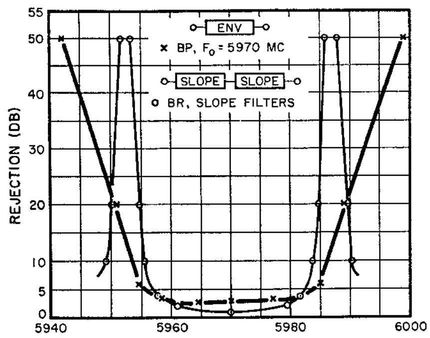

Fig. 4. Individual responses of envelope filters and pair of slope filters.

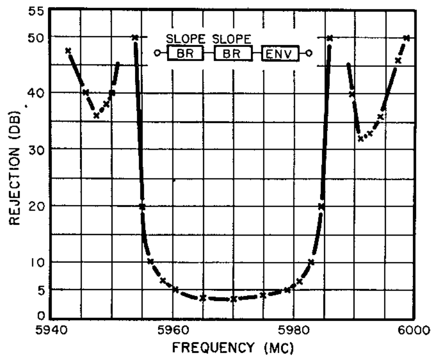

Fig. 5. Composite response of pair of slope filters and envelope filter.

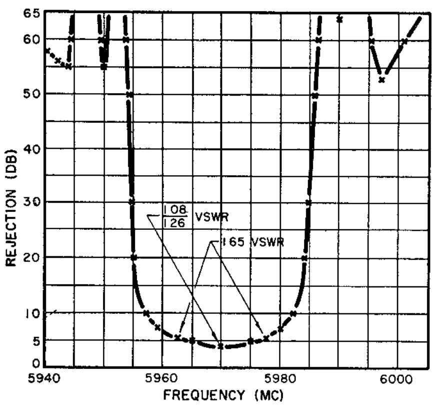

Fig. 6. Composite response—final filter.

essentially the same as that of the pair of band-reject filters of the previous figure, and also that the superposition assumption is substantiated to a high degree.

Figure 6 shows the final composite response obtained when the pair of fill-in band-reject filters is used to augment the previous response in the valley region. The slope of 5.5 Mc/s differs from the previous 4.5 Mc/s owing to the accumulated dissipation loss of the 3-dB frequency point. However, measured rejection has been increased to greater than 50dB over a broad range of frequencies on either side of the passband. Above the 10-dB level, the composite response coincides with the theoretical 2 Mc/s slope. This does not represent the optimum situation since Q's of 4000 have been used, while 9000 is readily obtainable.

Additionally it should be noted that the 27-resonator composite filter is easier to tune than an equivalent band-pass filter since band-reject resonators can be tuned independently, and the band-pass envelope filter requires only seven resonators.

Acknowledgment

The authors wish to thank the NASA personnel, and especially W. Allen, for advice and support during the program.

E. N. Torgow
Rantec Corporation
Calabasas, Calif.

P. D. Lubell
Adler Educational Systems
Div., Litton Systems, Inc.
New Rochelle, N. Y.

A New Isolator Using a Solid-State Plasma Waveguide

Nonreciprocal microwave circuits involving a tensor permeability were considered by Hogan in 1952 [1], [2], and many examples, such as isolators, circulators, modulators, switches, and phase shifters, have been developed. A gaseous plasma waveguide [3], [4] displays similar nonreciprocal properties, because of the plasma tensor permittivity in a magnetic field. The Faraday rotation and different losses for right-hand-polarized and oppositely-polarized waves lead to characteristics essentially similar to those of ferrites.

The isolator described here demonstrates the use at 24 Gc/s of a new type of electromagnetic wave [5], [6] which propagates only along one waveguide wall, determined by the propagation and external magnetic field directions. Since the theoretical upper frequency limit of the new isolator is determined by losses which appear at the cyclotron frequency, which was larger than 1000 Gc/s in the experiment described subsequently, the isolator opens the possibility of nonreciprocal devices in the mm and sub-mm wavelength region.

The properties of electromagnetic wave propagation in a solid-state plasma waveguide—for example an n-InSb bar which has been coated with copper plating—have been investigated, experimentally [5] and theoretically [6], for a plasma waveguide whose length was so large that the effect of the boundaries at the input and the output did not disturb the propagation mode. Since a short length is necessary to decrease the propagation loss for use in devices, it is also important to understand the situation for a length much shorter than the guide-wave length.

Figure 1 shows a one-dimensional model (at each quarter period of the cycle) of the propagation through a semiconductor plate whose electron mobility μ_e is so large that $\mu_e B_0 \equiv \omega_c \tau \gg 1$. Here B_0 is the external magnetic field, ω_c is the electron cyclotron frequency, τ is the electron scattering time, and the positive particles neutralizing the

Manuscript received June 19, 1964; revised August 24, 1964.

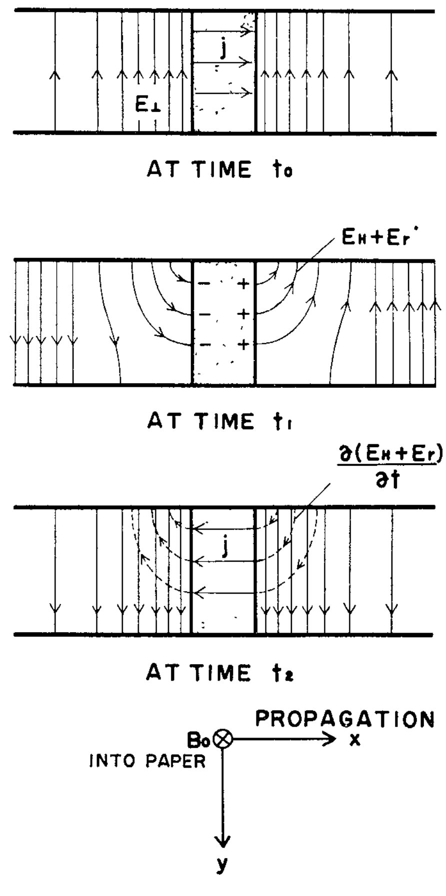

Fig. 1. Model of the propagation through a semiconductor plate in a waveguide. t_1 is one-quarter period later than t_0; t_2 is one-half period later than t_0.

electrons should be donor ions and not holes. When the electric field $E_\perp$ is maximum at the crystal at time t_0, an electron Hall current j flows in the direction perpendicular to both B_0 and E, and produces a rotational magnetic field B'. The directions of B' near the upper and lower walls are opposite so that B' adds to the magnetic field B of the normal TE mode at the upper side, and subtracts from it at the lower side. The Hall current j produces a space charge leading to a Hall field in the crystal. This "Hall" space charge and its Hall field, however, are not in the same phase as $E_\perp$, because the time constant for charging up the capacitance between the input and output boundaries is larger than the microwave period. The phase of the Hall field thus lags that of $E_\perp$ by $\pi/2$.

At time t_1, (one-quarter period later), the maximum "Hall" space charge results in an electric field equal to E_H at the outside of the crystal and the y component of E_H is reduced by $E_\perp$ near the lower wall. $B'+B$ at the upper wall is zero, and thus $\partial(B'+B)/\partial t$ is a maximum there. $\partial(B'+B)/\partial t$ produces a rotational electric field, E_r, that adds to E_H outside of the crystal but subtracts from E_H inside the crystal. Thus E_H+E_r exists only near the upper wall. At time t_2, (one-half period after t_0), E_H+E_r becomes zero and $\partial(E_H+E_r)/\partial t$ a maximum, contributing displacement current to the drift current, j.

The rotational magnetic field B'' produced by $\partial(E_H+E_r)/\partial t$ has the same effect as B', concentrating the field to the upper wall. $E_\perp$ exists in the crystal only near the upper side at t_2 because of the negative space charge, as explained in earlier papers by Toda [5], and Hirota [6]. Thus the field distribution outside of the crystal is also concentrated to one waveguide wall near the crystal, and the fields are consistently related to the mode inside the crystal through the boundary conditions.

The problem outlined is difficult to solve analytically. The physical picture indicates that the short solid-state plasma waveguide may be used as an isolator, if one of the copper walls along which the waves will propagate is replaced by absorbent material. It should also be possible to make an isolator using two absorbers mounted at the input and output sides of the crystal, near the one side of the waveguide wall along which waves travelling in the undersirable direction normally propagate.

To decrease the loss due to reflection, it is necessary to match the impedance of the solid-state plasma waveguide to that of the main waveguide. The solid has an effective height E direction less than that of the main waveguide, because of the presence of the plasma in the magnetic field. The necessary and sufficient conditions for matching are therefore that in the solid, the maximum voltage V between the upper and lower walls and the total current I through the walls be equal to those of the ordinary waveguide.

A plate of n-InSb single crystal ($n_0=8\times10^{13}$ cm^{-3}) was mounted in the tapered waveguide as shown in Fig. 2. All the experiments were done at 77°K. The side of the plate along which microwaves should propagate was plated with copper. The other side was covered by a silicone grease-carbon powder compound.

The attenuation of the transmitted microwave power is indicated by the curve (a) in Fig. 3, when the magnetic field direction was B_{01} in Fig. 2. In this case, the microwave fields are transmitted along the upper side of the crystal where copper plating is present. Curve (b) shows the attenuation for the magnetic field in the B_{02} direction, when the transmission is along the lower surface, i.e., along the vertical copper plating and the absorbing carbon powder. If the propagation direction of the microwaves is reversed, the microwave power should be absorbed for the magnetic field direction B_{01}, because of the symmetry of the system. Thus, this device has the properties of an isolator.

The forward loss does not decrease for magnetic fields in excess of 7kGs, presumably because it is a result of mismatch, since the absorption in the InSb has become very small at these strong magnetic fields. The backward transmission increases with increasing magnetic field. This transmission could be due to: 1) incomplete absorption due to reflection at the boundary between the crystal and the "carbon grease, "2) the increasing plasma volume containing the wave because of the increased resistance of the InSb in strong magnetic fields and/or 3) a cutoff mode which passes because of the short length. Theory [6] gives the effective distance of microwave falloff from the surface as 1 mm at 10 kGs. Since this isolator had a distance between surfaces of only 2 mm, there could be a large backward leakage.

The calculated decay constant, γ_y,

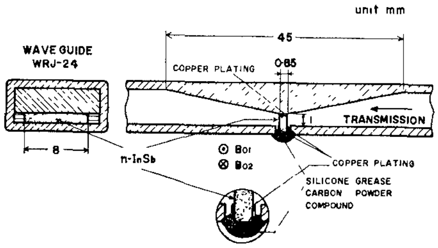

Fig. 2. Physical arrangement of the isolator in the waveguide.

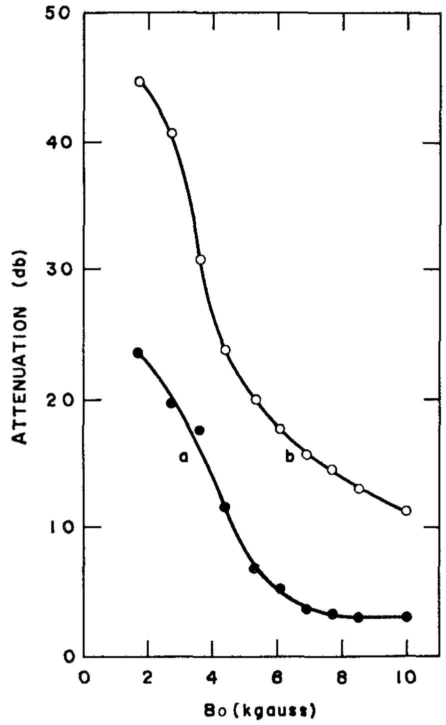

Fig. 3. Measured attenuation of microwave fields as a function of the magnetic field for forward (a) and reversed (b) directions of field. Curves (a) and (b) correspond to the directions B_{01} and B_{02}, respectively, as shown in Fig. 2.

agrees reasonably well with experiments, but the losses observed are larger than those calculated assuming an ideal, nonsaturating magnetoresistance. The use of experimental values of the magnetoresistance gives closer agreement between theory and experiment. γ_y is determined only by the drift current j and the Hall field and its theoretical value, therefore, may be used with some confidence in designing resultant devices.

Even though the length of the plasma waveguide in this device is much shorter than the wave length in the crystal (3 to 4 mm), we have observed strong nonreciporcal properties. This means that the propagation mode reported previously [5] is not impaired by the boundaries at the input and output of the plasma waveguide, as discussed above, and that further improvements in insertion loss and isolation should be possible.

ACKNOWLEDGMENT

The author wishes to thank Drs. R. Hirota and M. Glicksman for many helpful discussions.

MINORU TODA
RCA Laboratories Inc.
Tokyo, Japan

REFERENCES

[1] Hogan, C. L., The ferromagnetic Faraday effect at microwave frequencies and its applications—the microwave gyrator, *Bell Sys. Tech. J.*, vol 31, Jan 1952, pp 1–31.
[2] Hogan, C. L., The ferromagnetic Faraday effect at microwave frequencies and its applications, *Rev. Mod. Phys.*, vol 25, Jan 1953, pp 253–263.
[3] Goldstein, L., M. Lampert, and J. Heney, Magneto-optics of an electron gas with guided microwaves, *Phys. Rev.*, vol 82, Jun, 1951, pp 956–957.
[4] Goldstein, L., Nonreciprocal electromagnetic wave propagation in ionized gaseous media, *IRE Trans. on Microwave Theory and Techniques*, vol MTT-6, Jan 1958, pp 19–29.
[5] Toda, M., Propagation in a solid-state plasma waveguide in a transverse magnetic field, *J. Phys. Soc. Japan*, vol 19, Jul 1964, pp 1126–1130.
[6] Hirota, R., Theory of a solid-state plasma waveguide in a transverse magnetic field, *ibid.*, pp 1130–1134.

Millimeter Resonance Isolator Utilizing Multilayer Ni and NiZn Ferrite Films

This communication describes a significant improvement in the performance of a resonance isolator in the 35-Gc/s frequency region utilizing chemically deposited ferrite films. The performance of a millimeter resonance isolator utilizing single-layer ferrite films was reported earlier [1]. In the device described here an improvement in the isolator performance was achieved by utilizing combinations of Ni and NiZn chemical formulations to form new multilayer ferrite films. A description of the device configuration, isolation characteristics, and modification of previous chemically deposited ferrite film techniques is included.

Each of the multilayer ferrite films tested was 41.5 microns thick, and was deposited on tapered 99.5 per cent aluminum oxide substrates (see Fig. 1). The films were then placed in the region of circular polarization in RG-96/U waveguide, and isolation and insertion-loss characteristics were measured as a function of frequency (see Fig. 2). The greatest reverse-to-forward loss ratio obtained was 124 to 1 at 34.5 Gc/s, where the isolation was 62 dB. A maximum insertion loss of 0.9 dB was obtained across the 20-dB level, representing more than 20-dB isolation across a 9.2 per cent bandwidth. It is also to be noted that the dielectric losses of the 99.5 per cent Al_2O_3 substrate materials currently used were much less compared with the 96 per cent Al_2O_3 substrates reported earlier by Wade, et al. [1], and may be one reason for the reduction of insertion losses.

These new multilayer ferrite films were formed by chemical deposition techniques previously used in making single-layer ferrite films, with one modification. This modification consisted of the addition of distilled water to liquified stock solutions to keep then in a more stable liquid state and thus avoid changes in the required chemical concentration [2]. The two techniques employed in depositing multilayer ferrite films consisted of 1) coating a substrate with

Manuscript received August 28, 1964.