LEAKY WAVE BEHAVIOUR IN THE SILICON H-GUIDE WITH OPTICALLY INDUCED PLASMA REGION

Yutaka Satomura, Shinobu Sumida and Makoto Tsutsumi*

Department of Electrical Engineering
Osaka Institute of Technology, Osaka 535, Japan
* Department of Electronics and Information Science Engineering
Kyoto Institute of Technology, Kyoto 606, Japan

Abstract

The propagation properties of leaky millimeter waves in the silicon H-guide containing optically induced plasma region have been investigated at Q band including NRD-guide behaviour. The possible optical control devices, such as switching devices from guided to leaky waves, have been examined by utilizing the transition characteristics from guided waves into leaky waves due to optical illumination.

1. Introduction

Light controlled millimeter wave devices utilizing optically induced photoconductivity have been the subject of much interest over the past few years. Some new class of devices, such as optically controlled switches, phase shifters and attenuators, have been investigated using semiconductor waveguide, image line, finline, coplaner waveguide, and microstrip waveguide[1][2]. This paper deals with the propagation properties of guided and leaky millimeter waves in the silicon H-guide containing the optically induced plasma region, and they are experimentally examined at Q band.

2. Theory

Figure 1 shows the geometry of the silicon H-guide with optically induced plasma region of thickness d [3]. The propagation direction is in the x axis. The electromagnetic fields in the H-guide are expressed by the vector potentials $\boldsymbol{F}$ and $\boldsymbol{A}$

$$\left.\begin{aligned} \boldsymbol{E} &= -\nabla\times\boldsymbol{F} - j\omega\mu_0\boldsymbol{A} + \frac{1}{j\omega\varepsilon}\nabla(\nabla\cdot\boldsymbol{A}) \\ \boldsymbol{H} &= \nabla\times\boldsymbol{A} - j\omega\varepsilon\boldsymbol{F} + \frac{1}{j\omega\mu_0}\nabla(\nabla\cdot\boldsymbol{F}) \end{aligned}\right\} \tag{1}$$

In this geometry, we can express the vector potentials for LSE modes(TE$^{(z)}$) as follows.

$$\boldsymbol{A} = 0 \quad , \quad \boldsymbol{F} = F_z\boldsymbol{i}_z \tag{2}$$

Then, the field component of each region can be written by using F_z as

$$\left.\begin{aligned} &\text{region III } (z > a) \\ &F_z = D_1 e^{-pz}\cdot\cos\frac{n\pi}{b}y\cdot e^{-j\beta x} \\ &\text{region I } (0 \le z \le a) \\ &F_z = (A_1\cos k_z z + A_2\sin k_z z)\cdot\cos\frac{n\pi}{b}y\cdot e^{-j\beta x} \\ &\text{region II } (-d \le z < 0) \\ &F_z = (C_1\cos\delta z + C_2\sin\delta z)\cdot\cos\frac{n\pi}{b}y\cdot e^{-j\beta x} \\ &\text{region IV } (z < -d) \\ &F_z = D_2 e^{pz}\cdot\cos\frac{n\pi}{b}y\cdot e^{-j\beta x} \end{aligned}\right\} \tag{3}$$

where

$$k_z^2 = k_0^2\varepsilon_S - \left(\frac{n\pi}{b}\right)^2 - \beta^2 \quad , \quad \delta^2 = k_0^2\varepsilon_p - \left(\frac{n\pi}{b}\right)^2 - \beta^2$$
$$p^2 = \beta^2 + \left(\frac{n\pi}{b}\right)^2 - k_0^2 \tag{4}$$

In above equations, k_z, δ and p are the transverse propagation constant of each region. In the optically induces plasma region in the silicon slab, the relative dielectric constant ε_p is written in complex form and also is a function of the wave frequency as follows[3].

$$\begin{aligned} \varepsilon_p &= \varepsilon_S - \sum_{i=e,h}\frac{\omega_{pi}^2}{\omega^2+\nu_i^2}\left(1 + j\frac{\nu_i}{\omega}\right) \\ \omega_{pi}^2 &= \frac{n_p q^2}{\varepsilon_0 m_i^*} \end{aligned} \tag{5}$$

where ω_p denotes the plasma frequency. Applying the boundary condition at the boundary surfaces, we obtain the characteristic equation, that is , eigenvalue equation for LSE modes. Figure 2 shows the dispersion characteristics(β-ω diagram) of LSE modes for the silicon slab H-guide having

TU 4B

0-7803-3246-6/96/$5.00 © IEEE

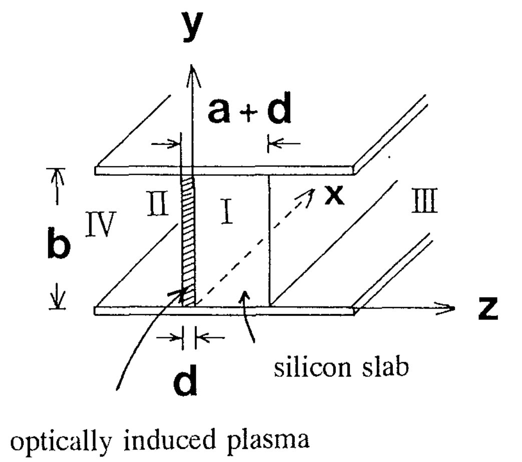


Fig.1 Geometry of the silicon H-guide with plasma region d.

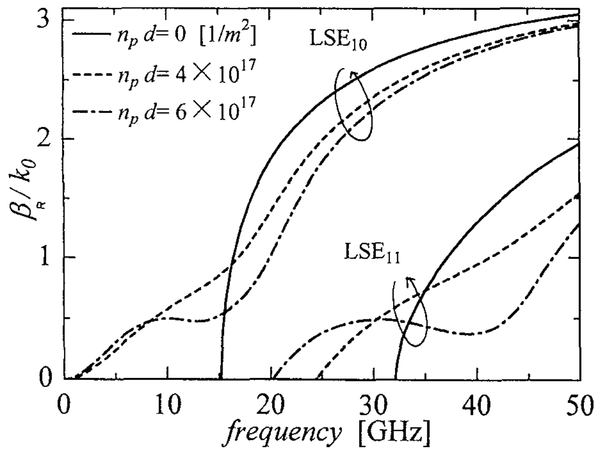


Fig 3 Dispersion characteristics of silicon NRD-guide: (phase constant β_R, $a+d$=1.5mm, b=4.5mm)

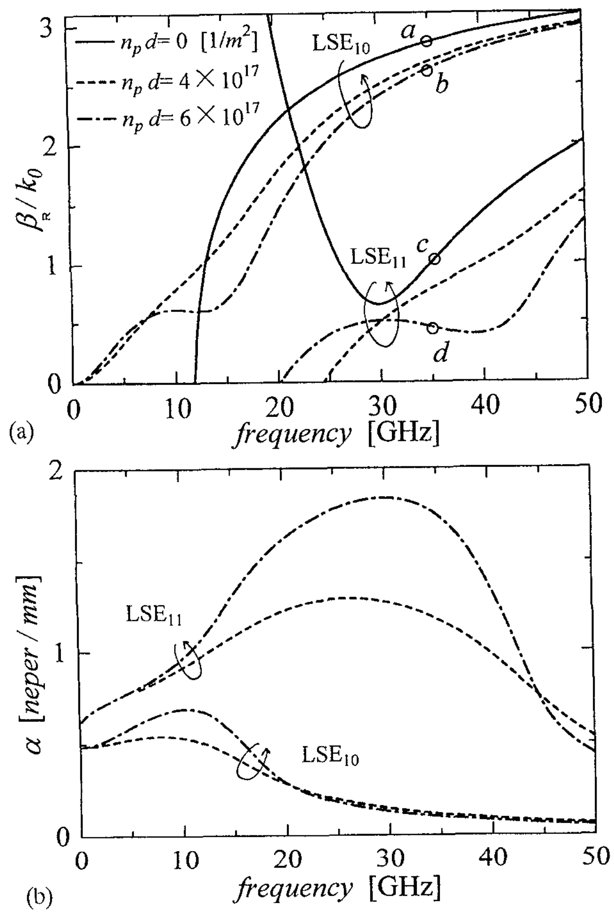
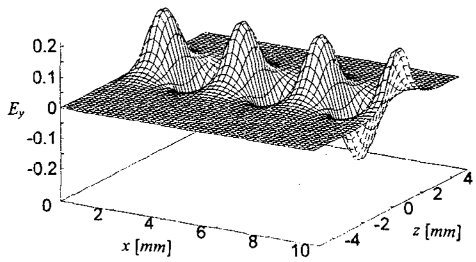


Fig.2 Dispersion characteristics of silicon H-guide. (a) phase constant β_R (b) attenuation constant α ($a+d$=1.5mm, b=6 5mm)

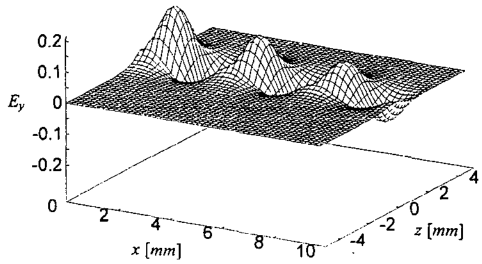
induced plasma region by optical illumination The parameters β_R and a are the real and imaginary parts of the complex propagation constant β (= $\beta_R - j\,\alpha$), respectively. These calculations have been carried out for different plasma density n_p by Muller's method. The thickness d of the plasma region and the resonant number n in the y direction are assumed to be 20μm and unity, respectively The dispersion curves for the NRD-guide with same thickness (a=1.5mm) of 4 5mm width are also shown in Fig.3. The cutoff frequencies for the dominant mode of the H- and NRD-guide for n_p=0 are about 23 and 33 GHz, respectively The second higher-order mode LSE$_{11}$ for the H-guide is in the leaky region below about 30 GHz

The field distributions of Ey component for LSE$_{10}$ and LSE$_{11}$ modes corresponding to the points depicted in Fig.2 are illustrated in Fig.4. The x- and z-axis denotes the propagation direction and the transverse direction, respectively, as shown in Fig 1 It is noted that at this frequency, both modes without illumination are in the guided region, and that when plasma is induced in a side of silicon slab, transition behaviour from guided to leaky waves occurs[4]. For LSM modes, their transition due to optical illumination is calculated to be smaller

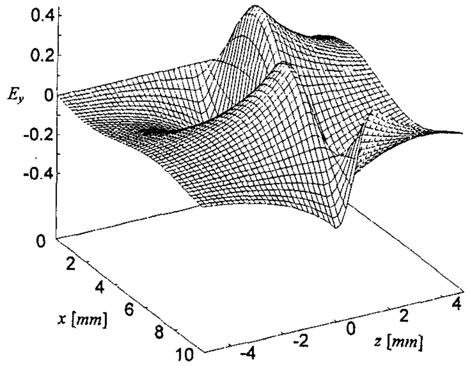
Next, we make the modal analysis in more detail The thinner silicon slab(0 4mm thick) of 6 5mm width is assumed to be sandwiched between two conducting plates The silicon with this size is used in the following experimental setup for transmission characteristics Figure 5 shows the dispersion curves of β_R of LSE$_{10}$ for several normalized plasma densities $n_p d$. Calculated values of the normalized propagation constant



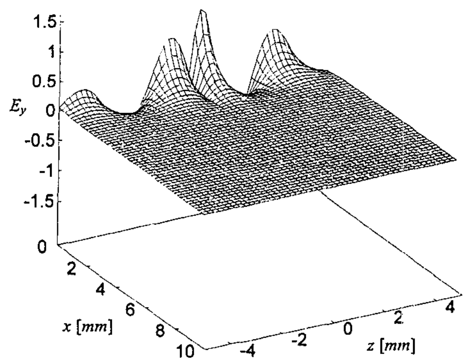
point a of Fig.2



point b of Fig.2



point c of Fig.2



point d of Fig.2

Fig.4 Field distributions of Ey component for LSE_{10} and LSE_{11} modes.

$\beta(=\beta_R - j\alpha)$ in the transmission direction, and the transverse propagation constants $k_z\ (= k_{zr} + jk_{zi})$, $p\ (= p_r + jp_i)$ of dominant LSE_{10} mode are also shown in Figs.5(a) and (b) for off-illumination (n_p =0) and on-illumination ($n_p\,d$ =6x10^{17} [1/m^2]), respectively. The transition of value of p_i in the outer region due to optical illumination indicates that the wave propagates to rather the transverse direction than the direction of transmission. This effect is promising for providing novel applications. Figure 7 shows the change of field distribution Ey for dominant mode. The solid line and the dotted line stand for $n_p = 0$ and $n_p\,d = 6 \times 10^{17}$ [1/m^2], respectively. The transitions of field distribution Ey to the x axis are illustrated in Figs.8 (a) and (b), which correspond to $n_p = 0$ and $n_p d = 6 \times 10^{17}$ [1/m^2], respectively.

3. Experiment

The experimental setup for the measurement of transmission characteristics and leaky waves in the silicon H-guide is shown in Fig.9. The 400 μm-thick silicon slab of 7 cm length is inserted and connected in the cascade form between two teflon slabs of 6.5 mm width in the H-guide, which is illuminated by Xenon arc lamp of optical power of 2W. These results will be discussed at the conference.

4 .Conclusions

Effects of optically switching behaviour from guided to leaky waves in the silicon H-guide containing the optically induced plasma region have been investigated at Q band. As the H-guide structure proposed here is convenient and effective for optical illumination, the optical control of leaky wave in the H-guide may be promising for providing a new signal processing devices such as leaky wave antenna, and interests in leaky behaviour of the NRD-guide.

References

[1] A.M.Vaucher, C.D.Striffler and C.H.Lee,"Theory of optical controlled millimeter-wave phase shifters",IEEE Trans. Microwave Theory and Tech.,vol.MTT-31,no.2, P.209,Feb.1983.

[2] P.Cheung,D.P.Neikirk and T.Ito,"Optically controlled coplanar waveguide phase shifters",IEEE Trans. Microwave Theory and Tech.,vol.MTT-38,no.5,P.586, May 1990.

[3] Y.Satomura and M.Tsutsumi,"Switching characteristics of optically controlled millimeter waves in the silicon H-guide",Digest of the 19th Int.Conf. on IR and MM Waves, P.512,1994.

[4] C.Di Nallo,F.Frezza,A.Galli,P.Lampariello and A.A.Oliner: " Properties of NRD-guide and H-guide higher-order modes: Physical and nonphysical ranges", IEEE Trans.Microwave Theory and Tech.,vol.MTT-42, no.12,P.2429,Dec. 1994.

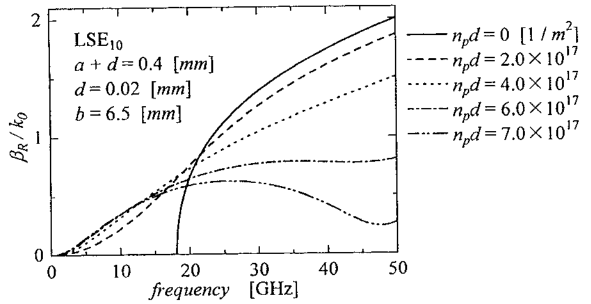


Fig.5 Dispersion curves of β_R (real part of propagation constant β) of LSE_{10} mode in the H-guide. ($a+d$=0.4mm, b=6.5mm)

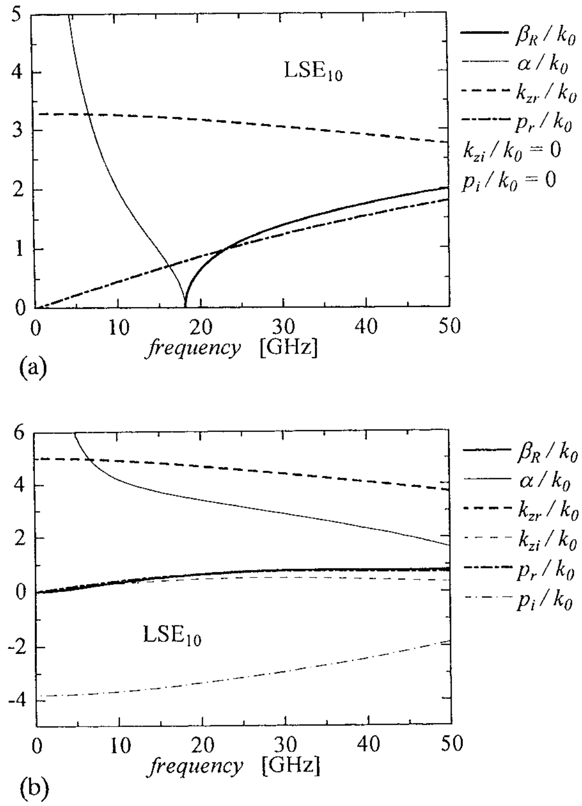


Fig.6 Dispersion curves of the complex proagation constants in each region , which are normalized by k_0. ($a+d$=0.4mm, b=6.5mm, (a)n_p=0, (b)n_pd=6×10[17][1/m[2]])

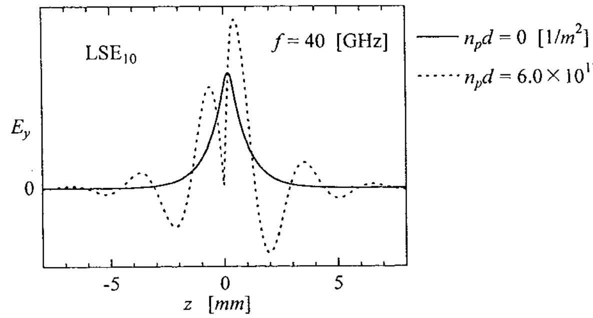


Fig.7 The change of distribution of field Ey due to optical illumination.

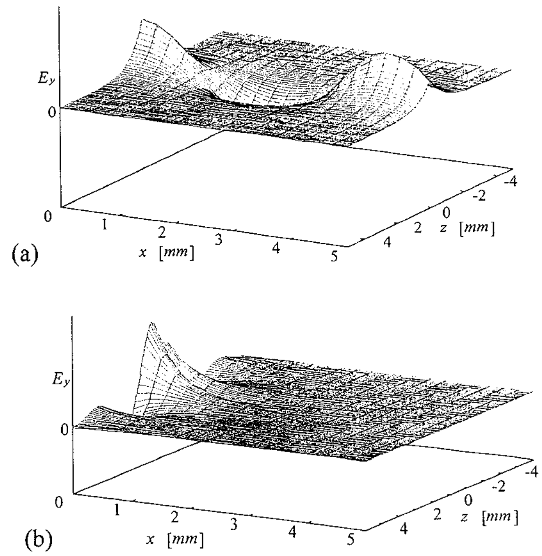


Fig.8 The transition of field distribution of Ey. ((a)n_p=0, (b)n_pd=6×10[17][1/m[2]])

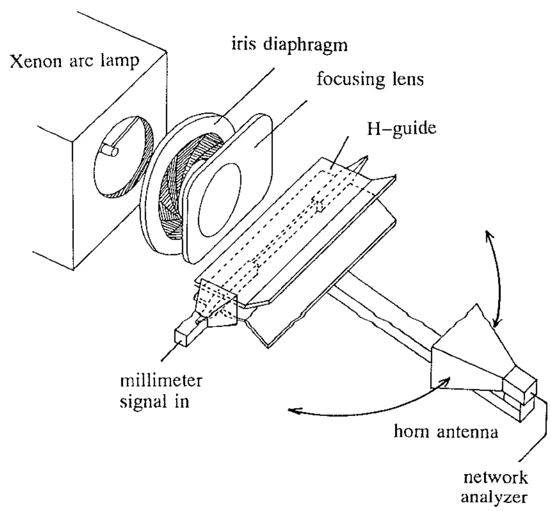


Fig9. Schematic diagram of the measurement arrangement.