocal rotation θl of the plane of polarization of the wave in passing along the axis of the ferrite rod of length l, as well as the attenuation αl, can be determined by first resolving the wave into right- and left-hand circularly polarized components having the propagation constants $\alpha_+ + j\beta_+$ and $\alpha_- + j\beta_-$, respectively.

Making the usual approximation that $(\omega_{res}/\omega_0\tau)^2 \ll (\omega_{res} \pm \omega)^2$, one finds that

$$\theta l = \frac{(\beta_- - \beta_+)l}{2} = \frac{\omega l \mu_0 \Delta s (H_e^2 + H_o^2)\omega\omega_m}{(4I_e^2 Z_{oe} + 4I_{oh}^2 Z_{oo})(\omega_{res}^2 - \omega^2)}, \quad (5)$$

and

$$\alpha l = \left(\frac{\alpha_+ + \alpha_-}{2}\right) l = \frac{\omega l \mu_0 \Delta s (H_e^2 + H_o^2)\omega_m \omega}{(4I_e^2 Z_{oe} + 4I_{oh}^2 Z_{oo})\omega_o\tau}\left[\frac{\omega_{res}^2 + \omega^2}{(\omega_{res}^2 - \omega^2)^2}\right]. \quad (6)$$

The relation getween θl and αl takes the particularly simple form of

$$\alpha l = \frac{1}{\omega_0 \tau}\left(\frac{\omega_{res}^2 + \omega^2}{\omega_{res}^2 - \omega^2}\right)\theta l. \quad (7)$$

In these expressions,

- $\omega_m = \gamma 4\pi M$,
- $4\pi M$ = saturation magnetization (gauss),
- $\gamma/2\pi = 2.8$ mc/oersted,
- $\omega_0 = \gamma H_{DC}$,
- H_{DC} = applied internal field in the ferrite rod (oersteds),
- $\omega_{res} = \omega_0 + \omega_m/2$,
- $\tau = 2/\gamma\Delta H = T\omega/\omega_0$,
- T = phenomenological relaxation time as defined by Lax,[5] and
- ΔH = ferrite line width measured to the one-half amplitude points.

Eq. (7) shows that for a given total rotation θl, the total attenuation αl experienced by a signal is independent of the cross section geometry. In the experimental gyrator and isolator to be described later, the ferrite used is Ferramic R-1. This material has a line width ΔH of about 500 oersteds at an operating frequency of 9000 mc. This value of line width yields $\omega_0\tau = \omega T$ of about

[5] B. Lax, "Frequency and loss characteristics of microwave ferrite devices," Proc. IRE, vol. 44, pp. 1368–1386; October, 1956.

12.7 over a wide band of frequencies centered at 9000 mc. Hence, far from resonance the theoretical attenuation through the gyrator, which has a $\theta l=\pi/2$ radians, is about 1.07 db. The theoretical minimum forward attenuation through the isolator which has a θl of about 0.91 radian is 0.62 db. Inspection of (7) reveals that, at frequencies removed from the ferromagnetic resonance frequency, the rotation θl is independent of the operating frequency.

When the operating frequency approaches the resonance frequency, (5) shows that θl increases. However, (6) predicts an even greater increase in αl. For a given size of ferrite, the amount of rotation is proportional to the ratio of $H_o^2+H_e^2$ (the square of the total unperturbed RF field at the axis position of the ferrite) to $4I_e^2Z_{oe}+4I_o^2Z_{oo}$ (twice the total power transmitted along the ferrite-loaded structure). In general, it is very difficult to determine this ratio quantitatively; however, it has been done for the case of thin, flat, co-planar coupled strips using a conformal mapping technique. The results of this analysis show that this ratio increases as the gap between the coupled strips is decreased. At the same time, it is found that the position where the magnetic fields of the even and odd mode are equal for equal power in the two modes moves closer to the plane of the coupled strips as the gap between the strips is decreased. It seems likely that this behavior will obtain for other conductors having different cross section shapes.

III. Detailed Description of Operation

Gyrator

When the correct biasing field for gyrator action is applied to the ferrite rod shown in Fig. 1, perfect transmission is achieved through the network, assuming a reflectionless and lossless ferrite when the terminating impedances at Port 1 and Port 2 are equal to the input impedances at each of these ports when the opposite port is terminated in a matched load. The input impedance at Port 1 under these conditions can be readily computed by noting that a signal entering Port 1 excites even and odd modes on the coupled lines, having equal voltages $V/2$ since it is necessary to have zero voltage on the shorted line. Hence, the current flowing on the coupled line connected to Port 1 is $V/2[1/Z_{oe}+1/Z_{oo}]$, while that induced on the shorted line is

$$V/2[1/Z_{oe} - 1/Z_{oo}].$$

Therefore, the input impedance at Port 1 is

$$2Z_{oe}Z_{oo}/(Z_{oe} + Z_{oo}).$$

In a like manner, it is seen that a signal entering Port 2 excites even and odd modes having equal currents, I. Hence the voltage on the line connecting to Port 2 is $I(Z_{oe}+Z_{oo})$, while that induced on the open-circuited line is $I(Z_{oe}-Z_{oo})$. Therefore, the input impedance at Port 2 is $(Z_{oe}+Z_{oo})/2$.

The inclination angle ϕ of the RF magnetic field along the axis of the ferrite as a signal passes through the gyrator can be computed in the following fashion. When a signal is incident on Port 1[6] with voltage amplitude V, the amplitude of the even current $\vec{I}_{1e}$ is $V/2Z_{oe}$ on each of the coupled lines while the amplitude of the odd current $\vec{I}_{1o}$ is $-V/2Z_{oo}$. Referring to Fig. 1 and remembering the condition of (4), it is seen that the even current produces an x-directed component of magnetic field $\vec{H}_{1x}=\vec{H}_{1e}$ at the axis of the ferrite rod having an amplitude proportional to $1/\sqrt{Z_{oe}}$. The odd-mode current produces a y-directed component of magnetic field $\vec{H}_{1y}=\vec{H}_{1o}$ at the axis of the ferrite rod having an amplitude proportional to $1/\sqrt{Z_{oo}}$. Thus,

$$\tan \vec{\phi}_1 = \frac{\vec{H}_{1y}}{\vec{H}_{1x}} = \sqrt{\frac{Z_{oe}}{Z_{oo}}}. \tag{8}$$

As the signal passes through the magnetized ferrite, the plane of polarization of the field at the axis of the ferrite rod rotates clockwise; however, its magnitude $\sqrt{H_o^2+H_e^2}$ is unchanged. When the wave reaches the end of the ferrite rod adjacent to Port 2, it is necessary that $\vec{I}_{2e}=\vec{I}_{2o}=V/2\sqrt{Z_{oe}Z_{oo}}$ in order that all the signal power will pass out Port 2. Therefore, the inclination angle ϕ_2 is

$$\tan \vec{\phi}_2 = \frac{\vec{H}_{2y}}{\vec{H}_{2x}} = \sqrt{\frac{Z_{oo}}{Z_{oe}}}, \tag{9}$$

showing that the plane of polarization of the wave at the center of the ferrite is rotated 90 degrees in passing once through the gyrator. When a signal passes through the device from Port 2 to Port 1, the plane of polarization of the RF magnetic field is rotated in the same sense with respect to the biasing field, as shown in Fig. 1. Hence, as explained above, this device functions as a gyrator since a signal undergoes 180 degrees more phase shift in going through the device in one direction than the other.

Wide-Band Isolator

When the correct biasing field is applied to the ferrite rod shown in Fig. 2 for isolator action, zero forward loss is achieved, again assuming a lossless and reflectionless ferrite when the characteristic impedances of the lines connected to Port 1 and Port 2 are $2Z_{oe}Z_{oo}/(Z_{oe}+Z_{oo})$ and $Z_{oe}/2$, respectively. Furthermore, it is necessary that the termination within the isolator perturb the phase velocities of the even and odd modes equally, in order that there be no reciprocal coupling between the lines.

[6] The arrows indicate the direction of power flow through the device with reference to Fig. 1.

When a signal is incident on Port 1, the inclination angle $\overrightarrow{\phi_1}$ of the RF magnetic field at the axis of the ferrite rod is $\overrightarrow{\phi_1} = \tan^{-1} \sqrt{Z_{oe}/Z_{oo}}$. As the signal passes through the isolator, the plane of polarization of the field at the axis of the rod is rotated until $\overrightarrow{\phi_2}$ is zero at Port 2. When a signal is incident on Port 2, the angle of inclination $\overleftarrow{\phi_2}$ of the field at Port 2 is again zero. As the signal passes through the device, the RF magnetic field is rotated in the same direction with respect to the biasing magnetic field so that the inclination angle $\overleftarrow{\phi_1}$ of the magnetic field at the center of the ferrite rod nearest Port 1 is $\overleftarrow{\phi_1} = -\overleftarrow{\phi_1}$. This orientation of the magnetic field corresponds to zero RF voltage on the line connecting to Port 1 and maximum voltage on the line containing the termination, which is the optimum condition for a large absorption in the termination.

It is interesting to note that should the direction of the biasing magnetic field be reversed, a signal incident on Port 2 will propagate through the isolator and emerge unattenuated from Port 1. However, a signal incident on Port 1, after passing through the isolator, will set up both even and odd mode currents on the lines adjacent to Port 2. The energy in the even mode will pass out of Port 2 while the energy in the odd mode will be reflected at the T-junction and later, after retraversing the network, be absorbed in the termination. Thus, other factors being the same, the reverse loss is less for this orientation of biasing field than for the correct orientation of the biasing field shown in Fig. 1. However, as discussed in Section IV, measurements made on an isolator with a lossy ferrite indicated only a small difference in attenuation when the biasing field was reversed.

IV. Measured Performance

Gyrator Experimental Results

A photograph of the experimental model of the wide-band gyrator is shown in Fig. 3. Its measured performance is shown in Fig. 4. The cross section dimensions of the coupled strip lines and the Ferramic R-1 ferrite rod are also shown in Fig. 4. The over-all length of the coupled lines is 8 inches. The over-all length of the ferrite rod is 5.75 inches and each end is tapered over a length of 0.625 inch. The theoretical values of Z_{oe} and Z_{oo} are 139 ohms and 88 ohms, respectively. These values were computed from (24) and (25) of Jones and Bolljahn,[2] suitably modified to account for the increased self-capacitance of the lines caused by the presence of the vertical side walls of the outer conductor of the network. Tapered transitions were employed at either end of the gyrator to match it to the 50-ohm impedance level of the measuring equipment. The transition at Port 1 transformed between 50 ohms and $2Z_{oe}Z_{oo}/(Z_{oe}+Z_{oo}) = 108$ ohms, while the transition at Port 2 transformed between 50 ohms and $(Z_{oe}+Z_{oo})/Z = 114$ ohms.

With no dc biasing field applied, the insertion loss through the gyrator is greater than 20 db, except near the highest frequencies measured where it drops to 16 db. When the magnetic field is applied to obtain gyrator action, the insertion loss decreases to less than 2 db except at a few isolated points in the band. At the upper end of the band, the insertion loss averages about 1 db, in agreement with the results of the perturbation analysis. Although the data were not recorded, it is believed that the gyrator shown would operate satisfactorily down to frequencies as low as 5.5 kmc, since one of the experimental isolators described in the next section operated down to this frequency.

It is believed that the insertion loss of the gyrator, caused mainly by ferrite losses, could be greatly reduced by employing an yttrium iron garnet rod which has a line width of about 50 oersteds, rather than the Ferramic R-1 which has a line width of about 500 oersteds.

Isolator Experimental Results

An experimental isolator design was constructed having cross-sectional dimensions as shown in Fig. 5. In this case, the even- and odd-mode impedances are approximately $Z_{oe} = 148$ and $Z_{oo} = 90.4$ ohms. The input impedance at Port 1 in Fig. 2 is $2Z_{oe}Z_{oo}/(Z_{oe}+Z_{oo}) = 112.5$ ohms, while the input impedance at Port 2 is $Z_{oe}/2 = 74$ ohms. In order to match the 112.5-ohm impedance at

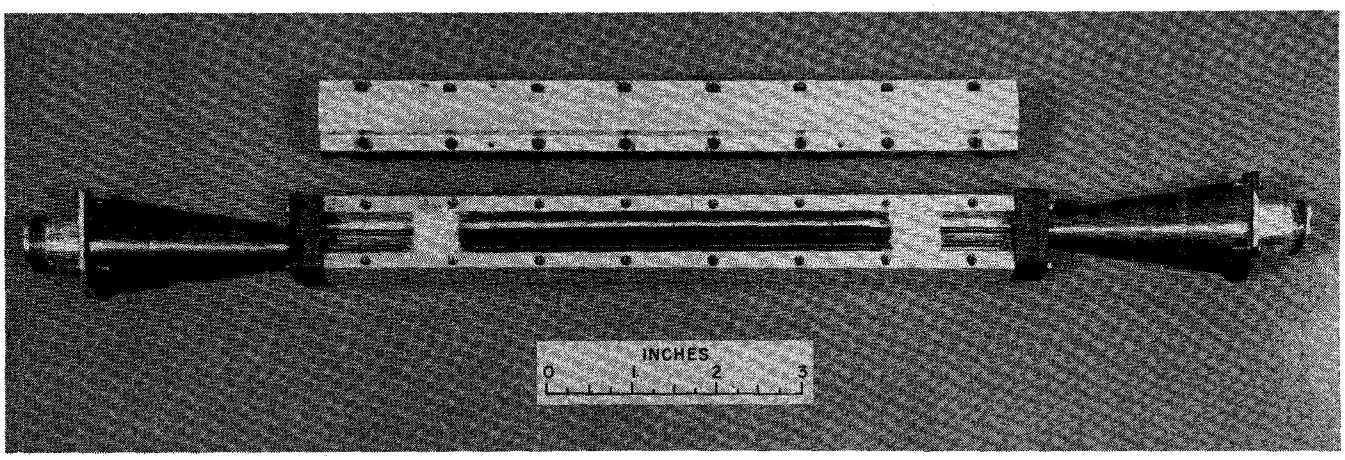

Fig. 3—Photograph of the wide-band gyrator.

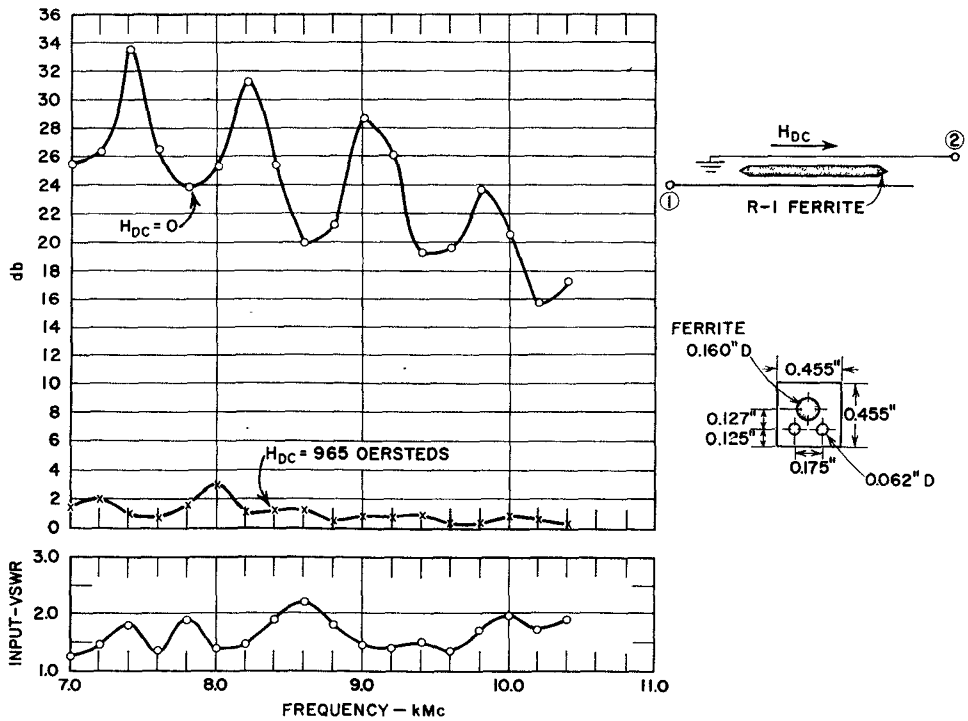

Fig. 4—Insertion loss of wide-band gyrator.

Port 1 to 50 ohms, a 2.4-inch taper section was used at that end. At Port 2, it was possible to achieve a good match by adjusting the position of the Y-junction with respect to the end wall, and by altering the diameter of the conductor between the junction and the end of the box. In order to test the VSWR of the transitions, long tapered sections of Polyiron were placed beside the conductors to act as terminations inside the box.

The isolator whose cross section is shown in Fig. 5 used a 0.147-inch diameter rod of Ferramic R-1 ferrite, 5.70 inches in over-all length, with each end tapered to a point in a distance of 1.2 inch. The ferrite rod was suspended within the outer shield by threads attached to metal pull rods and calibrated adjusting nuts so that it was possible to adjust the position of the ferrite rod while the isolator was in operation. Since the reverse loss is the most sensitive test of proper operation, the rod was positioned in such a way as to optimize the reverse loss characteristic. Because the thread system used for holding the rod was not very rigid, the rod position indicated in Fig. 5 can be regarded only as a close approximation.

The forward loss, shown in Fig. 5, of a signal traveling from Port 1 to Port 2, was measured with the biasing field oriented as shown in Fig. 2. The reverse loss was measured with the biasing field reversed. Within experimental error, the same result is obtained for the reverse loss with the biasing field oriented as shown in Fig. 2, but with the direction of propagation through the isolator reversed.

Fig. 5 shows that the device has high isolation; *i.e.*, reverse loss, over a considerable bandwidth. The forward loss is around 1.0 db over most of the band, with a few peaks reaching a maximum of 1.6 db. The VSWR at Port 1 and Port 2 was the same regardless of the H-field direction. The low VSWR at Port 2, which was observed for all biasing field strengths, is due to the fact that essentially all of the signal fed into Port 2 is absorbed either in the matched termination at Port 1 or in the matched internal termination. On the other hand, a low VSWR at Port 1 will only be obtained when the biasing field is adjusted to give the proper rotation. Therefore, it is believed that the relatively high VSWR observed at Port 1, when the isolator is adjusted for optimum reverse loss, indicates that the amount of "rotation" in the forward direction is different from that in the reverse direction, either because of reciprocal coupling or because of higher-order modes caused by the presence of the ferrite.

The data in Fig. 6 show the difference in decibels between the reverse and forward loss with the biasing field adjusted at each frequency to maximize the reverse loss. More biasing field is required at intermediate frequencies than at both the relatively low and the relatively high frequencies. At the lower frequencies it is possible that the proximity of ferromagnetic resonance diminishes the H-field required. The reduced biasing field required at the high frequencies may be due to increased concentration of energy in the ferrite rod.[7] It is probable that the rotation could be kept more constant with frequency for a given biasing field by introducing dielectric loading in the isolator box to draw away some of the energy from the ferrite rod at the higher frequencies.[7]

[7] E. A. Ohm, "Broad-band microwave circulator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 210–217; October, 1956.

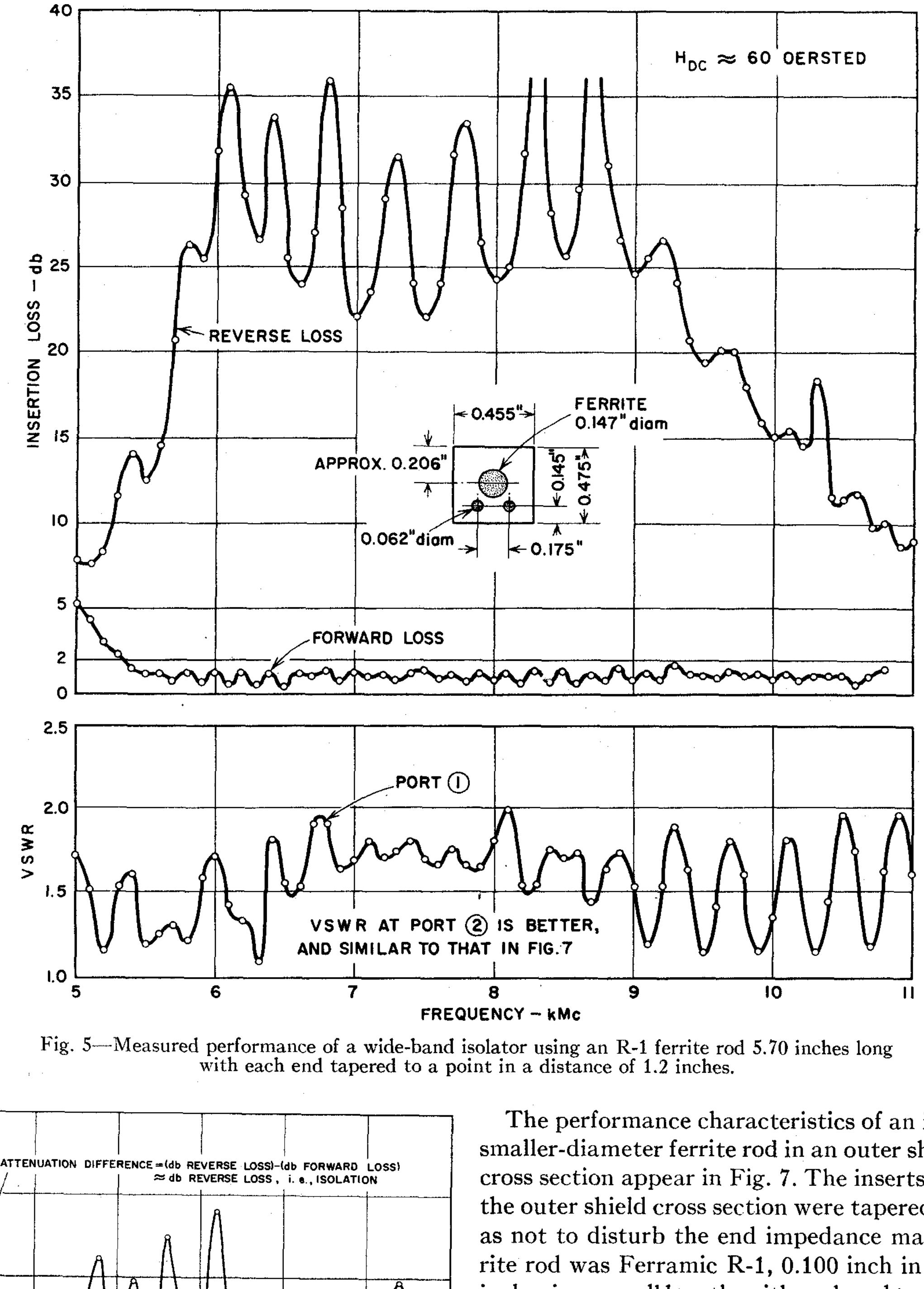

Fig. 5—Measured performance of a wide-band isolator using an R-1 ferrite rod 5.70 inches long with each end tapered to a point in a distance of 1.2 inches.

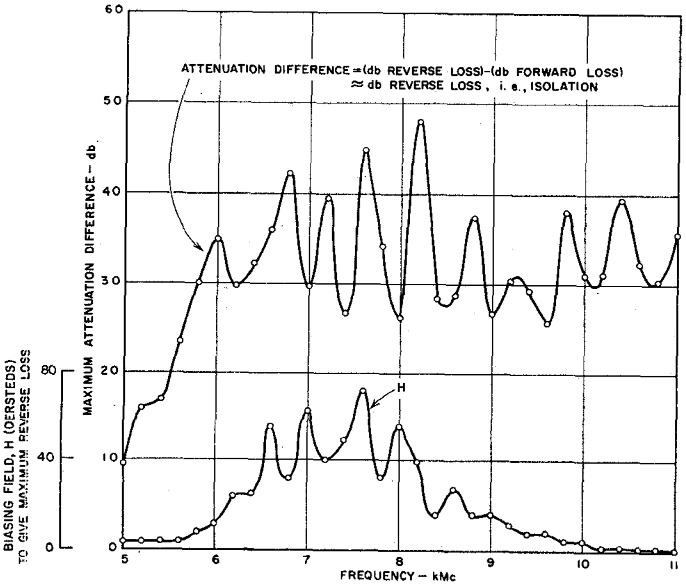

Fig. 6—Decibel difference between reverse and forward loss for the isolator in Fig. 5 when the biasing field is adjusted at each frequency to give the peak reverse loss.

The performance characteristics of an isolator using a smaller-diameter ferrite rod in an outer shield of reduced cross section appear in Fig. 7. The inserts used to reduce the outer shield cross section were tapered at the ends so as not to disturb the end impedance matches. The ferrite rod was Ferramic R-1, 0.100 inch in diameter, 6.00 inches in over-all length, with each end tapered to a point in a distance of 0.5 inch. The distance x in the cross section drawing in Fig. 7 was approximately 0.070 inch and was arrived at by adjusting for optimum reverse loss.

It is seen that the performance of this isolator is quite similar to that of the previously described isolator, except that the midband reverse loss is slightly lower. However, it is probable that the performance of this isolator could be improved by using a longer ferrite rod, since for frequencies beyond midband it was not possible to peak the reverse loss at a definite biasing field as was possible in the previous isolator. It was found possible to minimize the forward loss only at the lower frequencies, which again indicates that the rod was not long enough to give sufficient rotation at the higher frequen-

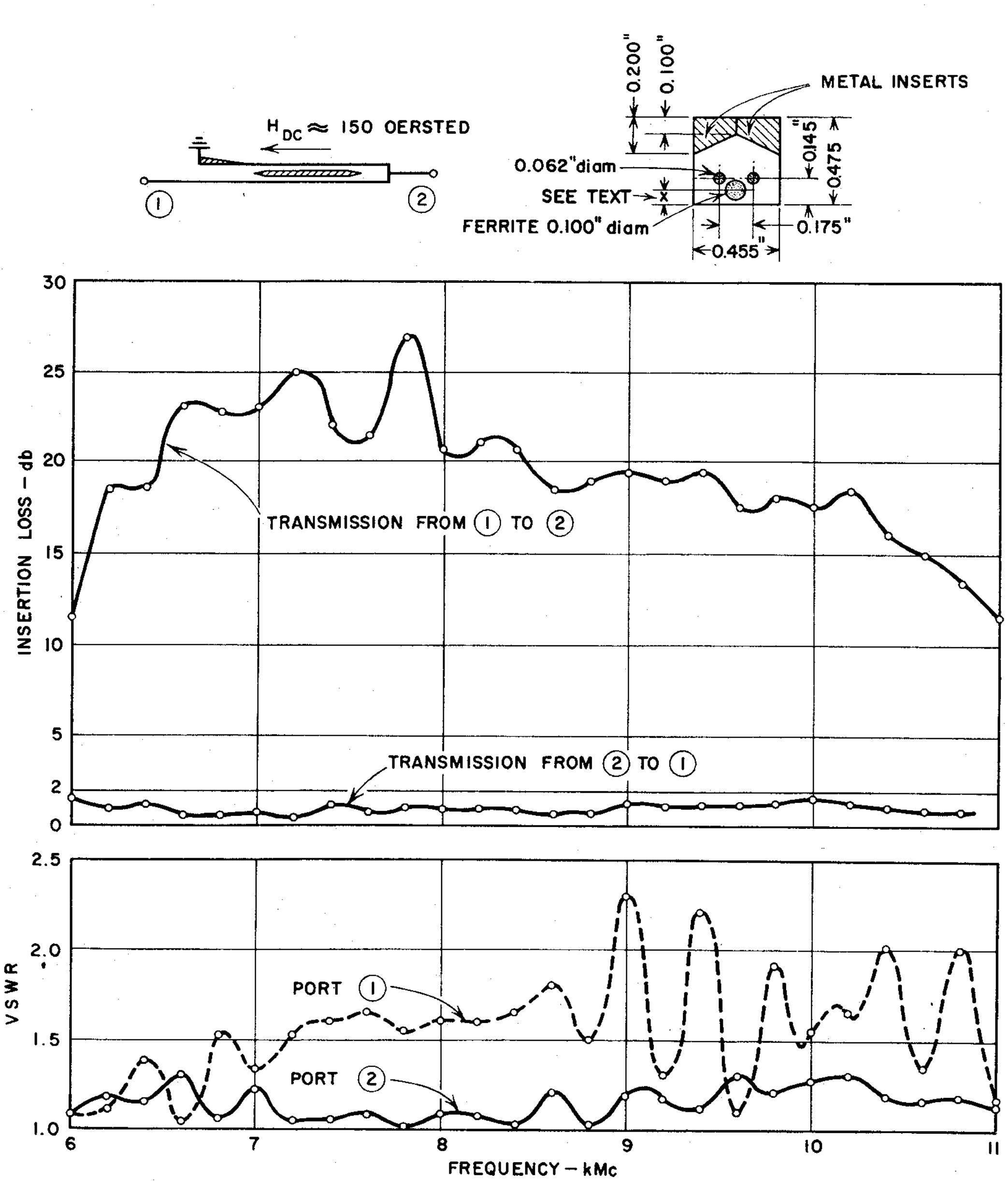

Fig. 7—Measured performance of a wide-band isolator using an R-1 ferrite rod 6 inches long with each end tapered to a point in a distance of 0.5 inch.

cies. At frequencies in the 7- to 8-kmc band, the optimum loss values ran around 0.5 db, or somewhat less, which agrees fairly well with the perturbation analysis and should be indicative of what optimum performance of the isolator would be. As seen from Fig. 7, the VSWR at Port 1 of the isolator is rather high, just as in the case of the previous isolator, while the VSWR at Port 2 is quite low. In this case, insertion loss data were taken for both directions of the H-field and for both directions of power flow. The differences in the measured data were quite small, although operation with the H-field, as shown, was slightly better in the forward loss characteristic.

Conclusion

The nonreciprocal TEM network described here can be used as a wide-band gyrator, isolator, switch, or modulator. The theoretical analysis of this network indicates that it should function over bandwidths even greater than an octave. Measurements on experimental versions of the network demonstrate that operation over almost an octave may be readily achieved in practice. If polycrystalline yttrium iron garnet is used in place of the R-1 ferrite, it is believed that low-loss operation can be achieved over even greater bandwidths.