Defense Technical Information Center
Compilation Part Notice

ADP011791

TITLE: Submillimeter-Wave Nonreciprocal Propagation Characteristics in Transversely Magnetized Image Guide and Two-Layer Parallel-Plate Waveguide Containing p- or n-InSb Slab

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: International Conference on Terahertz Electronics [8th], Held in Darmstadt, Germany on 28-29 September 2000

To order the complete compilation report, use: ADA398789

The following component part numbers comprise the compilation report:
ADP011730 thru ADP011799

Submillimeter-Wave Nonreciprocal Propagation Characteristics in Transversely Magnetized Image Guide and Two-Layer Parallel-Plate Waveguide Containing *p*- or *n*-InSb Slab

Shinichi Yodokawa and Tetsuo Obunai

Abstract - **The magnetic field dependence of 526 GHz and 671 GHz submillimeter-wave propagation in waveguides containing InSb slab was studied in detail varying the ambient temperature. It was shown that, at the liquid nitrogen temperature, submillimeter-wave propagation loss is very small, typically 0.3 dB/mm, and that a submillimeter-wave image guide employing *p*-InSb slab may be possible. At the dry ice temperature, slow surface wave resonance clearly appeared, and a nonreciprocity of at least 15 dB was obtained with an insertion loss of 5 dB. The possibility of constructing electrically controllable nonreciprocal devices in submillimeter-wave monolithic integrated circuits is presented.**

I. INTRODUCTION

In a previous paper, [1] we reported that the propagation loss of a 70 GHz millimeter-wave dielectric image guide consisting of a *p*-type InSb slab is extremely small, typically about 0.43 dB/mm, and that the propagation characteristics of this structure can be controlled by generating plasma in the InSb material by means of light irradiation. Our recent results of numerical calculations predict that the submillimeter-wave propagation loss of such a *p*-InSb image guide is far smaller than the above-mentioned value. These results suggest that it is possible to apply this waveguide configuration to the transmission line in the submillimeter-wave range. In this paper, we report the preliminary results of nonreciprocal propagation characteristics of InSb dielectric waveguides. The possibility of constructing nonreciprocal devices embedded in one body in the dielectric waveguide material and of controlling their nonreciprocal propagation characteristics electrically by varying the plasma density are suggested.

II. EXPERIMENTAL PROCEDURE AND APPARATUS

A. Submillimeter-Wave Measuring System

In this work, the characteristics of transmission through the two structures shown in Fig.1 are studied. Fig.1(a) shows a rectangular metal waveguide with the cross-sectional dimensions of 0.3 mm × 1.5 mm where a thin InSb slab of thickness b is inserted as a plasma material with a vacuum gap of thickness a. Fig.1(b) shows an image guide employing an InSb slab in stead of the conventional dielectric material. Transverse static magnetic field B is applied to these waveguides, the direction of which is defined as indicated by B+ and B- in Fig.1. The length L of the InSb sample slab is typically 3.4 mm.

The experimental setup is outlined in Fig.2. The submillimeter-wave source used is a conventional CO_2-excited submillimeter-wave gas laser, and submillimeter outputs of 526 GHz and 671 GHz are obtained by exciting CH_3OH and CH_3I by the 9P16 line and 10P18 line of the CO_2 laser, respectively. The submillimeter laser output is

The authors are with Department of Electrical and Electronic Engineering, Faculty of Engineering and Resource Science, Akita University, Akita 010-8502, Japan.

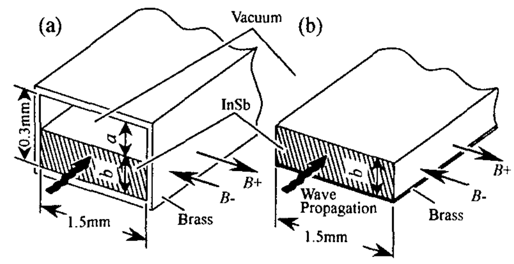

Fig. 1. Two-layer parallel-plate waveguide (a) and image guide structure (b) used in experiments.

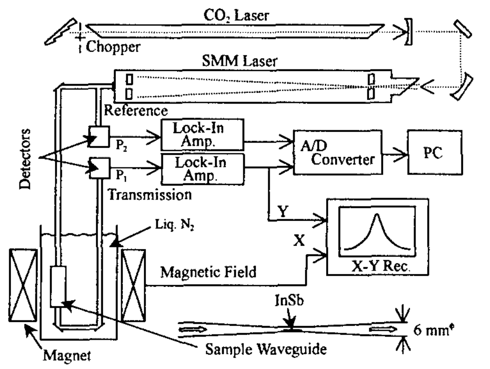

Fig. 2. Schematic of the measurement setup.

introduced into the cryostat through a copper light pipe of 6 mm diameter, and supplied to the sample waveguide through a long taper. In the following, the B-dependence of the transmission, which is defined by the ratio of the outputs of pyrodetectors P_1 and P_2, is mainly discussed for various values of the sample temperature T as the parameter.

B. Carrier Density and Carrier Mobility of Sample

Slabs of *p*-type and *n*-type single-crystalline InSb were used as the solid-plasma material. The hole density n_{h0} and the hole mobility μ_{h0} of the *p*-type material at 77 K are 1.1×10^{20} m^{-3} and 0.7 m^2/(V·s), respectively. The electron density n_{e0} and the electron mobility μ_{e0} of the *n*-type material at 77 K are 1.55×10^{21} m^{-3} and 50.0 m^2/(V·s), respectively.

First, the temperature dependences of carrier density and carrier mobility of the *p*-InSb material determined from the Hall coefficient are plotted in Fig.3. The experimental value of the electron density n_e shows reasonable agreement, especially in the T-region above 200 K, with the empirical expression given by Hrostowski et al. [2]:

$$n_e = n_h = [\, 3.6\times10^{41}\, T^3 \exp(-0.26/kT)\,]^{1/2} . \qquad (1)$$

On the other hand, the theoretical values of the electron and hole mobilities were calculated by assuming $T^{-3/2}$ dependence and by setting their theoretical values at 77 K to be equal to their experimental ones of μ_{e0} = 50 m^2/(V·s) and μ_{h0} = 0.7 m^2/(V·s). The measured value of the carrier mobility shows reasonable agreement with the theoretical values of the holes at T < 120 K, and of the electrons at T > 170 K. Taking these results into account, the electron density and the hole density employed for *p*-InSb used in the following theoretical work

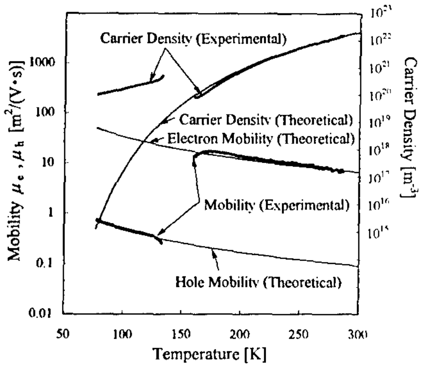

Fig. 3. Carrier density and carrier mobility of the InSb sample as a function of temperature.

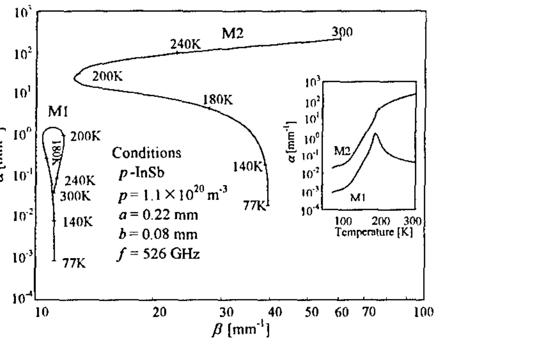

Fig. 4. Loci of γ (= α + jβ) for the two propagation modes with varying temperature (two-layer parallel-plate waveguide structure containing p-InSb at 526 GHz).

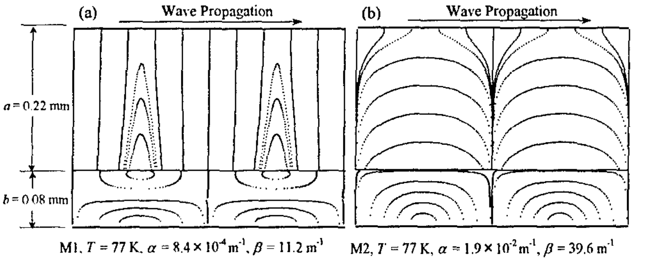

Fig. 5. Electric field distributions of the two propagation modes (two-layer parallel-plate waveguide structure containing p-InSb at 526 GHz).

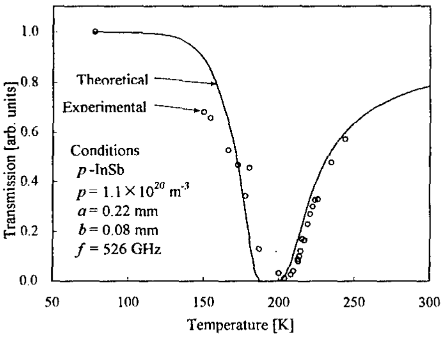

Fig. 6. Variation of the transmission for $B = 0$ as a function of temperature (two-layer parallel-plate waveguide structure containing p-InSb at 526 GHz).

were assumed to be equal to n_e and $n_h + n_{h0}$, respectively, over the whole temperature range, where n_e and n_h represent the empirical values given by eq.(1). Similarly, the electron density and the hole density for n-InSb material were assumed to be equal to $n_e + n_{e0}$ and n_h, respectively. As for the electron and hole mobilities, theoretical values were employed over the entire temperature range. The electron effective mass $m_e^* = 1.23 \times 10^{-32}$ kg, the hole effective mass $m_h^* = 3.99 \times 10^{-31}$ kg and the lattice dielectric constant of InSb $\varepsilon_l = 16.0$ were employed in the following calculations.

III. RESULTS AND DISCUSSIONS

A. Transmission Characteristics of Two-Layer Structure

1) Two-Layer Structure with p-InSb Slab

The results of the two-dimensional analysis reveal that, for $B = 0$, the two-layer structure containing the p-InSb slab with $a = 0.220$ mm and $b = 0.08$ mm supports two separate propagation modes, as shown in Fig.4, where their attenuation constant α and phase constant β are plotted on the phase plane of α versus β with the ambient temperature T as the parameter. At 77 K, one of the modes, denoted M1, has a field distribution similar to that of a higher-order mode of the transverse magnetic (TM) image guide mode, as shown in Fig.5(a). The other mode, denoted M2, has a field distribution similar to that of the fundamental TM image guide mode [see Fig.5(b)]. Since the attenuation constant α of M2 is more than one order greater than that of M1 over whole temperature range, as shown in Fig.4, only M1 is surmised to appear experimentally.

First, the experimentally observed temperature dependence of the 526 GHz submillimeter-wave transmission is plotted for $B = 0$ in Fig.6, for $a = 0.220$ mm and $b = 0.080$ mm. The corresponding theoretical variation for M1 is also presented in the same figure by a solid line such that the theoretical and experimental values coincide at 77 K. The experimental results are generally in good quantitative agreement with the theoretical variation for the M1 mode. The results in Fig.6 are explained as follows. First, at a sufficiently low temperature, the only existing carrier is holes, which negligibly move, regardless of the submillimeter-wave fields. Thus, in this T-region, the p-InSb slab acts as a dielectric material with the dielectric constant of 16.0, and the wave propagation experiences very small attenuation. On the other hand, the InSb material becomes intrinsic near room temperature, and it acts as a poor conductor. Consequently, the electromagnetic fields are driven out of the InSb slab and concentrate mostly in the vacuum region. Thus, the InSb slab again induces only small attenuation. In contrast, in the intermediate temperature range, electrons in InSb dissipate considerable energy, and consequently a minimum appears in the transmission curve at a certain T-value.

The experimentally observed insertion loss of the InSb slab is about 0.3 dB/mm for $B = 0$ T and $T = 77$ K, which is much greater than the theoretical prediction of 7.3×10^{-3} dB/mm. The discrepancy is attributed to the reflection of the wave at each end of the sample slab. The theoretical value of the propagation loss of the image guide mode M2 is also very small, and is calculated to be 0.16 dB/mm for $B = 0$ T and $T = 77$ K, although no corresponding experimental data have been obtained. This indicates that the construction of image-guide-type transmission lines in the submillimeter-wave frequency range is possible by using p-type InSb slabs. Indeed, results of calculations show that a p-InSb image guide with a thickness of 0.05 mm has a 526 GHz propagation loss of 0.19 dB/mm at 77 K.

Except for the case where T is very near the liquid nitrogen temperature, a maximum and a minimum appear in the B-dependence of the transmission. They are classified into two classes arising from different origins.

Figures 7(a) to (c) show the B-dependence of the 526 GHz submillimeter transmission for various ambient temperatures in the T-region $T < 190$ K for both B+ and B- directions. Corresponding theoretical values for M1 are calculated using the electron and hole densities and their mobilities at each

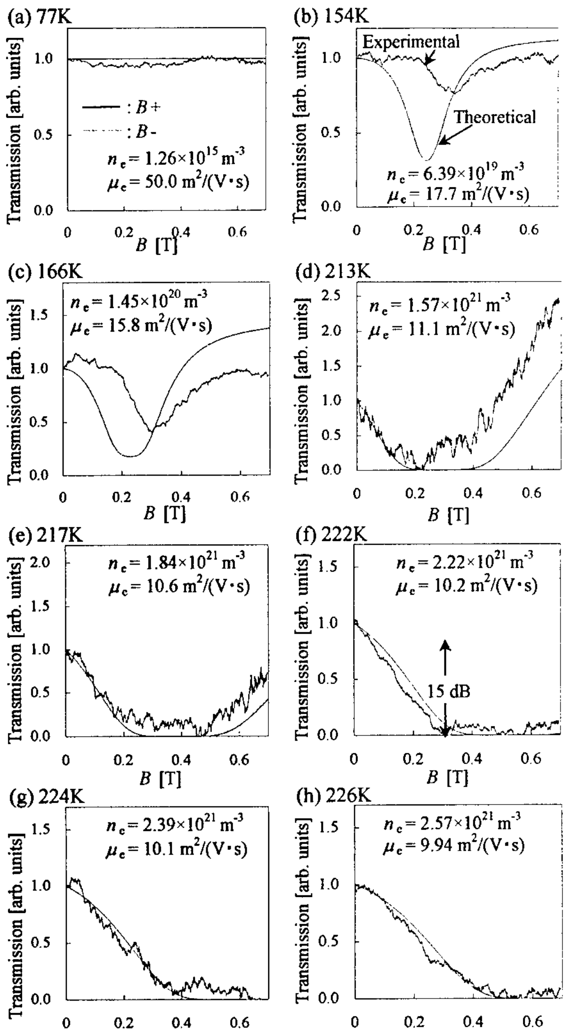

Fig. 7. Variations of the transmission as a function of B for various temperatures [two-layer parallel-plate waveguide structure containing p-InSb (b = 0.08 mm) at 526 GHz].

temperature, and are also plotted in the figure as thin lines such that the experimental and theoretical values coincide at $B = 0$ T.

First, at 77 K, both theoretically and experimentally, the transmission is almost independent of the magnetic field, as shown in Fig.7(a). This is clearly because the holes in InSb can move only negligibly, regardless of the submillimeter-wave fields.

Next, at T = 154 K [Fig.7(b)], a small dip appears on the theoretical and experimental transmission curves at B = 0.24 T and at B = 0.3 T, respectively, for both B+ and B- directions. They originate from the electron cyclotron resonance caused by the rotating electric field in the InSb slab. The discrepancy between the magnetic fields that cause the experimental and theoretical dips is explained by nonuniform energy intervals between succeeding Landau levels of InSb arising from the nonparabolic feature of the conduction band.

As the temperature further increases, the magnetic field that causes the minimum transmission considerably decreases for both B+ and B- direction. This indicates that the resonance became a hybrid one whose resonant magnetic field B_r is given by $eB_r/m_e = (\omega^2 - \omega_{pe}^2/\varepsilon_l)^{1/2}$, where ω_{pe} denotes the electron plasma frequency $\omega_{pe}^2 = n_e e^2/m_e\varepsilon_0$. The experimental results are in agreement with the theoretical ones only qualitatively.

As the sample temperature increases over 200 K, the propagation characteristics vary drastically. Large dips clearly

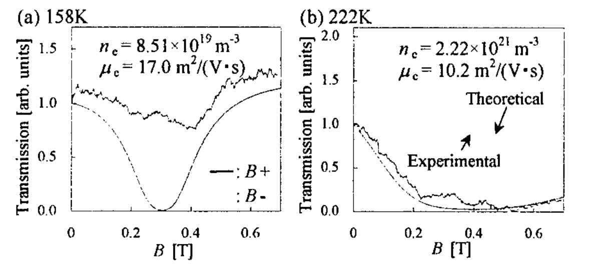

Fig. 8. Variations of the transmission as a function of B for various temperatures [two-layer parallel-plate waveguide structure containing p-InSb (b = 0.026 mm) at 671 GHz].

appear again on the theoretical and experimental transmission curves for both B-directions, as shown in Figs.7(d) to (h). The magnetic field giving the minimum transmission greatly increases for both B+ and B- directions as the carrier density increases with increasing T. The dip in the B- direction occurs at a higher magnetic field than that in the B+ direction. The experimental results indicate very good quantitative agreement with the theoretical prediction. These variations in the present temperature region originate from the slow surface wave resonance which has already been reported for the 70 GHz millimeter-wave frequency range and for n-type InSb[3]. The slow surface wave resonant magnetic field B_s is given by the relation

$$B_s = (m_e^*/e)\,\{\omega_{pe}^2/[\omega\,(\varepsilon_l+1)]-\omega\}\ . \qquad (2)$$

It should be noted that the T-value of 200 K corresponds to the electron density at which the above B_s-value vanishes. Thus, the surface wave resonance appears only for the T-region higher than 200 K. It is interesting from the viewpoint of device application that, in the submillimeter-wave region, the slow surface wave resonance is observed at the dry ice temperature with p-type material. In addition, it is to be noted that this surface wave resonance exhibits large nonreciprocal characteristics. For example, it is indicated in Fig.7(f) that, at the temperature of 222 K, a nonreciprocity of more than 15 dB is obtained with an insertion loss of 5 dB at a moderate magnetic field of 0.3 T. This result indicates that our two-layer structure with a p-InSb slab functions as a submillimeter-wave nonreciprocal device which operats at the dry ice temperature. It is surmised that the wave propagation in p-InSb at 77 K can be made to have a nonreciprocal nature by injecting plasma in an appropriate part of the material in the presence of an externally applied magnetic field, and can be easily controlled by varying the plasma density.

Next, the magnetic field dependence of the transmission of 671 GHz submillimeter waves through the p-InSb two-layer waveguide are presented in Fig.8 for a = 0.274 mm and b = 0.026 mm. The situation is quite similar to the case of Fig. 7. As a consequence of the increase in frequency, the magnetic field that induces cyclotron resonance in the case shown in Fig.8(a) is larger than that in the case shown in Fig.7(b). On the other hand, the theoretical value of the surface wave resonant magnetic field in the case of Fig.8(b) is 0.396 T, which is somewhat smaller than that in the case of Fig.7(f) (0.526 T). The experimental results are consistent with the theory.

2) Two-Layer Structure with n-InSb Slab

Figure 9 shows the 526 GHz transmission characteristics of a two-layer waveguide containing an n-InSb slab with the electron density 1.55 × 10^{21} m^{-3} and electron mobility 50.0 $m^2/(V{\cdot}s)$. Since the electron density is sufficiently large, even at 77 K, in this case, the B_s-value of eq.(2) remains positive. Thus surface wave resonance clearly appears even at 77 K, in

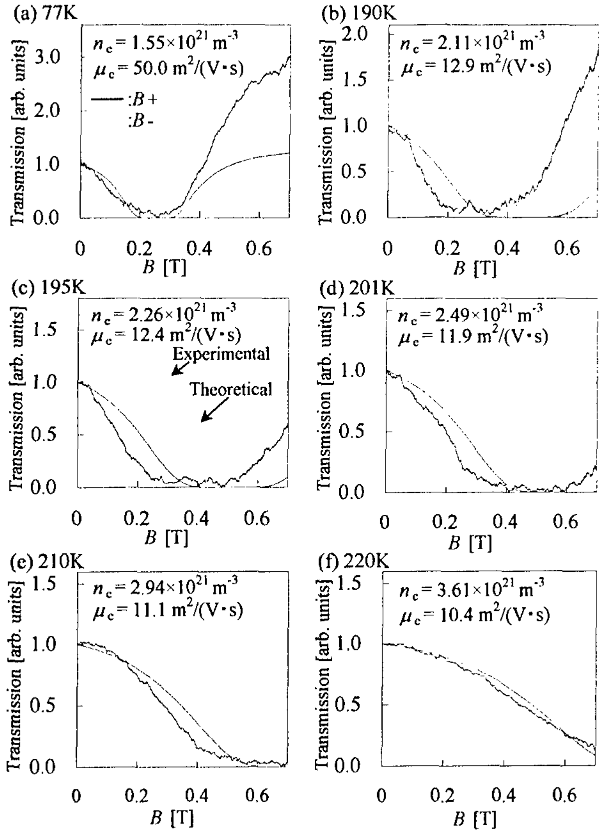

Fig. 9. Variations of the transmission as a function of B for various temperatures [two-layer parallel-plate waveguide structure containing n-InSb (b = 0.09 mm) at 526 GHz)].

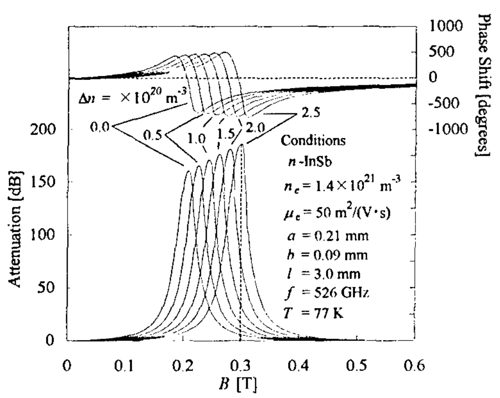

Fig. 10. Variations of the attenuation and phase sift as functions of B for various values of the injected plasma density [two-layer parallel-plate waveguide structure containing n-InSb (b = 0.09 mm) at 526 GHz].

contrast with the case of p-InSb. The resonance in this case is very sharp, and large nonreciprocity, 15 dB at B = 0.25 T, is obtained because of the high electron mobility. As the electron density increases with T, the magnetic field giving the minimum transmission considerably increases, which is again consistent with eq.(2), and simultaneously, the resonance becomes very broad because of the reduction of the electron mobility.

The dependence of the surface wave resonance on the injected plasma density Δn is calculated and presented in Fig.10 for an n-InSb slab with the initial electron density of 1.40×10^{21} m^{-3} and electron mobility of 50.0 m^2/(V·s). The surface wave resonant magnetic field, which is defined as the B-value corresponding the peak of the attenuation, increases with increasing plasma density. This result shows that, at B = 0.3 T, the submillimeter-wave transmission theoretically varies over 150 dB with $\Delta n = 2.5 \times 10^{20}$ m^{-3}. This indicates the possibility of applying our configuration to a submillimeter-wave variable attenuator.

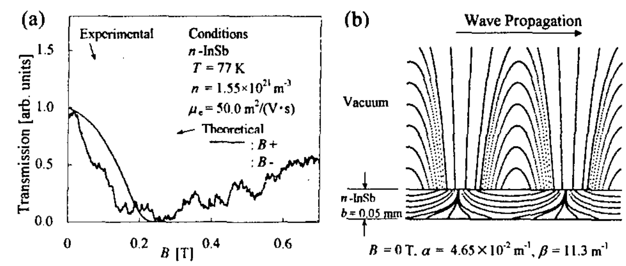

Fig. 11 (a) Variations of the transmission as a function of B and (b) electric field distributions [image guide structure containing n-InSb (b = 0.05 mm) at 526 GHz].

B. Transmission Characteristics of Image guide

For the case where a sufficiently dense plasma is injected into the p-InSb image guide shown in Fig.1(b), we present here the transmission characteristics of the image guide made of an n-InSb slab. This guide also supports, as presented below, a slow surface wave resonance similar to the one observed for the two-layer structure. Figure 11(a) shows the experimentally observed B-dependence of the 526 GHz transmission through the n-InSb image guide depicted in Fig.1(b). For the B+ direction, transmission first decreases with magnetic field, and then becomes minimum at B = 0.35 T. For B-, transmission initially increases and becomes maximum at B = 0.15 T. It then decreases and becomes minimum at B = 0.4 T. These variations are similar to those for the two-layer structure, and are the characteristic of slow surface wave resonance. As seen in the results, nonreciprocity of 8.4 dB also appears in this configuration at B = 0.13 T. The electric field for B = 0 of this propagation mode is shown in Fig.11(b). In contrast to the case of p-InSb where the image guide mode propagates, this mode in n-InSb is the well-known Zeneck surface wave.

IV. CONCLUSIONS

The magnetic field dependence of 526 GHz and 671GHz submillimeter-wave transmission characteristics through a two-layer waveguide containing a p- or n-InSb slab was studied in detail theoretically and experimentally at various ambient temperatures. For p-InSb, submillimeter-wave propagation loss at 77 K is very small, at most 0.3 dB/mm, which suggests that the construction of dielectric transmission lines, such as an image guide using p-InSb material, is possible. For T > 200 K, slow surface wave resonance occurs, and nonreciprocity of more than 15 dB appears at B = 0.3 T at the dry ice temperature, which indicates the possibility of applying our waveguide configuration to submillimeter-wave nonreciprocal devices. The resonance occurs also in the n-InSb image guide. The possibility of controlling these nonreciprocal propagation characteristics easily by injecting plasma was also revealed. Experimental study on this point is now under way.

ACKNOWLEDGEMENT

This work was supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture.

REFERENCES

[1] S. Yodokawa and T. Obunai: Jpn. J. Appl. Phys. **36** (1997) 2101.

[2] H. J. Hrostowski, F. J. Morin, T. H. Geballe and G. H. Wheatley: Phys. Rev. **10** (1955) 1672.

[3] T. Obunai and T. Sekiguchi: Jpn. J. Appl. Phys. **13** (1974) 93.