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 ($n_0 = 8 \times 10^{13}$ 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,

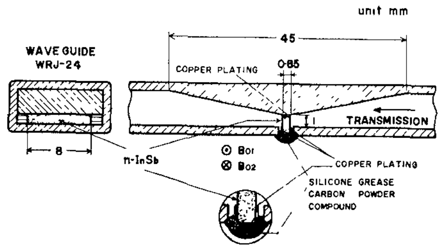

Fig. 2. Physical arrangement of the isolator in the waveguide.

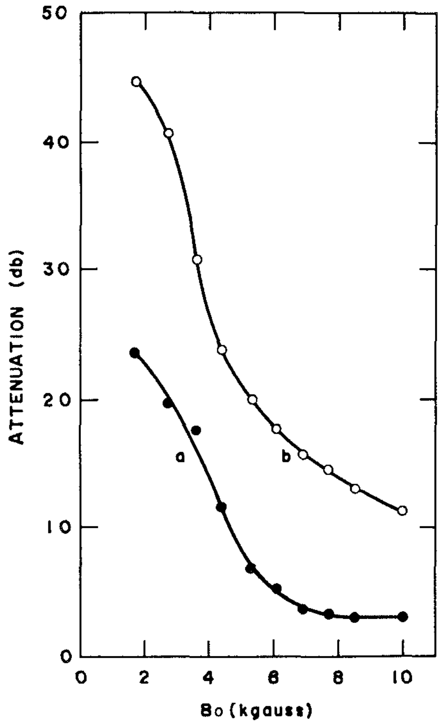

Fig. 3. Measured attenuation of microwave fields as a function of the magnetic field for forward (a) and reversed (b) directions of field. Curves (a) and (b) correspond to the directions B_{01} and B_{02}, respectively, as shown in Fig. 2.

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.

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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

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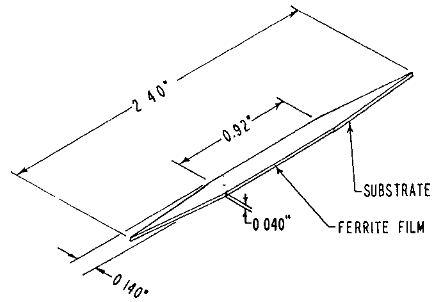

Fig. 1. Ferrite-dielectric configuration.

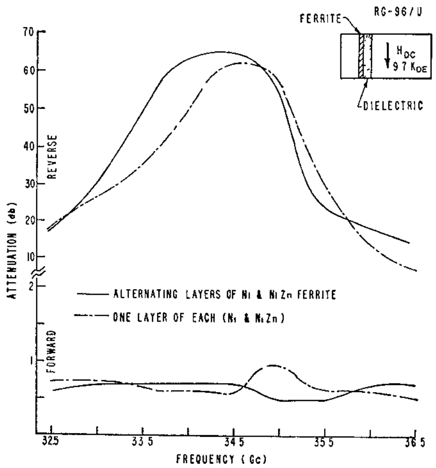

Fig. 2. Isolation characteristics.

alternating layers of Ni and NiZn (74 alternating layers resulting in 41.5 microns ferrite thickness), and 2) the deposition of 20.75 microns of Ni film on a substrate and then an additional deposition of 20.75 microns of NiZn film, resulting in a composite layer of 41.5 microns thickness.

The large reverse-to-forward loss ratios and increased bandwidth obtained with the new multilayer ferrite films represent a significant improvement in nonreciprocal properties over the single-layer ferrite films. The techniques for depositing these two different ferrite films can now be extended to include several different compositions in order to obtain high reverse attenuation over considerable bandwidths with low insertion losses.

It is also to be noted that chemically deposited multilayer ferrite films will have advantages over thin ferrite bulk sections for applications where the magnetic field required is fixed and unsuitable for broadbanding purposes such as in traveling-wave masers.

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Temperature Calibration of Microwave Thermal Noise Sources

The theory of microwave thermal terminations is discussed with emphasis on equivalent noise temperature calibrations.

The general expression is given for the equivalent noise temperature with an arbitrary temperature and loss distribution. This expression is solved for a constant loss various temperature distributions, and the results are tabulated. An error analysis is presented to show the importance of the insertion-loss calibrations.

An example is given showing a liquid-helium-cooled S-band termination calibrated with these techniques. The input equivalent noise temperature is determined to an accuracy of better than 0.1°K.

Introduction

Thermal noise sources of known absolute equivalent noise temperatures are needed [1]–[3] for radiometry, antenna temperature measurements, and low-noise amplifier performance evaluation. One form of thermal noise source consists of a uniform transmission line with distributed temperature and power loss terminated by a matched resistive element. Nyquist's theorem states that the available thermal noise power from the termination is given by kTB (assuming $hf/kT \gg 1$) where

k = Boltzmann's constant (1.38×10^{-23} J/°K)
T = temperature of the termination in °K
B = bandwidth in c/s
f = operating frequency in c/s
h = Planck's constant (6.624×10^{-34} J/s).

A method is presented for calculating the increase of equivalent noise temperature of a cooled microwave termination due to distributed temperature and transmission-line attenuation. The general equation is solved for various applicable temperature and attenuation distributions, and approximate expressions are given for low-loss transmission lines.

It is assumed that the transmission line is terminated in a matched load so that mismatch errors [4], [5] can be neglected. The temperature calibration error resulting from the transmission-line-attenuation measurement error is shown to be about 0.010°K for each 0.002 dB.

Transmission Line With Distributed Temperature and Attenuation

The differential equation for a traveling wave of power P toward positive x (Fig. 1) in a transmission line with attenuation $\alpha(x)$ and temperature $T_L(x)$ is [6, Eq. (20)].

$$dP/dx = -2\alpha(x)P + 2\alpha(x)kT_L(x)B \quad (1)$$

Substituting $P = kT_xB$ from Nyquist's theorem and dividing by kB, the differential equation in terms of equivalent noise temperature T_x is

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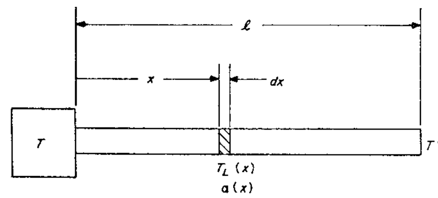

Fig. 1. Lossy transmission line, with attenuation and temperature each a function of position.

$$(dT_x/dx) + 2\alpha(x)T_x = 2\alpha(x)T_L(x) \quad (2)$$

This is a linear first-order differential equation with the solution [7]

$$T' = \frac{T + \int_0^l 2\alpha(x)T_L(x)e^{\int 2\alpha(x)dx}dx}{\left[e^{\int 2\alpha(x)dx}\right]_{x=l}} \quad (3)$$

for a transmission line of length l, with input and output equivalent noise temperatures T and T'.

If $T_L(x) = T_0$ and $\alpha(x) = \alpha$ are constant,

$$e^{\int 2\alpha dx} = e^{2\alpha x}$$

and

$$\begin{aligned} T' &= \frac{T + T_0(e^{2\alpha l} - 1)}{e^{2\alpha l}} \\ &= Te^{-2\alpha l} + T_0(1 - e^{-2\alpha l}) \end{aligned} \quad (4)$$

or

$$\begin{aligned} T' &= T + (T_0 - T)(1 - e^{-2\alpha l}) \\ &= T_0\left(1 - \frac{1}{L}\right) + \frac{1}{L}T \end{aligned}$$

Here, $e^{2\alpha l}$ is the insertion-loss ratio L.

If the transmission-line loss is small $2\alpha l \ll 1$,

$$e^{-2\alpha l} = 1 - 2\alpha l + \frac{(2\alpha l)^2}{2} + \cdots$$

and

$$\begin{aligned} T' &= T + (T_0 - T)2\alpha l \\ &\quad - \frac{(T_0 - T)}{2}(2\alpha l)^2 + \cdots \end{aligned} \quad (5)$$

Since

$$2\alpha l = \frac{L(\mathrm{dB})}{10 \log_{10} e} \simeq \frac{L(\mathrm{dB})}{4.343}$$

we have

$$\begin{aligned} T' &\simeq T + (T_0 - T)\frac{L(\mathrm{dB})}{4.343} \\ &\quad - \frac{(T_0 - T)}{2}\left[\frac{L(\mathrm{dB})}{4.343}\right]^2 + \cdots \end{aligned} \quad (6)$$

The terms involving L^2(dB) and higher order are normally dropped in calculations, but the L^2(dB) term is retained here for use in evaluating the error involved in the series expansion. For example, with $L = 0.1$ dB, $T_0 = 290$°K, and $T = 0$°K, the error is less than 0.1°K.

For the case with constant attenuation $\alpha(x) = \alpha$, but retaining an arbitrary temperature distribution, (3) gives

$$T' = \frac{T + \int_0^l 2\alpha e^{2\alpha x}T_L(x)dx}{e^{2\alpha l}} \quad (7)$$

With constant attenuation and a linear tem-