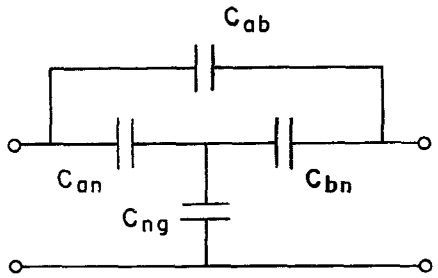

Fig. 2. Capacitance network at an arbitrary cross section of coupled lines.

The static capacitance network of the coupled lines at an arbitrary cross section of the geometries of Fig. 1(a), (b), and (c), is given in Fig. 2. In this figure, C_{an} is the capacitance between line a and the shield; C_{bn} is similarly defined for line b; C_{ab} is the mutual capacitance between lines a and b; and C_{ng} is the total capacitance between the shield and ground. It is assumed that the shield is long enough that direct capacitance between line a or b and ground is negligible.

The relationship between the several static capacitances and the even-mode, odd-mode admittances (or capacitances) are given in the following equations. Define the parameters α, β, γ as follows:

$$\alpha = \left\{ \frac{376.7Y}{\sqrt{\varepsilon_r}} Y_{oe}^{a} \right\}, \tag{2}$$

$$\beta = \left\{ \frac{376.7}{\sqrt{\varepsilon_r}} Y_{oe}^{b} \right\}, \tag{3}$$

$$\gamma = \left\{ \frac{376.7}{\sqrt{\varepsilon_r}} \left[\frac{Y_{oo}^{b} - Y_{oe}^{b}}{2} \right] - \frac{C_{ab}}{\varepsilon} \right\}. \tag{4}$$

Choose a convenient value[1] for C_{ab}/ε. Then,

$$C_{an}/\varepsilon = \alpha + \gamma + (\alpha/\beta)\gamma, \tag{5}$$

$$C_{bn}/\varepsilon = \beta + \gamma + (\beta/\alpha)\gamma, \tag{6}$$

$$C_{ng}/\varepsilon = \alpha + \beta + (\alpha/\beta)\gamma. \tag{7}$$

To relate the normalized capacitances C_{an}/ε, C_{bn}/ε, and C_{ab}/ε to geometric dimensions using graphs or experimental methods, use the network of the shield and coupled lines a and b, considered alone (i.e., without the ground plane), as a coupled pair of transmission lines. To relate C_{ng}/ε to geometric dimensions, use the network of the ground planes and shield, considered as a single transmission line (i.e., the shield is excited in the even mode with respect to the ground plane).

As a check on (5), (6), and (7), it can be verified that for symmetrical lines (i.e., $\alpha = \beta$) the equations reduce to those previously given [10]. Furthermore, for symmetrical lines and also $C_{ab}/\varepsilon = 0$, the equations are equivalent to those given by Cohn [6] for the case of directional couplers.

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[1] C_{ab}/ε must be small enough for C_{an}/ε, C_{bn}/ε, and C_{ng}/ε in (5), (6), and (7) to be positive. Typically, $0 \leq C_{ab}/\varepsilon \leq 3$.

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Circulator Action at 140 GHz in a Semiconductor Loaded Waveguide Junction

***Abstract*—Circulator action has been observed in an *E*-plane "Y" waveguide junction having an InSb rod aligned with the principal symmetry axis of the junction. With the junction cooled to 77°K, typical isolations of 14–17 dB have been obtained at 138.5–140.1 GHz by applying a 10.5-kG magnetic field along the symmetry axis. Standing wave ratio was 1.92 at the input port but showed an unexplained decrease to 1.27 at a temperature slightly above 77°K. When the apparatus was warmed up to room temperature, only reciprocal behavior was observed.**

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In this correspondence we report our observation of circulator action in a semiconductor loaded E-plane "Y" junction. The experiment was carried out at a wavelength of 2.2 mm, and typical isolations of 14–17 dB were observed. The semiconducting sample was an indium antimonide post aligned with the principal symmetry axis of the junction.

The experiment was suggested by previous work on a gas plasma[1] in which a low-density plasma was similarly located in a junction and nonreciprocity was observed at 3-cm wavelengths.

The basic thesis is that the anisotropic material removes the degeneracy associated with the two counter-rotating polarizations along the principal symmetry axis of the junction. A measure of the anisotropy is the value of the off-diagonal component of the conductivity tensor[2]

$$\sigma_{31} = \frac{\mu B \sigma_0}{(\mu B)^2 + (1 + j\omega\tau)^2},$$

where μB is the product of the mobility and static magnetic flux density, σ_0 is the dc conductivity, and $\omega\tau$ is the product of observing frequency and relaxation time.

A survey of high-mobility semiconductor materials indicated that indium antimonide would be a likely candidate for this experiment. A computation of the complex off-diagonal component of the tensor with the following values:

$$\mu = 2.6 \times 10^5 \text{ cm}^2/\text{V} \cdot \text{s},$$
$$\tau = 2.07 \times 10^{-12} \text{ s},$$
$$\sigma_0 = 95.5 \, (\Omega \cdot \text{cm})^{-1}$$

has been carried out, and a graph of the complex component is shown in Fig. 1. The graph contains both the real and imaginary parts of the conductivity tensor element and the range of μB over which the experiment was carried out.

A rod of indium antimonide was placed in the center of a milled brass "Y" junction and placed in a styrofoam Dewar. At 77°K, experiments were performed to measure the insertion loss between an input port and two output ports as a function of the magnetic field.

The results of this experiment are shown in Figs. 2 and 3. The zero field losses in the empty junction and the connecting guides have been subtracted from the overall insertion loss. The insertion loss in the figure therefore represents only the contribution of the anisotropic semiconductor. The discrepancy in zero field insertion loss between the two graphs is probably due to misalignment of the rod.

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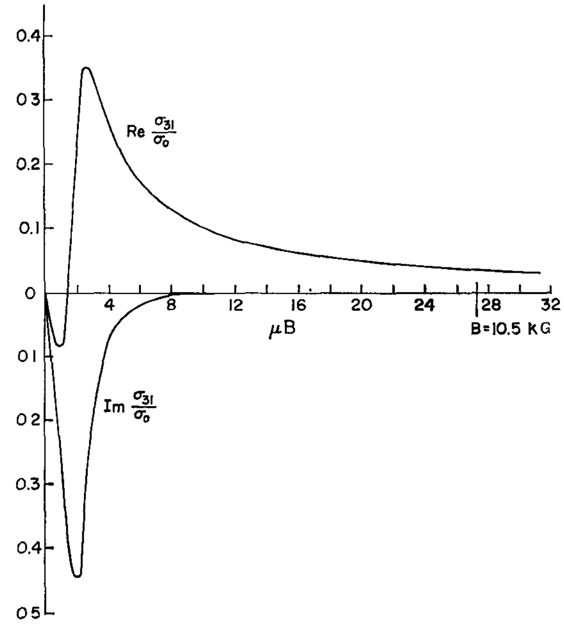

Fig 1. Magnitude of real and imaginary parts of the normalized off-diagonal component σ_{31}/σ_0 of the complex conductivity tensor versus magnetic field-mobility product μB.

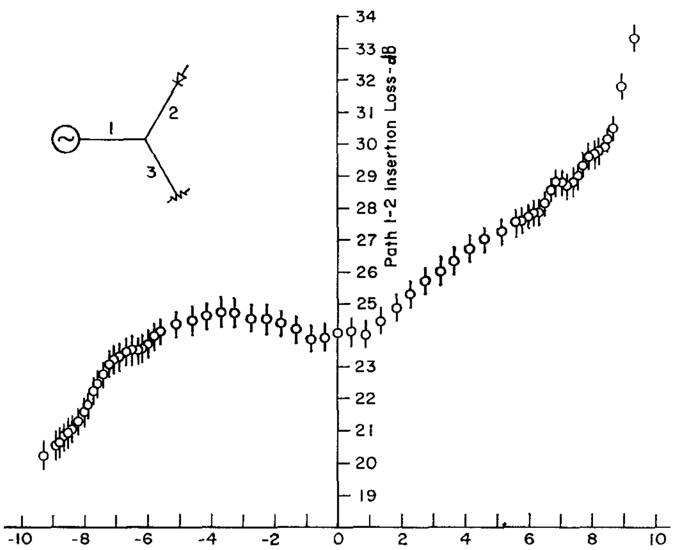

Fig 2. Insertion loss from port 1 to port 2 of the circulator versus applied magnetic field at 138.5 GHz and 77°K.

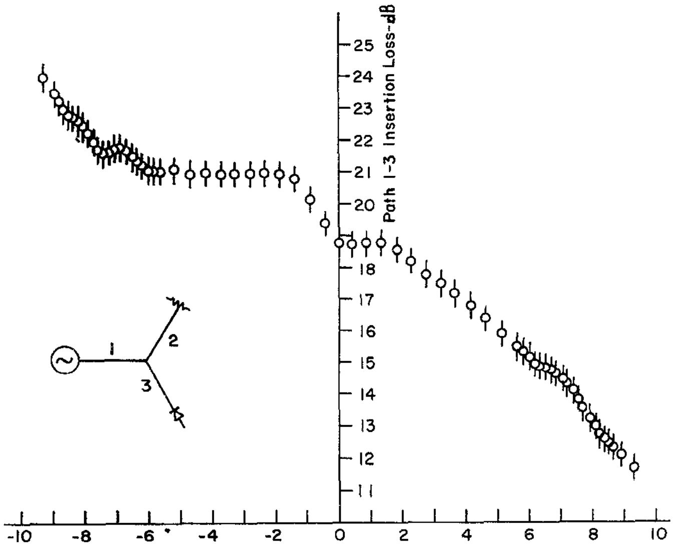

Fig. 3. Insertion loss from port 1 to port 3 of the circulator versus applied magnetic field at 138.5 GHz and 77°K.

The reflection coefficient at the input port was also measured and it was found that the zero field standing wave ratio was 1.92 and decreased slightly as the magnetic field was increased. This result suggests that the losses in the waveguide, sample, and junction effectively mask any significant magnetic field dependence of the reflections from the junction. When the apparatus was warmed up to room temperature, it was found that the attenuation decreased with magnetic field in a manner consistent with the strong magnetoresistive effect in indium antimonide. At room temperature, only reciprocal behavior was observed. The nonreciprocal effects decreased monotonically with increasing temperature, the only noteworthy result being an unexplained decrease in input standing wave ratio to 1.27 at a temperature slightly above 77°K. As the frequency was varied between 138.5 and 140.1 GHz, no strong frequency-dependent effects were observed.

The junction was milled in two halves from brass and joined by contact flanges to standard U/G 138 waveguide. A rod was spark cut from single-crystal indium antimonide, ground down to a 0.046-inch diameter, and cut to 0.080-inch length. The rod filled the center of the junction that was sealed with mica windows, evacuated through a 0.006-inch slot in the connecting waveguide, and placed in a styrofoam Dewar. The junction was excited at one arm by a Varian VC-715R millimeter wave klystron, modulated with a 1.0-kHz square wave. Power was measured by a bolometer on one arm, with a matched termination placed on the other arm. The reflection data was obtained at the input arm by using a directional coupler in a reflectometer arrangement.

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