Electromagnetic Wave Transmission across a Thin Plasma Layer Comparable to Incident Wavelength

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The transmission of electromagnetic waves across a thin plasma layer whose width is comparable to the wavelength of an incident wave is studied. The transmittances of transverse electric and transverse magnetic modes for both underdense and overdense plasmas are obtained as a function of the angle of incidence. It is thought that the significant reduction of transmittance in overdense plasma's transverse magnetic modes is caused by the excitation of the electron plasma wave on the plasma resonance layer.

Keywords: electromagnetic wave, wave propagation, thin plasma layer, plasma resonance

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The reflection and transmission of electromagnetic waves in plasma layers is a fundamental problem in electromagnetic wave interaction with plasmas [1]. Microplasmas have attracted growing attention [2], and in this paper, we discuss electromagnetic wave transmission across a thin unmagnetized plasma layer having a thickness comparable to the wavelength of an incident wave. Since we can expect the tunneling propagation of electromagnetic waves in such a thin plasma layer even if the plasma is overdense for electromagnetic waves to propagate, we are interested in the difference of the wave transmittance between transverse-electric (TE) and transverse-magnetic (TM) modes. In light of the above, in the present study, we numerically analyze the wave transmittance in overdense plasma as well as in underdense plasma.

In Fig. 1, we present a two-dimensional simulation model of this problem. Our basic equations are Maxwell equations for the electromagnetic wave fields $\boldsymbol{E}$ and $\boldsymbol{B}$ and an equation of motion for the induced plasma current $\boldsymbol{J}$, which is given approximately by $\boldsymbol{J} = -en_0\boldsymbol{V}_e$, as we are intersted in frequency region comparable to the electron plasma frequency. That is,

$$\frac{\partial}{\partial t}\boldsymbol{B} = -\nabla\times\boldsymbol{E}, \tag{1}$$

$$\frac{\partial}{\partial t}\boldsymbol{E} = \nabla\times\boldsymbol{B} - \boldsymbol{J}, \tag{2}$$

$$\frac{\partial}{\partial t}\boldsymbol{J} = f\boldsymbol{E}, \tag{3}$$

where each physical quantity is normalized as follows: $\omega_0 t \rightarrow t$, $\omega_0\boldsymbol{r}/c \rightarrow \boldsymbol{r}$, $\boldsymbol{E}/E_0 \rightarrow \boldsymbol{E}$, $c\boldsymbol{B}/E_0 \rightarrow \boldsymbol{B}$, $\boldsymbol{J}/\varepsilon_0\omega_0 E_0 \rightarrow \boldsymbol{J}$, and $\omega_{pe} = (e^2 n_0/\varepsilon_0 m)^{1/2}$ is the electron plasma frequency. In addition, $f = (\omega_{pe}/\omega_0)^2$, and ω_0 is a reference frequency for normalization. We use here the well-known Fininite Difference Time Domain (FDTD) scheme for numerical computation. As the boundary condition, we impose the out-going wave condition.

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Hereafter, we show the 2-d simulation results. If we assume $\omega_0 = 3\times10^{11}$, the unit length c/ω_0 corresponds to 1 mm. We here assume a density profile given by

$$n(\xi) = n_0 \exp\left[-\left(\frac{\xi}{d}\right)^4\right], \tag{4}$$

and assume that $d = 1$ and $n_0 = 6\times10^{13}\ \mathrm{cm}^{-3}$. In this case, the cutoff frequency for this n_0 is 69.6 GHz. For incident waves, we excite E_y for TE modes and E_z for TM modes at the boundary. We also assume that an incident electromagnetic wave has a Gaussian distribution along the direction perpendicular to the propagation direction; that is,

$$E(z) = E_0 \exp\left[-\left(\frac{z}{12}\right)^2\right]. \tag{5}$$

The transmittance of electromagnetic waves across a thin plasma layer is defined by the ratio of the Poynting vec-

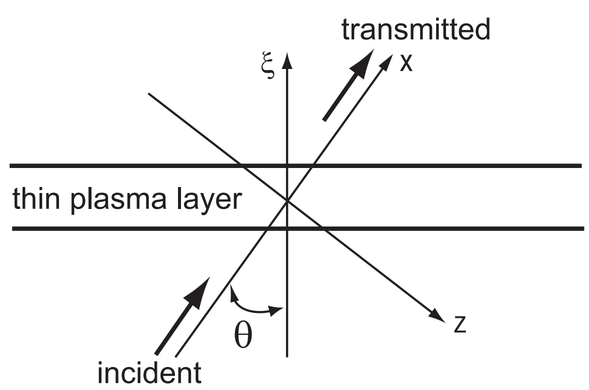

Fig. 1 The present simulation model.

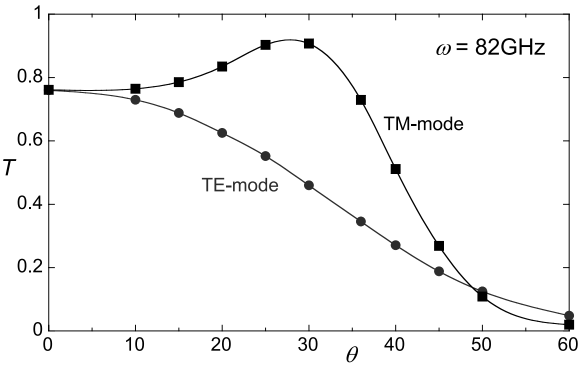

Fig. 2 Transmittance of TE and TM modes at 82 GHz.

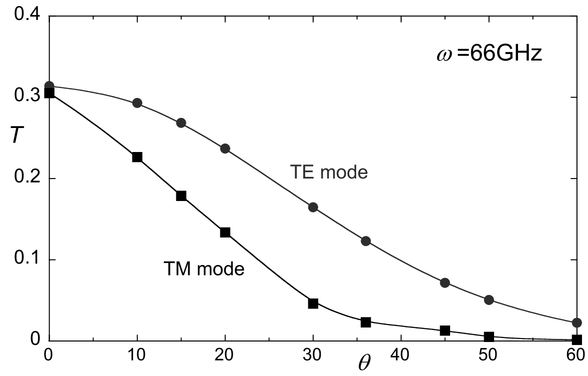

Fig. 3 Transmittance of TE and TM modes at 66 GHz.

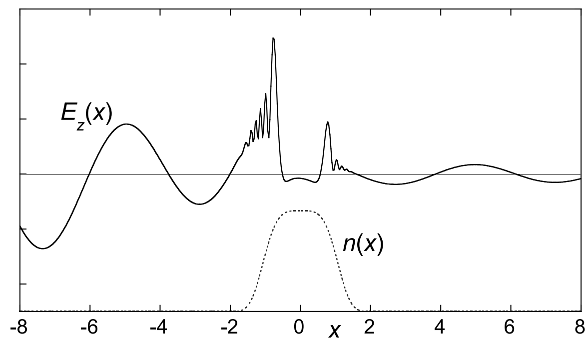

Fig. 4 Wave Pattern of $E_z(x)$ at 66 GHz for θ = 30°.

tor of the transmitted wave to an incident wave along the x axis. We can here neglect the diffraction effect of the transmitted wave as the plasma layer is vey thin. Thus, the transmittance at the beam center ($z = 0$) is given by

$$T = \frac{(\boldsymbol{E} \times \boldsymbol{B})_{x,\mathrm{after}}}{(\boldsymbol{E} \times \boldsymbol{B})_{x,\mathrm{before}}}, \tag{6}$$

where $(\boldsymbol{E}\times\boldsymbol{B})_{x,\mathrm{before}}$ and $(\boldsymbol{E}\times\boldsymbol{B})_{x,\mathrm{after}}$ mean the magnitudes of $(\boldsymbol{E} \times \boldsymbol{B})_x$ just before the wave enter into a plasma and just after the wave passes through the plasma, respectively.

We first show the numerical result of electromagnetic wave transmittance in Fig. 2 at $\omega/2\pi$ = 82 GHz, which is larger than the maximum cutoff frequency 69.6 GHz. The figure shows the transmittance's dependence on the incident angle for both TE and TM modes. The transmittance for TE mode and that for TM mode become equal to each other in the case of normal incidence; however, the transmittance for the TM mode becomes larger than that for the TE mode for $\theta = 0 \sim 50°$. This phenomenon seems to resemble the transmission phenomenon from a uniform dielectric medium (refractive index n_1) to another one (n_2). If we assume the formula for the case of uniform media, the Brewster angle maximizing the wave transmittance from the vacuum to the plasma side is estimated as

$$\tan^{-1}\left(\sqrt{1-\left(\frac{\omega_{\mathrm{pe}}}{\omega}\right)^2}\right) = \tan^{-1}\left(\sqrt{1-\left(\frac{69.6}{82}\right)^2}\right) \simeq 27.9°,$$

and we see that this value coincides with the numerical result shown in Fig. 2.

Figure 3 shows the numerical result of the electromagnetic wave transmittance at $\omega/2\pi$ = 66 GHz. In this case, as the wave frequency is lower than 69.6 GHz, we see that TM modes meet with the plasma resonance layer of $\omega = \omega_{\mathrm{pe}}$ where the wave equation becomes singular if the plasma is collision-free. However, the TE modes do not experience plasma resonance. The transmittance of the TE and TM modes becomes equal to each other in an error range in the case of normal incidence; however, in this case, the tansmittance of the TM modes become smaller than that of the TE modes. This phenomenon can be interpreted as follows. A part of the wave energy of an incident electromagnetic wave is spent on the excitation of the electron plasma wave on the plasma resonance layer of $\omega = \omega_{\mathrm{pe}}$ and then the wave energy of the electromagnetic wave traversing the plasma layer decreases. This in turn causes a reduction in the transmittance for the TM mode. In Fig. 4, we show a snapshot of the wave profile of $E_z(x)$ at $\omega/2\pi$ = 66 GHz in the case of θ = 30°, where the dashed line denotes the density profile. We can see two strong peaks due to the plasma resonance of $\omega = \omega_{\mathrm{pe}}$.

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