Criteria for Designing High-Power Coupled Wave Duplexers and Isolators*

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Summary—**This paper presents criteria for designing nonreciprocal coupled-wave devices which may be used as isolators, circulators and duplexers. An experimental model of such a device was designed and tested over a 6 per cent frequency band centered at 35 kMc, and the obtained data are in good agreement with the theory. Such devices should have numerous applications as they offer the capability of operating under extremely high power levels, and are not restricted to dominant mode operation.**

Introduction

In conventional solid-state circulators which utilize hybrid couplers, the ferrimagnetic material is subjected to a large percentage of the transmitted power.[1] Another approach that employs coupled wave theory allows the ferrimagnetic material to be placed in a secondary transmission line, which is somewhat isolated from the transmitted power. A sketch of such a circulator is given in Fig. 1.

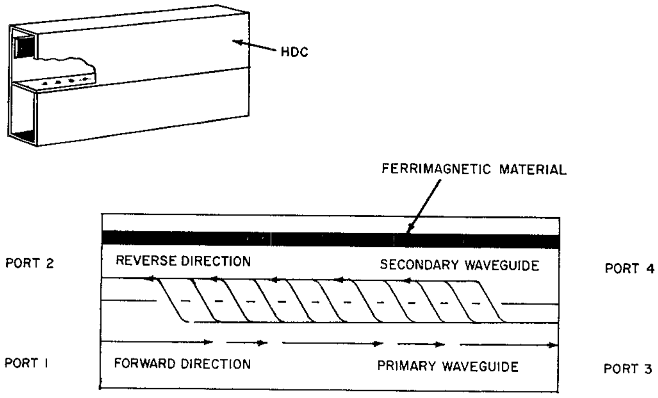

Fig. 1—Typical structure for obtaining circulator action.

If the construction of the depicted device is such that the coupling length and coupling coefficient per unit length are properly chosen, circulator action may be obtained by utilizing the nonreciprocal characteristics of magnetically biased ferrimagnetic material placed in the secondary waveguide. Mention of this type of structure can be found in the literature,[2] but further exact design criteria are needed by the component designer. The purposes of this paper are to formulate relationships which can be directly applied to component design, and to verify the design procedure on a rather complex component. In particular, the procedure is used in the design of a duplexer operating in the millimeter wavelength region.

The Distributed Coupled Transmission Line

Coupled wave transmission systems can be approximated by numerous configurations, some of which are depicted in Fig. 2. For these types of systems, it has been shown by Miller[3] and other workers[4,5] that, if an analysis is restricted to waves propagating in one direction, the space variations of the wave amplitudes are, in Miller's notation

$$\frac{dE_1}{dx} = -(\Gamma_1 + K_{11})E_1 + K_{21}E_2 \tag{1}$$

and

$$\frac{dE_2}{dx} = K_{12}E_1 - (\Gamma_2 + K_{22})E_2, \tag{2}$$

where

- K_{11}, K_{22} represents the reaction of the coupling mechanisms on the primary and secondary lines, respectively;
- K_{21}, K_{12} represent the effects of transfer coupling reaction on the primary and secondary lines, respectively;
- Γ_1, Γ_2 are the propagation constants of the primary and secondary lines when there is no coupling;
- E_1, E_2 are the complex-wave amplitudes on the primary and secondary lines.

E_1 and E_2 are also chosen such that $|E_1|^2$ and $|E_2|^2$ represent the power in lines 1 and 2 at either end of the coupling regions. For cases in which reciprocity holds and for loose coupling per wavelength,

$$K = K_{12} = K_{21} \approx K_{11} \approx K_{22}. \tag{3}$$

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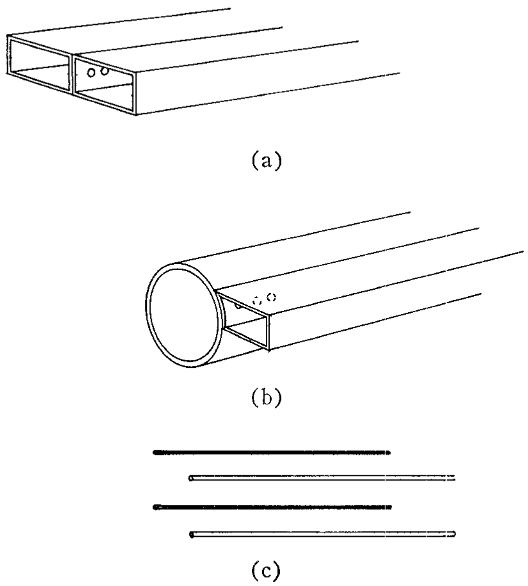

Fig. 2—Configurations for approximating coupled wave transmission systems. (a) Rectangular-to-rectangular waveguide. (b) Circular-to-rectangular waveguide. (c) Two-wire-to-two-wire transmission line.

It can also be shown that, on the basis of energy conservation, K is purely imaginary. That is,

$$K \equiv jc$$

where c is a real number.[3] If this substitution is made in (1) and (2), and if Γ_1 and Γ_2 are replaced by their real and imaginary parts $\alpha_1+j\beta_1$ and $\alpha_2+j\beta_2$, respectively, then, after manipulation, the solutions to the equations become

$$\begin{aligned} E_1 = &\left\{\cosh\frac{cxr}{2}\cos\frac{cxs}{2}+j\sinh\frac{cxr}{2}\sin\frac{cxs}{2}\right. \\ &\left. -(u+jv)\left[\sinh\frac{cxr}{2}\cos\frac{cxs}{2}+j\cosh\frac{cxr}{2}\sin\frac{cxs}{2}\right]\right\} \\ &\cdot\exp\left\{-x\left[\alpha_1+j\left(c+\beta_1+\beta_2\right)\right]\right\} \\ &\cdot\exp\left\{\frac{cx}{2}\frac{(\alpha_1-\alpha_2)}{c}\right\}, \end{aligned} \qquad (4)$$

and

$$\begin{aligned} E_2 = &\left[\sinh\frac{cxr}{2}\cos\frac{cxs}{2}+j\cosh\frac{cxr}{2}\sin\frac{cxs}{2}\right] \\ &\cdot\exp\left\{-x\left[\alpha_1+j\left(c+\frac{\beta_1+\beta_2}{2}\right)\right]\right\}\cdot\exp\frac{cx}{2}\frac{(\alpha_1-\alpha_2)}{c} \end{aligned} \qquad (5)$$

where

$$r+js=\sqrt{\left[\frac{\alpha_1-\alpha_2+j(\beta_1-\beta_2)}{c}\right]^2-4} \qquad (6)$$

and

$$u+jv=\frac{\dfrac{\alpha_1-\alpha_2}{c}+j\dfrac{(\beta_1-\beta_2)}{c}}{r+js}. \qquad (7)$$

For brevity, (4) and (5) may be written as

$$E_1 = A_1\cdot\exp\left\{-x\left[\alpha_1+j\left(c+\frac{\beta_1+\beta_2}{2}\right)\right]\right\} \qquad (8)$$

and

$$E_2 = A_2\cdot\exp\left\{-x\left[\alpha_1+j\left(c+\frac{\beta_1+\beta_2}{2}\right)\right]\right\}. \qquad (9)$$

The above analysis is nearly identical to that presented in Miller's paper. It is repeated in this particular form because it provides a clear analysis of the problem under discussion.

In order to determine the effects of loss exhibited by ferrimagnetic material in configurations similar to the one shown in Fig. 1, families of curves of $|A_1|$ vs cx were calculated as function of

$$\frac{\alpha_1-\alpha_2}{c} \qquad (10)$$

and

$$\frac{\beta_1-\beta_2}{c}. \qquad (11)$$

These curves are shown in Figs. 3–6; and, for convenience, the relationships between $(\alpha_1-\alpha_2)/c$, c, and α_2 are given in Fig. 7. Fig. 3 is essentially Miller's Fig. 19 and is included for comparison with cases in which $(\alpha_1-\alpha_2)/c\neq 0$. The curves in Figs. 3–6 indicate that, if $cx\approx\pi/2$ and $(\beta_1-\beta_2)/c$ is varied, different values of energy transfer between the primary and secondary waveguide result. If $(\beta_1-\beta_2)/c=0$, then nearly complete energy transfer results, but if

$$-0.20\le\frac{\alpha_1-\alpha_2}{c}\le 0 \qquad (12)$$

and $(\beta_1-\beta_2)/c\approx\pm 3.5$, less than eight per cent of power in the primary waveguide is lost to the secondary waveguide.

Design Considerations

The design of a device similar to that shown in Fig. 1 can be obtained more easily by considering the necessary operating conditions for the two separate directions of propagation. The reverse direction of propagation (see Fig. 1) will be considered first.

The Reverse Direction of Propagation

For the reverse direction of propagation, nearly all of the energy should be coupled from the primary waveguide into the secondary waveguide. The curves in

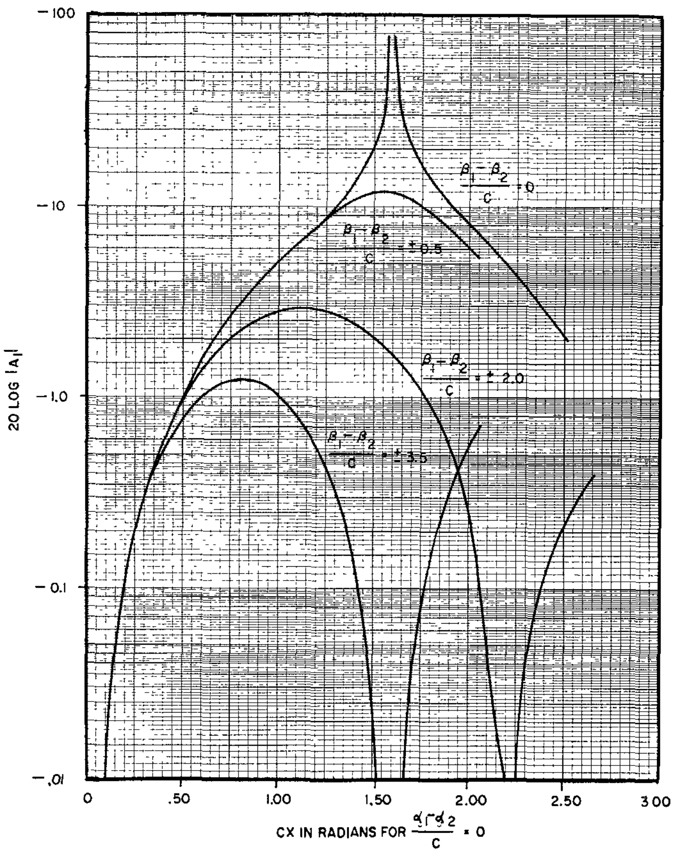

Fig. 3—Input line insertion loss vs cx as a function of phase differences and with $(\alpha_1-\alpha_2)/c=0$.

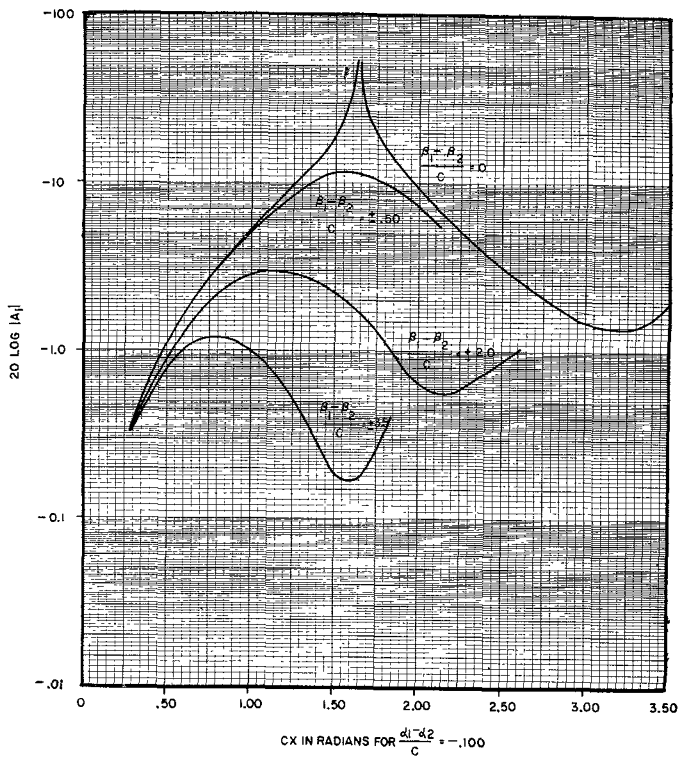

Fig. 5—Input line insertion loss vs cx as a function of phase differences and with $(\alpha_1-\alpha_2)/c=-0.100$.

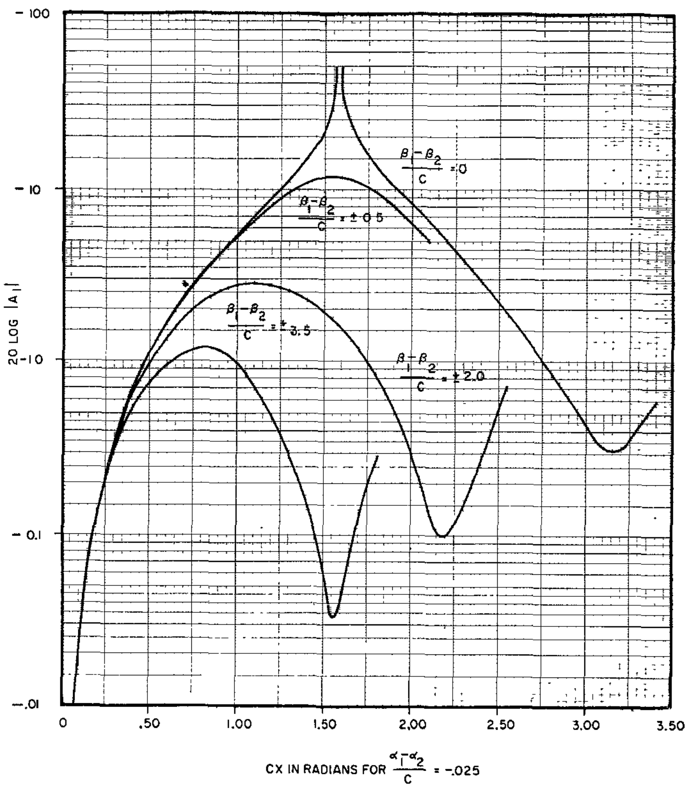

Fig. 4—Input line insertion loss vs cx as a function of phase difference and with $(\alpha_1-\alpha_2)/c=-0.025$.

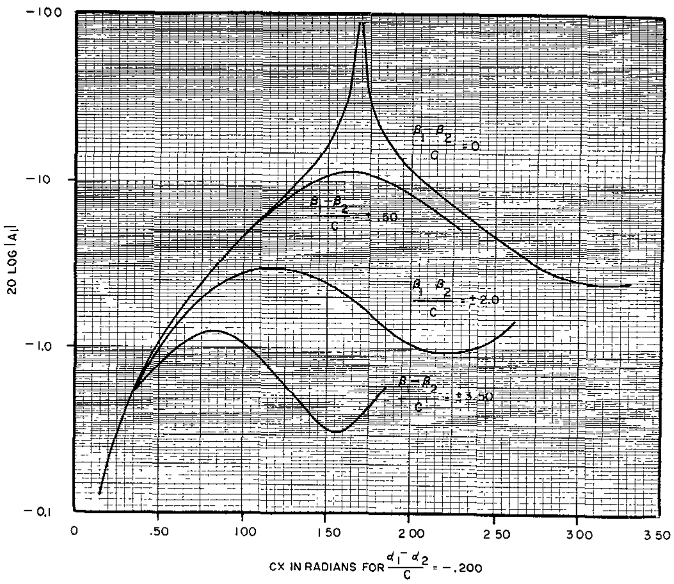

Fig. 6—Input line insertion loss vs cx as a function of phase differences and with $(\alpha_1-\alpha_2)/c=-0.200$.

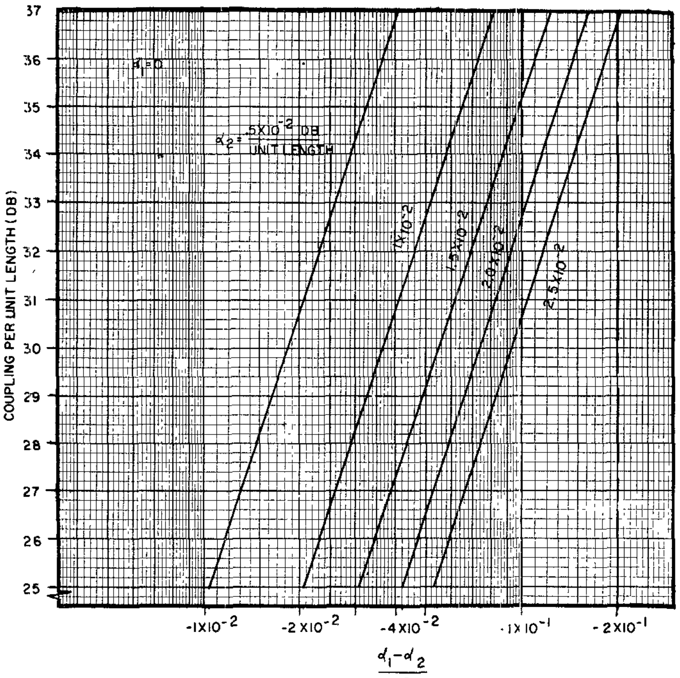

Fig. 7—The relationship between $(\alpha_1-\alpha_2)/c$, c, and α_2.

Figs. 3–6 indicate that this will happen when the following conditions are satisfied:

$$\frac{\beta_1-\beta_2}{c}=0 \tag{13}$$

$$\frac{\alpha_1-\alpha_2}{c}=\text{minimum} \tag{14}$$

$$cx=\frac{\pi}{2}\cdot \tag{15}$$

For a reciprocal device, (13) could be satisfied by choosing equal mode cutoff frequencies for the two waveguides. However, the nonreciprocal requirement necessitates the inclusion of ferrimagnetic material in the secondary waveguide.

When a flat slab of ferrimagnetic material is placed in the plane of circular polarization of the secondary waveguide, the phase constant β_2 varies nonreciprocally as a function of the biasing field; this effect is shown in Fig. 8. Before a magnetic field is applied, a condition for which $\beta_2>\beta_1$ is obtained. In order to satisfy (13), β_2 must be reduced from the value obtained for zero magnetic field. This can be accomplished by using either negative- or positive-wave phase characteristics.

If it is desired to use the negative-wave phase characteristics for the reverse direction of propagation, β_2 must be reduced until $\beta_2=\beta_1$. This could be accomplished at some particular operating frequency by reducing the width of the secondary waveguide. This effect would, however, be restricted to a relatively narrow band. This is analogous to the effect encountered when it is desired to fill any waveguide with a medium whose relative dielectric constant is greater than one,

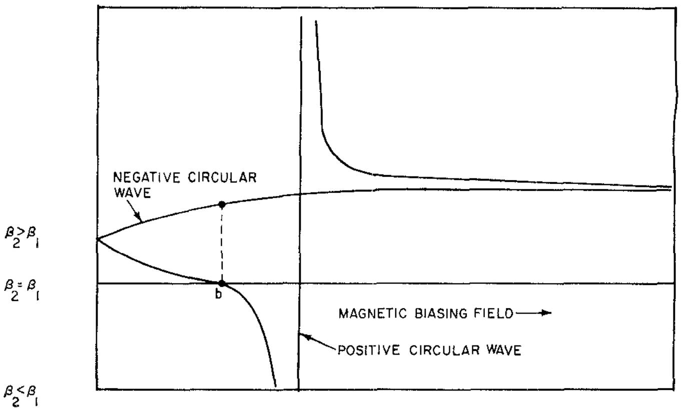

Fig. 8—Nonreciprocal variation of β_2 vs magnetic field at a fixed frequency.

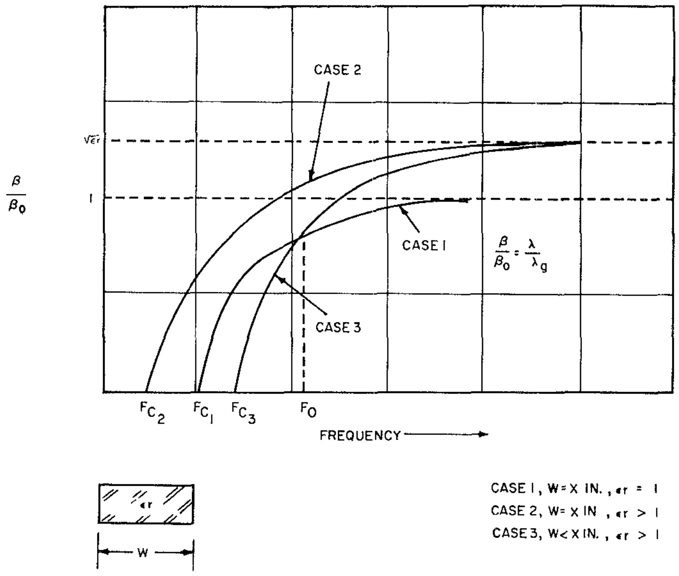

Fig. 9—The effects of inserting a dielectric in a uniconductor waveguide.

and at the same time, retain the original phase constant by reducing the waveguide width. As is shown in Fig. 9, the phase constants for the empty waveguide and the reduced width waveguide containing dielectric media may be made equal only for one frequency. Thus, it appears that negative-wave phase characteristics are not well suited for use in the reverse direction of propagation.

If positive-wave phase characteristics are utilized for the reverse direction of propagation, then by operating at magnetic field bias shown at point b in Fig. 8, the secondary waveguide has approximately the same characteristics as an empty waveguide. Thus, the effect depicted in Fig. 9 is eliminated, and the resultant bandwidth is governed by the variation of ferrimagnetic characteristics and coupling with frequency. It is believed that five to ten per cent bandwidths can be obtained with reasonable insertion loss. From bandwidth considerations, it appears that positive-wave phase characteristics are desirable for use in the reverse direction of propagation.

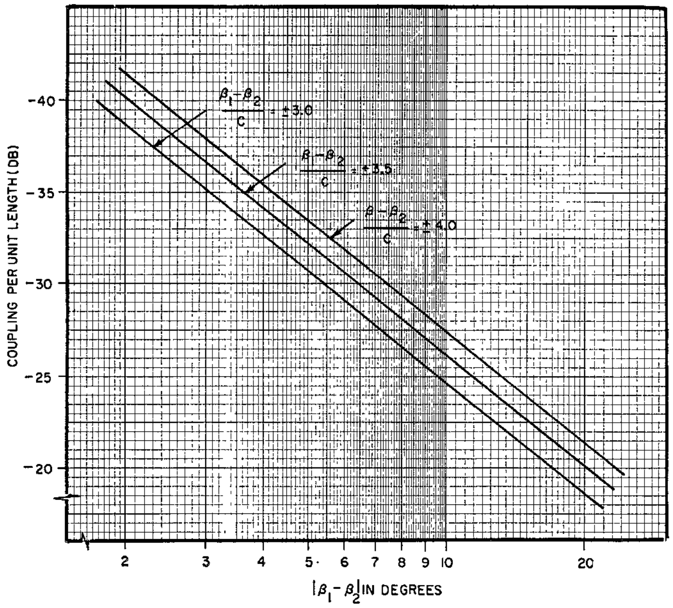

Fig. 10—The relationship between $|\beta_1, -\beta_2|$ and c.

The Forward Direction of Propagation

For the forward direction of propagation, it is desired that little or none of the energy in the primary waveguide be coupled into the secondary waveguide. The curves in Figs. 3–6 indicate that this may be accomplished if the following conditions are satisfied:

$$\frac{\beta_1 - \beta_2}{c} \approx \pm 3.5 \tag{16}$$

$$\frac{\alpha_1 - \alpha_2}{c} = \text{minimum} \tag{17}$$

$$cx = \frac{\pi}{2} \cdot \tag{18}$$

These conditions are the same as for the reverse direction of propagation except for the condition stated in (16). From previous considerations, it is deemed advisable to utilize the negative-wave phase characteristics and magnetic biasing field as shown at point b in Fig. 8. From the negative-wave characteristics as depicted in Fig. 8, it is seen that it is possible to satisfy (16) by a judicious choice of ferrimagnetic-material characteristics and geometry, and the coupling value per unit length. For ease of design, the relationship between $\beta_1 - \beta_2$ and c in decibels is shown in Fig. 10.

Design of Experimental Duplexer

To demonstrate the feasibility of a coupled wave duplexer, an experimental model was designed and fabricated. The structure of the experimental duplexer is depicted in Fig. 2(b), and it uses TE_{01} mode circular waveguide as the primary line and TE_{10} rectangular waveguide as the secondary line. The operating center frequency is 35 kMc.

In order to satisfy the necessary relationships for circular action over a large bandwidth, a reciprocal

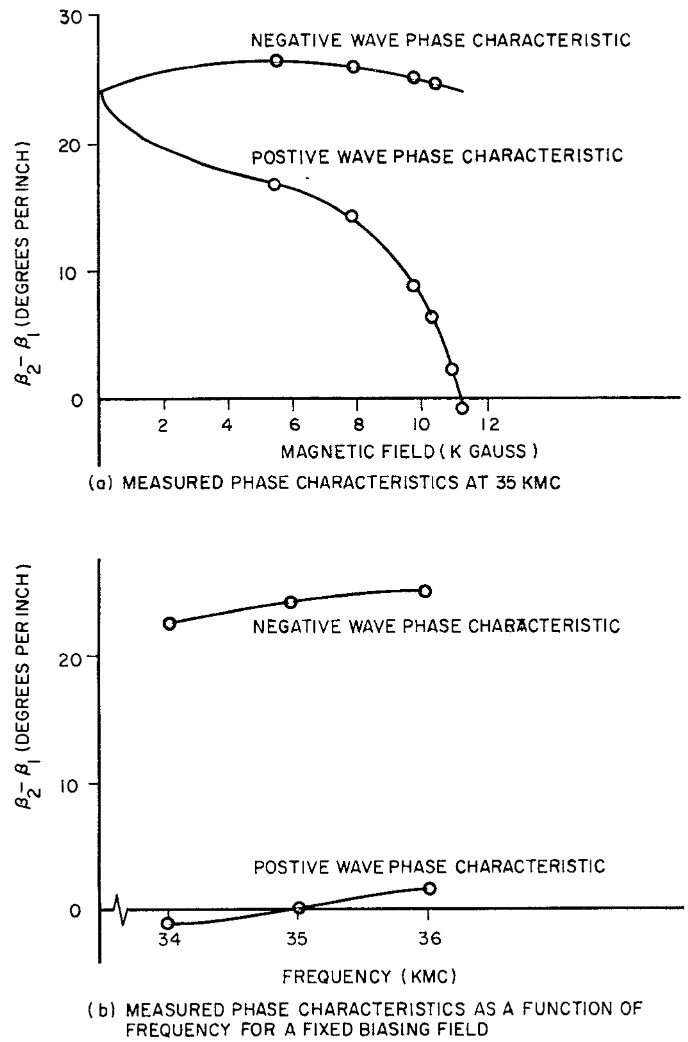

Fig. 11—Measured phase characteristics of a flat slab of magnesium-manganese ferrite placed on the broadwall of the secondary waveguide.

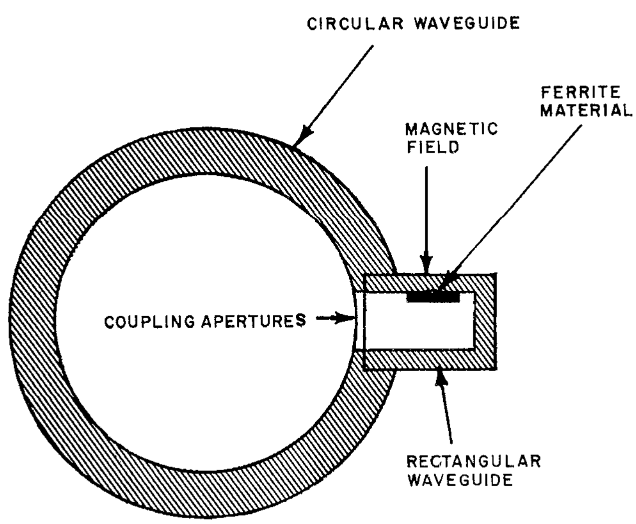

Fig. 12—Cross-sectional view of experimental duplexer.

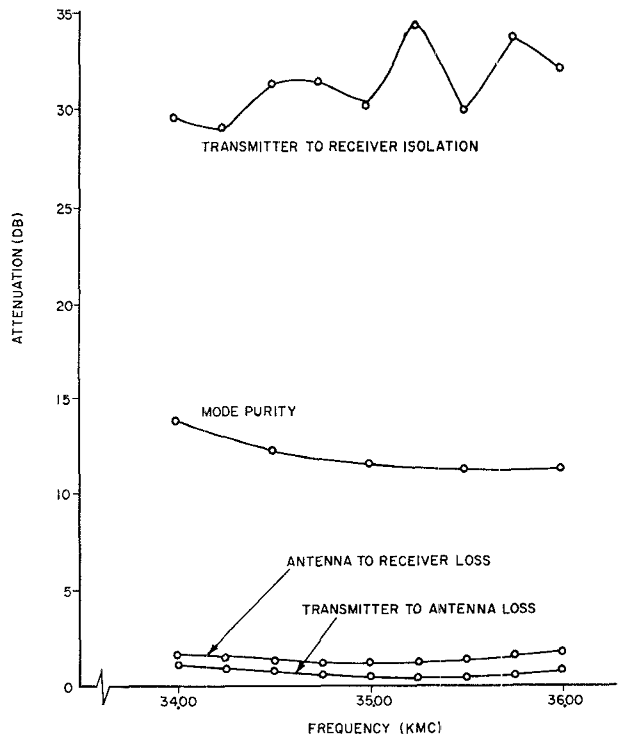

Fig. 13—Measured data for experimental duplexer.

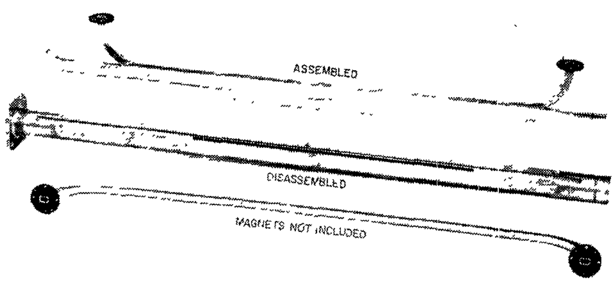

Fig. 14—Photographs of TE_{01} mode circular waveguide duplexers.

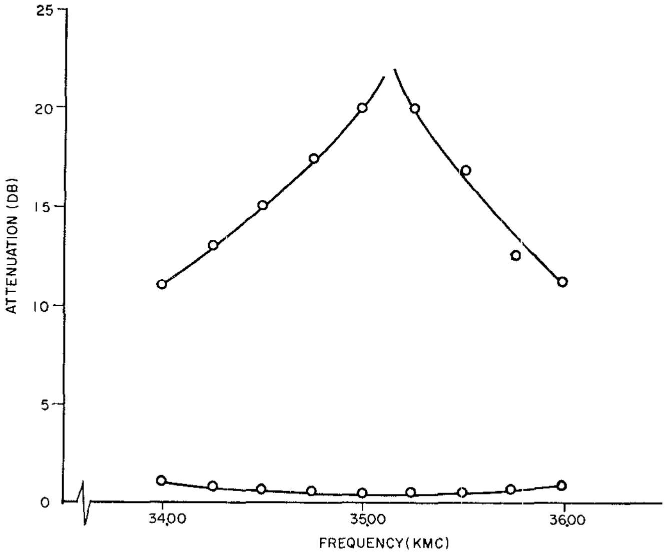

Fig. 15—Measured data for experimental device used as an isolator.

zero decibel coupler between TE_{01} mode energy in circular waveguide and TE_{10} mode in rectangular waveguide was built. After choosing a circular waveguide inner diameter of 0.725 inch, the width of the rectangular waveguide and the size and number of coupling apertures were varied until a minimum transfer loss between the two waveguides was obtained. The obtained transfer was approximately 0.9 db at 35 kMc. This is in general agreement with values reported previously in the literature for similar devices.[6]

The phase shift and loss characteristics of several ferrimagnetic materials and geometries were investigated, and a flat slab of magnesium-manganese ferrite, with a $4\pi M_s = 2200$ gauss, was found to give satisfactory phase shift characteristics with an $(-\alpha_1\alpha_2)/c \approx -0.15$ for the coupling value of interest. Typical phase-shift data are depicted in Fig. 11.

The ferrimagnetic material was added to the experimental structure as shown in Fig. 12, and its position and the magnetic biasing field were varied until optimum duplexing characteristics were obtained. The obtained data for the duplexer are shown in Fig. 13, and a photograph of this experimental model is shown in Fig. 14. From the data displayed in Fig. 13, it is seen that a low transmitter-to-antenna loss is obtained over most of the desired frequency band. A somewhat higher antenna-to-receiver loss is obtained due to multimode problems associated with the device. Also, it is seen from the data that the duplexer has a minimum mode purity of 11 db; however, with a small helical mode absorber incorporated into the device, the mode purity increases to values in excess of 20 db.

By changing the magnetic biasing field by a small percentage, maximum isolation between antenna and transmitter is obtained at 35 kMc. These data are depicted in Fig. 15. Thus it is seen that, by terminating the outputs of secondary waveguide, the duplexer can be used as an isolator.

Conclusions

Devices of the sort described in this paper offer considerable promise for use as high-power duplexers, isolators, circulators, and switches. Also, these devices can be readily designed to operate in modes other than the dominant; therefore, they are particularly well suited for use at millimeter wavelength frequencies where TE_{01} circular electric mode components are receiving much consideration.

Acknowledgment

The authors would like to express their thanks to R. W. Coston for experimental assistance, and to D. C. Scott and W. B. Day for many informative discussions.

[6] A. A. Blaisdell and P. D. Rutledge, "Research and Development Program on Circular Waveguide Components—Final Report," Microwave Assoc., Inc. Burlington, Mass. (Contract No. DA-36-039-sc-63230), pp. 53–54; February, 1958.