NONRECIPROCAL EFFECTS IN SEMICONDUCTOR LOADED WAVEGUIDE AT MILLIMETER WAVELENGTHS

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Summary

Nonreciprocal propagation in a waveguide partially loaded with a semiconductor slab in a transverse D.C. magnetic field at 92 GHz is investigated. A model was developed to predict the propagation characteristics and experiments were conducted for comparison. Experimental data for a Si semiconductor slab are reported, which show increased nonreciprocal attenuation when carrier mobility is increased.

Introduction

Now that millimeter wave systems are being investigated at frequencies where ferrite component performance is diminished, it is desirable to examine some alternative means to achieve nonreciprocal behavior. The purpose of this work is to investigate the nonreciprocal effects caused by partial loading of waveguides with semiconductors in a transverse magnetic field at 92 GHz.

The geometry studied is shown in Figure 1, which illustrates a metallic waveguide inhomogeneously loaded with a semiconductor slab in the presence of a magnetic field, $\vec{B}$, parallel to the slab surface. The semiconductor has an asymmetric permittivity tensor of the form (1):

$$\bar{\bar{\varepsilon}} = \begin{bmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & \varepsilon_3 \\ 0 & -\varepsilon_3 & \varepsilon_2 \end{bmatrix}$$

whose elements depend upon the carrier concentration, mobility, and permittivity of the semiconductor and the applied magnetic field.

If the slab loading is asymmetric with respect to the top and bottom of the waveguide, there will be more power transmitted for one direction of propagation than the other due to displacement of the electromagnetic fields. Hence, nonreciprocal propagation occurs. The mechanism of this unequal distribution of power can be analyzed in terms of the coupling of higher order modes (i.e. TE_{01}, TE_{11}, TM_{11}, etc.) with the dominant TE_{10} mode via the off-diagonal permittivity tensor elements (1,2).

An important requirement for effective interaction between the semiconductor and the incident electromagnetic field is for the ratio of the cyclotron frequency of the electrons (ω_c) and their phenomenological collision rate ($1/\tau$) with scatterers in the medium to be greater than unity, i.e. $\omega_c\tau > 1$ (3). Free carrier motion is damped for $\omega_c\tau < 1$. Structures were investigated both at room and liquid nitrogen temperatures to study the effects of $\omega_c\tau \lessgtr 1$, respectively: $\omega_c\tau$ increases at liquid nitrogen temperatures since ω_c increases with electron mobility.

Theoretical Predictions

A computer algorithm was developed which solves for the propagation constant of the coupled TE_{10} and TM_{11} modes in the semiconductor loaded waveguide (1). The TE_{10} mode is important since it is the dominant mode of the empty waveguide. The permittivity tensor elements ε_3 and $-\varepsilon_3$ will cause the TE_{10} mode to be coupled to the TM modes, with the TM_{11} mode coupled most strongly due to its low cutoff frequency.

In Figure 2, the predicted attenuation constants of a 10 µm and a 100 µm thick slab of 10^{16} cm^{-3} Si are plotted as functions of the transverse magnetic field strength. Important quantities obtained from these plots are the attenuation constant, α, for $B_o = 0$ and the absolute change in the attenuation constant, $|\Delta\alpha|$, for propagation in opposite directions when $B_o > 0$. The coordinate system used for the H-plane loading is shown in Figure 1 where the magnetic field is parallel to the $\hat{a}_x$ axis and propagation is parallel to the $\hat{a}_z$ axis. The two attenuation constant branches for each slab are labeled with a $\pm\hat{a}_z$ to denote the direction of propagation. In our experiments a 10 KG transverse magnetic field was used.

Experimental Results

Typical experimental results at room temperature are plotted in Figure 3, which shows the transmitted power (normalized to 1 mW for $B_o = 0$) versus the applied magnetic field for an n^--type Si semiconductor slab. This figure is the experimental equivalent of Figure 2. For comparison the theoretical results are also plotted in Figure 3, and it is seen that the predictions agree qualitatively with the experimental results showing that for one direction of propagation the transmitted power will increase if $B_o > 0$, and decrease for propagation in the other direction. The disagreement between the predicted and experimental data has been explained by the imperfect fit of the slab in the waveguide.

Figure 4 shows the attenuation constant as a function of carrier concentration for a Si slab 250 µm thick. The solid curve shows the predicted value of α for $B_o = 0$ at room temperature, while the dashed curves show the effect of increased

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mobility obtained by reducing the sample temperature to 77°K. Also plotted on the same figure are the theoretical forward and reverse propagation attenuation characteristics at 77°K for B_o = 10 KG. The theoretical change in attenuation at room temperature when B_o = 10 KG is too minor to be distinguished from the B_o = curve, thus they are not shown. Experimental results are indicated by open circles. Notice that the measured zero field attenuation improves by 18.7 dB for a 1 cm long sample. The measured forward loss of this sample was 4.2 dB while the reverse loss was 13.0 dB leading to 8.8 dB of isolation. These results suggest that the use of a high mobility semiconductor at room temperature having a carrier concentration in the region of 10^{14} - 10^{15} cm^{-3} might show significant nonreciprocal effects. A possible candidate may be one of the lead salts.

Conclusions

Room temperature millimeter wave nonreciprocal devices based on a semiconductor inhomogeneously loading a waveguide with a transverse magnetic field may be possible if materials which satisfy $\omega_c \tau > 1$ can be found. Other factors that may enhance nonreciprocal effects are slab and waveguide geometries which might support modes that are strongly affected by semiconductor loading, such as the TM_{11} mode.

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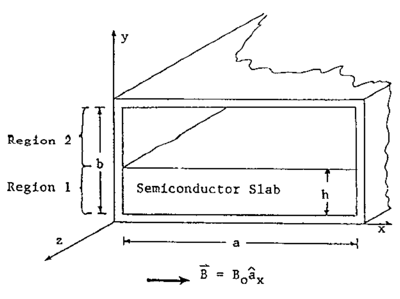

FIGURE 1. The H-plane loading geometry.

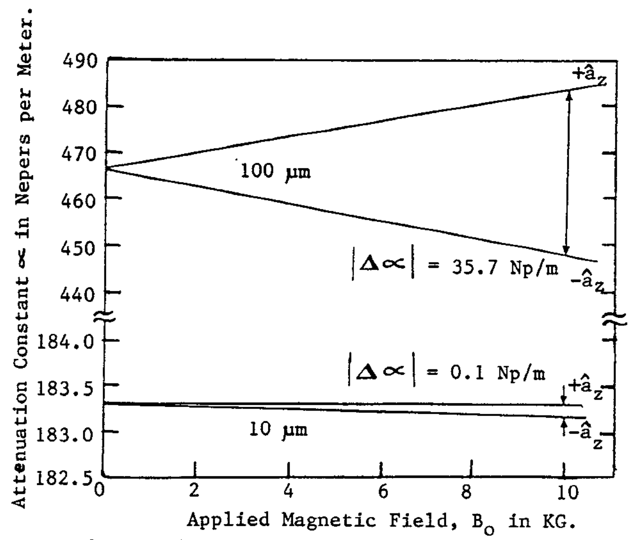

FIGURE 2. Predicted attenuation constant versus magnetic field strength for a 10 µm and a 100 µm thick slab of Si.

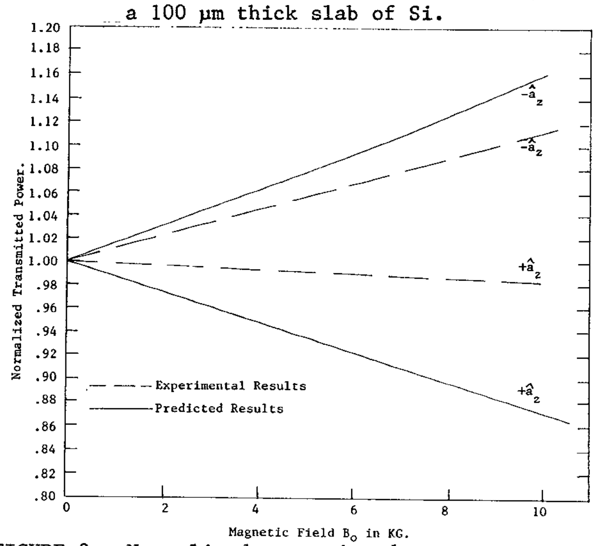

FIGURE 3. Normalized transmitted power versus magnetic field for a 180 µm thick slab of 2×10^{14} cm^{-3} Si.

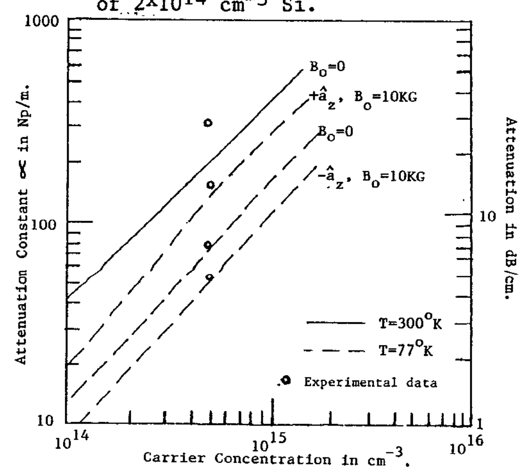

FIGURE 4. Attenuation versus carrier concentration for a 250 µm thick slab of Si.