Short Papers

Nonreciprocal Properties of Vacuum-Deposited InSb Films at 87 GHz

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***Abstract*—Room-temperature measurements were taken at 87 GHz on isolators fabricated by using thin vacuum-deposited hot-wire-recrystallized InSb films in both the Faraday-rotation mode and the field-displacement mode. In the Faraday-rotation mode, an insertion loss of 9 dB, a nonreciprocity of 10 dB, and an isolation of 19 dB were obtained in an external magnetic field of 8 kOe.**

INTRODUCTION

In an earlier publication [1] we reported work on the application of InSb films in isolators of the field-displacement type at frequencies near 24 GHz. In this short paper we discuss recent efforts to use the nonreciprocal properties of InSb films in isolators at 87 GHz. In addition to the field-displacement configuration [2], measurements were also made on films in the Faraday-rotation configuration. Although neither configuration gives an isolator with a totally satisfactory performance at 87 GHz, the possibility of using the same principle of operation into the infrared (at least to 10-μm wavelengths) makes the use of thin InSb films in the superior Faraday-rotation mode worthy of further study.

The InSb films used in the present work had somewhat better properties than the InSb films used for the work reported in [1]. The films were vacuum deposited on glass substrates and then recrystallized by slowly moving a hot wire, which is immediately above the film surface, along the length of the substrate. The preparation technique is described in [3]. The samples were cut from four different films having room-temperature mobilities (measured by the van der Pauw method) ranging from $\mu = 5\times10^4$ to 6.3×10^4 cm^2/V·s, carrier concentrations of $n = 10^{16}$ to 3×10^{16} cm^{-3}, and thicknesses of 2 μm to 10 μm.

All data reported here were taken at room temperature and at a frequency of 87 GHz. The millimeter-wave circuit used to measure the insertion loss and nonreciprocity was similar to the circuit used in [1]. As in [1], an *E–H* tuner and phase shifter were used ahead of the film as a matching network. As before, matching the film at zero magnetic field matched the film at all fields.

FIELD-DISPLACEMENT MODE

The field-displacement mode configuration used here is shown in Fig. 1(a). Fig. 2 is a graph of insertion loss versus *H* for film 884A. As is evident the insertion loss is quite large, being 18.8 dB at the optimum operating point of 12.5 kOe. Generally similar results were obtained on other samples.

The film shape and carbon overlay parameters were varied in in an attempt to find an optimum, but no improvement over the results in Fig. 2 could be obtained. Unfortunately, the field-displacement configuration seems to be singularily unamenable to theoretical analysis and one is limited to "cut-and-try" methods.

A large fraction of the insertion loss is traceable to the substrate. Whereas at 24 GHz [1] the effect of the substrate was completely negligible, at 87 GHz a bare substrate was found to have a loss of 3 dB. The substrates were Corning 7059 glass, 0.81-mm thick. Pos-

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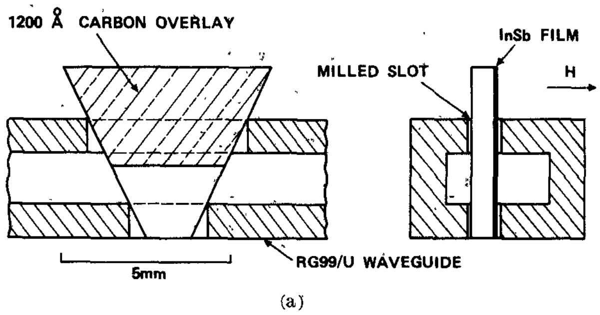

Fig. 1. (a) Diagram, to scale, of InSb film in *E*-band waveguide for the field displacement mode. Film dimensions: lower base, 1.40 mm; upper base, 6.0 mm; altitude, 5.1 mm. (b) Diagram, to scale, of InSb film in TE_{11}-mode circular waveguide. Inside dimension of waveguide is 3.58 mm. To the left, the circular waveguide meets a circular-to-rectangular transition, preceded by a rectangular 45° twist. To the right, the circular waveguide meets a circular-to-rectangular transition.

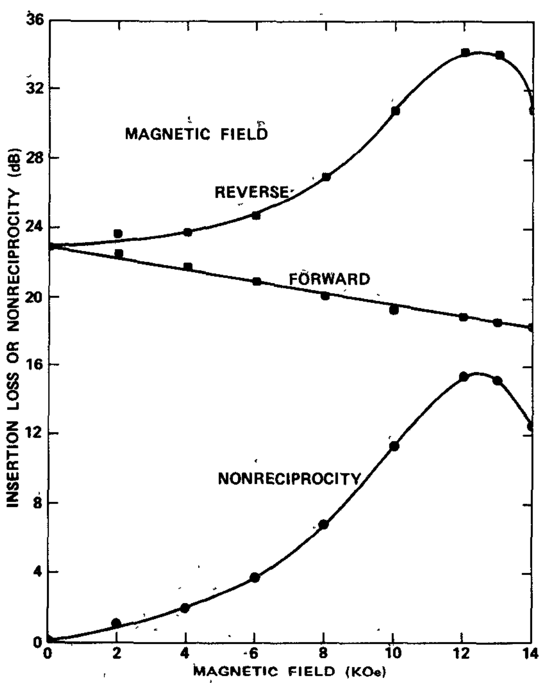

Fig. 2. Plot of insertion loss and nonreciprocity versus applied magnetic field for film 884 A in the field-displacement configuration. The nonreciprocity curve is the difference between the forward and reverse insertion-loss curves. Film parameters: $d = 6.1$ μm, $\mu = 6.3 \times 10^4$ cm^2/V·s, and $n = 3 \times 10^{16}$ cm^{-3}.

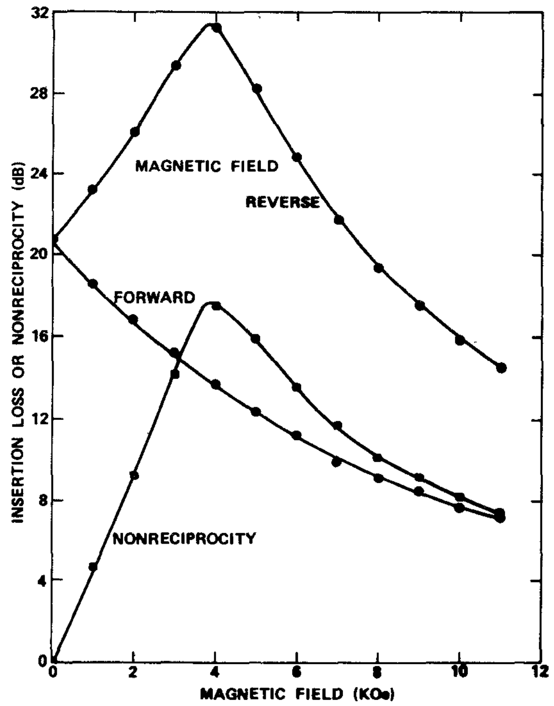

Fig. 3. Plot of insertion loss and nonreciprocity versus applied magnetic field for film 878 in the Faraday-rotation configuration with standard-size circular waveguide. The nonreciprocity curve is the difference between the forward and reverse insertion-loss curves. Film parameters: $d = 2\ \mu m$, $\mu = 5.3 \times 10^4\ cm^2/V \cdot s$, and $n = 1.2 \times 10^{16}\ cm^{-3}$.

sibly a better substrate for millimeter-wave transmission would be quartz. Unfortunately, however, quartz is not compatible with the recrystallization growth technique, because its thermal expansion coefficient is considerably different than the coefficient for InSb, and the InSb films tend to peel away from the quartz substrate.

FARADAY-ROTATION MODE

The Faraday-rotation mode configuration is shown in Fig. 1(b), and results for the Faraday-rotation mode are shown in Fig. 3. As is evident, large values of nonreciprocity are easily obtainable at relatively low magnetic fields. Very disappointing, however, are the relatively large values of insertion loss encountered, albeit they are significantly lower than the values of insertion loss for the field-displacement mode. The peak in transmission is expected and corresponds to the magnetic-field value at which the Faraday rotation in the InSb film is approximately equal to 45°. It is near this magnetic-field value that the nonreciprocity is a maximum and would be the operating point of a practical isolater. The theory of Faraday rotation in thin films, which is discussed in [4]–[7], accounts for the large values of rotation by considering multiple reflections within the film. The results in Fig. 3 were obtained on samples in standard size TE_{11} commercial waveguide (diameter is 3.58 mm). Measurements taken on samples in oversized guide (diameter is 7.1 mm) did not produce significantly different results. Essentially, the only method available to decrease the insertion loss is to make the film thinner. However, as the films are made thinner, the mobilities decrease and the extrinsic carrier concentration increases. The thickness of the films for which data are shown in Fig. 3 is 2.1 μm and is essentially as thin as the films can be grown and still have acceptable mobilities and carrier concentrations. The insertion loss due to a bare substrate in the Faraday-rotation mode is about 2 dB. A small decrease in insertion loss could be realized by using a less lossy substrate material.

CONCLUSIONS

Large values of nonreciprocity were measured for the InSb films in the Faraday-rotation mode, and these large values were obtainable at reasonably low values of the applied magnetic field. An insertion loss of 9 dB was measured, which includes 2 dB of attenuation due to the substrate, at a nonreciprocity of 10 dB. Commercially available ferrite isolators in this frequency range have insertion losses of 1.0 dB. Possibly, with a less lossy substrate material and with a high-mobility film which is 1 μm or less thick, this figure could be approached. Insertion loss with the field-displacement mode was disappointingly large and all attempts to decrease it failed.

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Moment Method of Calculating Discontinuity Inductance of Microstrip Right-Angled Bends

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***Abstract*—A method of estimating quasi-static discontinuity inductances in microstrip lines is outlined. Numerical results for symmetric right-angle bends are presented and compare well with experimental results.**

I. INTRODUCTION

The study of microstrip discontinuities has resulted in several papers [1]–[4] which evaluate the capacitive components of the discontinuity equivalent circuits, under static conditions. Estimating the inductive components of these equivalent circuits has received little attention to the present time. One method based on charge estimates [5], [6] is not rigorous and the results and trends published are not in agreement with experimental measurements obtained by the method of a previous publication [7]. A second method is the evaluation of these inductances based on a skin-effect formulation [8], but several difficulties have been encountered in extending this method to the accurate evaluation of discontinuity inductances. These have currently been resolved, and results are to be published shortly [9]. The present short paper outlines an alternative method based on an extension of the moment method, using current loops as elements. The method also incorporates the excess current (charge) technique used by Benedek and Silvester [10] for preserving the accuracy of calculated parameters. This short paper outlines the formulation used and presents specific results for symmetric right-angled bends. It is hoped a subsequent paper will present a comprehensive set of results of various other discontinuities.

II. STATEMENT OF PROBLEM

The moment method of inductance estimation outlined here can be used for a variety of strip geometries, but is illustrated only for the case of the symmetrical right-angle bend. We first define in the

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