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Excitation of surface plasmons at the boundary of overdense plasma

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The excitation of surface plasmons (SPs) with a strip grating at the boundary of an unmagnetized overdense plasma has been investigated theoretically and experimentally. An incident electromagnetic radiation was *p*-polarized at the frequency of 5 GHz. Experiments showed that when the plasma density was four times higher than the critical density with the grating present, and the SPs could be excited at the boundary of the overdense plasma. Contribution of the glass layer in the formation of the SP dispersion relation was examined. When the incident electromagnetic radiation was coupled into SPs the coupling order with the effective permittivity was simulated qualitatively. We find that the existence of SPs at the boundary of overdense plasma indicates that the reflection coefficient of the incident electromagnetic radiation reaches its minimum and even becomes total absorption. In this work the plasma density was diagnosed by a Langmuir double probe.

Keywords: surface plasmons, overdense plasma, electromagnetic radiation, coupling order
PACC: 7320J, 5240, 5270G

1. Introduction

The interaction of electromagnetic radiation with a suitable interface can generate interesting surface excitation, which has been of great interest to many researchers for years since Ritchie started the pioneering work of surface plasmons (SPs)[1] in the 1950s. A lot of theoretical and experimental work focused on SPs at the interface between metal and vacuum or air[2−16] has been carried out. The surface behaviour of plasma has also been examined theoretically.[17−19] Surface plasmons are waves that propagate along the interface but decay exponentially with the distance from the boundary on both sides.[13] There are three main techniques to excite SPs[13] at the interface between metal and outer medium, which are all based on the theory of keeping momenta matched.[4,20] The existence of SPs at the interface of metal requires that ω (the frequency of incident electromagnetic radiation) be in the range of $\varepsilon < 0$, where ε is permittivity which depends on the frequency of the incident electromagnetic radiation. The plasma permittivity $\varepsilon_{\rm p} = 1 - \omega_{\rm pe}^2/\omega^2$ is negative when the plasma is overdense (corresponding to $\omega/\omega_{\rm pe} < 1$, where $\omega_{\rm pe} = \sqrt{4\pi n_{\rm e} e^2/m_{\rm e}}$ is the plasma frequency). In spite of such similarity of metal and overdense plasma, all experimental investigations had been carried out with metal only until Bliokh *et al.* reported for the first time on an experimental observation of the phenomenon due to the excitation of SPs employing subwavelength grating.[21] The existence of SPs along the boundary of an overdense plasma is manifested by the reflectivity of incident electromagnetic radiation.[21,22] The reflection coefficient would approach zero when SPs are excited, i.e. total absorption would be achieved.

In this paper, an extended investigation of Refs.[21] and [22] was made. We focused on the excitation of SPs at the boundary of an unmagnetized overdense plasma with a strip grating when the incident radiation was p-polarized. It was shown that a p-polarized incident electromagnetic radiation could be coupled to SPs under suitable arrangements when the density of overdense plasma $n_{\rm e} > 4n_{\rm c}$ (here $n_{\rm c} = m_{\rm e}\omega^2/4\pi e^2$, is the critical density of the plasma). We also compared our results with those in Refs.[21] and [22] by a combination of the SP dispersion relation at the boundary of the overdense plasma and the coupling equation from the incident electromagnetic radiation to SPs. The contribution of a glass layer to exciting SPs from outside was investigated when the

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density was four times higher than the critical density. Simulation was made qualitatively for the relationship between the coupling order and the effective permittivity at the coupling of the incident electromagnetic radiation into SPs.

2. Physical model

Solving Maxwell's equations under appropriate boundary conditions yields a dispersion relation of SPs[4,23] along the interface between a metal and a medium, that is, the frequency-dependent SP wave-vector, $\kappa_{\rm sp}$

$$\kappa_{\rm sp}^2 = \frac{\omega^2}{c^2}\left\{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right\}, \tag{1}$$

where ε_1 and ε_2 are the permittivities of the metal and the medium respectively, which must be of opposite signs. It is also suitable for SPs along the interface between the overdense plasma and the outer medium when an external magnetic field is absent, since plasma is quasi-neutral, which is necessary to satisfy the boundary conditions in deriving Eq.(1). Therefore, the dispersion relation of SPs along the interface between the overdense plasma and the outer medium is

$$\kappa_{\rm sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{\rm m}\varepsilon_{\rm p}}{\varepsilon_{\rm m}+\varepsilon_{\rm p}}}, \tag{2}$$

where $\varepsilon_{\rm p}$ and $\varepsilon_{\rm m}$ are the permittivities of the overdense plasma and the outer medium respectively. As the overdense plasma has $\varepsilon_{\rm p} = 1-\omega_{\rm pe}^2/\omega^2 < 0$, then if SPs are excited, $\varepsilon_{\rm m}$ should be positive and less than $-\varepsilon_{\rm p}$.

It has been shown that the requirement of $\kappa_{\rm sp} > k_0\sqrt{\varepsilon_{\rm m}}$ is indispensable in the excitation of SPs at the interface between an unmagnetized overdense plasma and an outer medium. Generally $\varepsilon_{\rm m} > 1$, and hence the wave-vector of SPs must be above that of the incident electromagnetic radiation. There are several ways to make up for this mismatch,[13] such as using a prism or a periodic structure on the surface. We experimentally examined the mechanism to excite SPs using a strip grating. Figure 1 illustrates the coupling arrangement of a p-polarized electromagnetic radiation into SPs. In terms of p-polarization, the incident radiation has its $\boldsymbol{E}$ vector in the plane of incidence. Under such conditions the $\boldsymbol{B}$ vector has only one component B_y tangential to the interface, and this corresponds to TM radiation, the mode in which SPs can exist at the interface.[17]

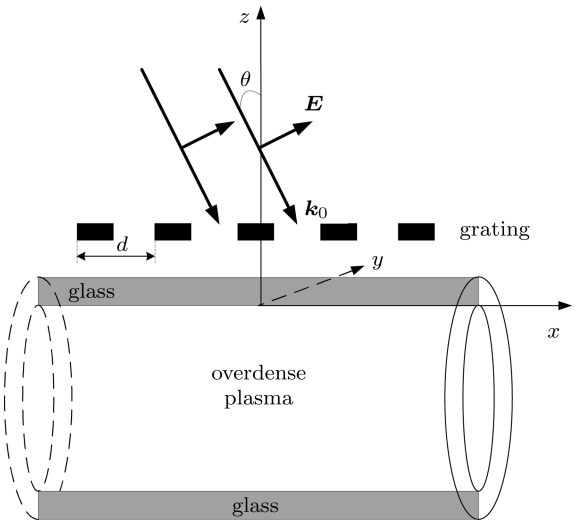


Fig.1. Coupling arrangement of a p-polarized electromagnetic radiation with an angle of incidence θ into SPs at the boundary of unmagnetized overdense plasma. d is the wavelength of the diffraction grating which lies in the y-direction and parallel to the $x-y$ plane.

The surface of a strip diffraction grating can be regarded as a one-dimensional (1D) lattice.[11] SPs are excited when their momentum matches that of the grating and the incident electromagnetic radiation with wave-vector $k_0(=2\pi/\lambda_0=\omega/c)$; and the conservation of momentum is now in the x-direction[4,20]

$$\kappa_{\rm sp} = k_0\sin\theta \pm nG. \tag{3}$$

Here $G = 2\pi/d$ is the Bragg reciprocal-lattice vector, and n is the coupling order that can only be integers.

If more than one SP is excited, the components $f(x,z)$ of the electromagnetic field in the unmagnetized overdense plasma shall be given by[4,5]

$$f(x,z) = \sum_n A_n \exp[{\rm i}(\kappa_{{\rm sp}n}x - \chi_n z)], \quad z<0 \tag{4}$$

where $\chi_n = {\rm i}\left(\kappa_{{\rm sp}n}^2 - \dfrac{\omega^2}{c^2}\varepsilon_{\rm p}\right)^{1/2}$, and A_n is the amplitude of the corresponding field component of the coupling order n.

3. Experimental scheme

Figure 2 is a schematic diagram of our experimental setup and diagnostic method. The discharge chamber, whose length and inner radius were 630 mm and 100 mm respectively, was made from a glass cylinder with a 4 mm-thick glass layer. A DC high voltage

discharge up to 3 kW was used as the plasma source which produced a dense plasma steadily. The density of plasma could be varied over a wide range by varying the gas pressure and/or the power of the plasma source, and the neutral gas pressure p could be varied within the range of $10^{-2} - 10^{2}$ Pa of Xe by a mass flow controller (MFC). A circular microwave horn antenna, BJ58, was placed on each side of the discharge chamber surrounded by the electromagnetic wave attenuating material. A microwave diffraction grating for coupling into SPs was placed to face the emission antenna ($\theta = 0$). The grating consisted of a periodical set of aluminium strips with a width of 20 mm and a period of 60 mm, and could be moved back and forth within a precision of 0.01 mm. The Langmuir probe was located at the core of the plasma column to obtain the time series of the plasma density with a 1 MHz/s data acquisition system developed in this laboratory. We employed a Langmuir double cylindrical probe with a diameter of 0.7 mm and length of 11.5 mm. At the same time, the real time series of reflection $S11$ was recorded by a PNA E8362B network analyser. As illustrated in Fig.2, antenna 1 was used to radiate electromagnetic waves and receive the signal backward synchronously, the other antenna was used to verify the probe measurement by the microwave cutoff method. The distance between the radiation surface of antenna 1 and the diffraction grating was fixed at 35 mm, while the surface of antenna 2 was located 100 mm away from the discharge chamber.

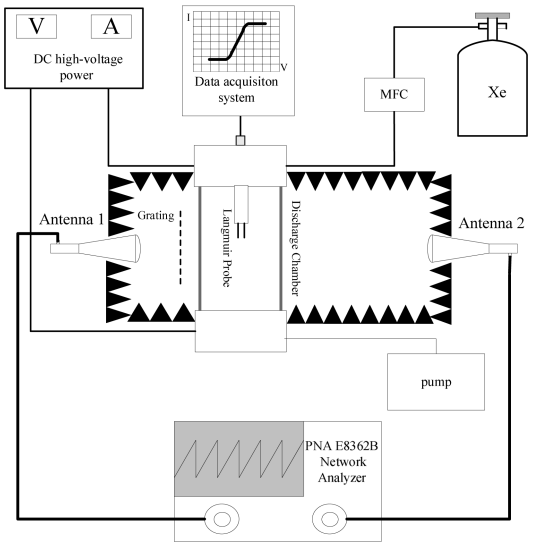


Fig.2. Experimental arrangement and diagnostic method. The discharge chamber is a cylinder with a 630 mm length and 100 mm inner radius. The grating consists of a periodical set of aluminium strips with a width of 20 mm and a period of 60 mm.

In this work, we measured the reflection parameter $S11$ of the incident p-polarized electromagnetic radiation when the overdense plasma is present ($S11_{\mathrm{plasma}}$), and compared the results with those when the plasma is absent ($S11_{\mathrm{initial}}$). Scanning measurement ranging from 4.8 to 5.8 GHz were made when the plasma is overdense and 2-minute series measurement at 5 GHz when plasma density changed with time. Compared with the work in Refs.[21] and [22], we further performed an experimental study of SPs when the density of the overdense plasma exceeded $4n_{\mathrm{c}}$ for the first time so far as we know. Reference [21] provided the measured result at a frequency of 9.37 GHz, without discussing the role of incident polarization in the coupling into SPs. The instance when an s-polarized incident electromagnetic radiation (TE) cannot be coupled into SPs has been demonstrated experimentally by Ref.[22]. It was indicated[21,22] that the reflection coefficient of the incident electromagnetic radiation would reach nearly zero when SPs are excited at the boundary of the overdense plasma.

We also found that when the density of the overdense plasma changed, the excitation of SPs would depend strongly on the distance l between the diffraction grating and the boundary of the overdense plasma. Experiments indicated that the condition for excitation of SPs is that the diffraction grating must be fixed at $l = 12.5$ mm when the plasma density $n_{\mathrm{e}} > 4n_{\mathrm{c}}$.

4. Results and discussion

Figure 3 shows the scanning results of the reflection parameters when the overdense plasma density is 1.36×10^{12} cm^{-3} (if normalized to the critical density of 5 GHz, the density is $4.26n_{\mathrm{c}}$). The frequency of the p-polarized incident electromagnetic radiation is in the range of 4.8 GHz$< f <$ 5.8 GHz. The strip grating is fixed at $l = 12.5$ mm. The reflection coefficient $R = (S11_{\mathrm{plasma}}/S11_{\mathrm{initial}}) \times 100\%$. Note that only the region of $R \leq 1$ is presented in the figure. The microwave results are recorded by the network analyser and the plasma density is diagnosed by a Langmuir double probe.

As described in Fig.3, the value of the reflection coefficient R would be less than unity for 4.9423 GHz$< f <$ 5.2794 GHz, and a sharp minimum would be achieved at $f = 5$ GHz. Furthermore, the reflectivity at 5 GHz approached zero. We considered it was due to the excitation of SPs[20,21,24] at the boundary

of the overdense plasma.

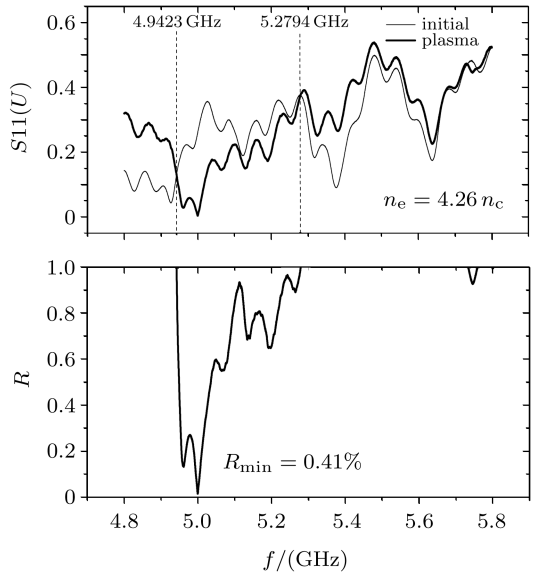


Fig.3. Comparison of $S11$ at $n_e = 4.26n_c$ to that without plasma for the p-polarized incident radiation ranging from 4.8 to 5.8 GHz. The grating is present, and the reflection coefficient $R = (S11_{plasma}/S11_{initial}) \times 100\%$. Here $p = 18$ Pa, $l = 12.5$ mm.

Figure 4 illustrates the change of the reflection coefficient R when the plasma density changes with time. The strip grating is present and the incident electromagnetic radiation at the frequency of 5 GHz is p-polarized. Here, plasma density n_e is normalized to the critical density n_c, corresponding to 5GHz as diagnosed by the Langmuir double-probe. A pair of values of R and n_e is given per second.

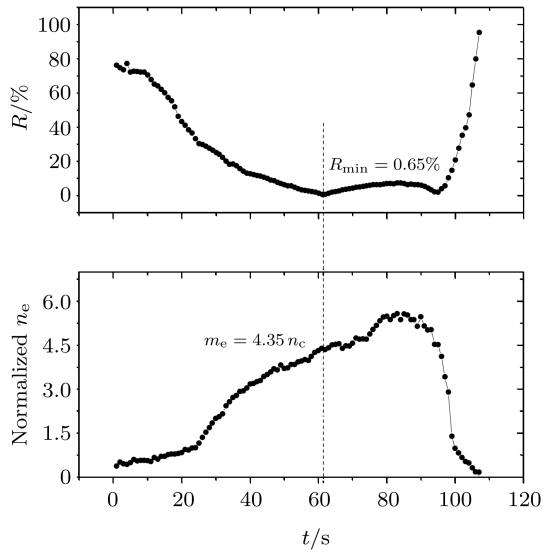


Fig.4. Two-minute series of R and n_e with grating present when the incident electromagnetic radiation at 5GHz is p-polarized. Here $p = 18$ Pa, $l = 12.5$ mm.

Unlike the experiments made in Ref.[22], we have obtained the results in a range of overdense plasma density that is remarkably high and may exceed by four times the critical density corresponding to a 5 GHz frequency. Since we have demonstrated experimentally in Ref.[22] that SPs along the interface between the overdense plasma and the outer medium can only be excited when the incident electromagnetic radiation is p-polarized in the presence of the grating, we focus on this situation only. As illustrated in Fig.4, when the plasma density is near $4.35n_c$, the reflection coefficient reaches nearly zero, which can be viewed as the total absorption. And it is in good agreement with the plasma density $n_e = 4.26n_c$ shown in Fig.3. The minimum 0.65% in Fig.4 is much less than that in Ref.[22]. It should be noted that the reflection coefficient does not reach its minimum when $n_e = 2.42n_c$ as in Ref.[22]. That is because when the plasma density reaches the value, the overdense plasma has not become stationary, which can be seen clearly through the slope of n_e in Fig.4.

The phenomenon of nearly total absorption is due to the excitation of SPs at the boundary of the overdense plasma. The incident energy is not reflected back by the overdense plasma but transferred along the interface between the overdense plasma and the outer medium. From Fig.4 we learn that when SPs are excited, $\varepsilon_p = 1 - n_e/n_c = -3.35$. If we still consider that the dispersion relation of SPs is mainly contributed by the air layer (whose permittivity can be considered to be that of vacuum $\varepsilon_0 = 1$) and ignore the contribution of the glass layer,[21] the expression for the dispersion relation and the coupling order may be obtained by a combination of Eqs.(2) and (3).

$$\kappa_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_p}{1+\varepsilon_p}}, \tag{5}$$

$$n = \pm\frac{d}{\lambda_0}\sqrt{\frac{\varepsilon_p}{1+\varepsilon_p}}. \tag{6}$$

However, we will not obtain an integer for the coupling order n from Eq.(6) even though the measuring errors are taken into consideration.

On the other hand, if we ignore the contribution by the air layer and only take the glass layer into consideration, then

$$\kappa_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_g\varepsilon_p}{\varepsilon_g+\varepsilon_p}}, \tag{7}$$

$$n = \pm\frac{d}{\lambda_0}\sqrt{\frac{\varepsilon_g\varepsilon_p}{\varepsilon_g+\varepsilon_p}}, \tag{8}$$

where ε_g is the glass permittivity (4.2 in our experiments). The fact that $|\varepsilon_g| > |\varepsilon_p|$ when SPs are excited, renders the solution for Eqs.(7) and (8) physically meaningless. It violates the necessary requirement that $\varepsilon_m < -\varepsilon_p$ in Eq.(2). Moreover, even if we take the measuring error of the plasma density into consideration, it is impossible to obtain a fixed integer for the coupling order n.

Therefore, the contribution to SPs by both the air layer and the glass layer should be taken into account. Figure 5 provides the description; Fig.5(b) takes the glass layer and air layer as a uniform medium whose permittivity is ε_{eff}. The decay length δ_{eff} in Fig.5(b) is equivalent to δ_m in Fig.5(a).

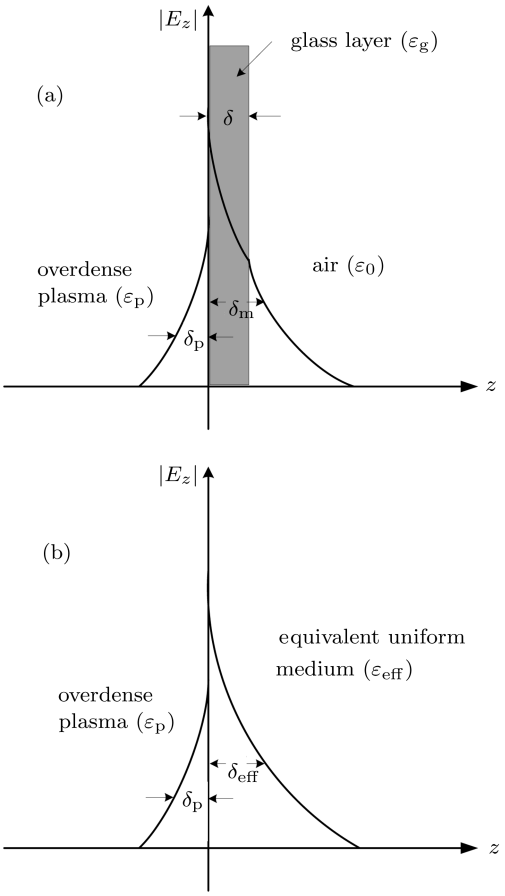


Fig.5. Schematic diagram of the relation between $|E_z|$ and the distance from boundary on both sides. (a) the real situation, and (b) an equivalent description.

As shown in Fig.5, we can find that the contribution of the glass layer to the effective permittivity depends on its thickness δ. If $\delta \gg \delta_m$, the contribution would be mainly made by the glass layer; if $\delta \ll \delta_m$, the contribution would be mainly from the air layer whose permittivity can be considered as that of vacuum. The latter is the case in Ref.[21], in which SPs were excited when the normalized density was 2.5. To substitute corresponding parameters into Eq.(6), we could have the coupling order $n' = \pm 1.08$, which is in good agreement with the default order ± 1 there. Similarly, to the result reported in Ref.[22], if we follow the case where the excitation of SPs is mainly contributed by the vacuum and ignore the contribution of the glass layer, we will have the coupling order $n'' = \pm 1.85$, which can be considered to be ± 2 (corresponding to the theoretical plasma density $n_e/n_c = 2.33$) with the plasma density measuring error taken into account.

As discussed above, in our situation when SPs are excited at $\varepsilon_p = -3.35$, we can ignore neither layers in the formation of SP dispersion. The thickness of the glass layer δ and the decay length δ_{eff} should be in the same range, that is, $\delta \sim \delta_{eff}$. The permittivity in Eq.(2) subsequently should be modified by an effective permittivity ε_{eff},

$$\kappa_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{eff}\varepsilon_p}{\varepsilon_{eff}+\varepsilon_p}}. \tag{9}$$

And the coupling order

$$n = \pm\frac{d}{\lambda_0}\sqrt{\frac{\varepsilon_{eff}\varepsilon_p}{\varepsilon_{eff}+\varepsilon_p}}. \tag{10}$$

The effective permittivity ε_{eff}, which is determined by the glass layer and air layer, should be greater than that of air and less than that of glass which we use. Moreover, ε_{eff} must be less than $-\varepsilon_p$ when SPs are really excited with an exhibition of nearly total absorption of reflectivity. Figure 6 shows a simulation on the relation between the coupling order n and the effective permittivity ε_{eff}, with ε_{eff} in the range of $1.25 - 3.25$. SPs are excited when $\varepsilon_p = -3.35$.

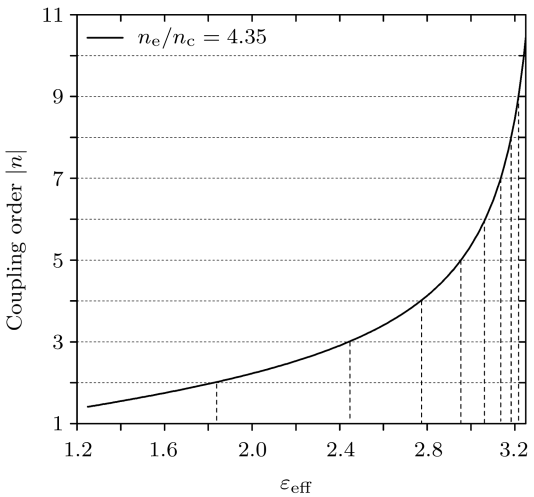


Fig.6. Simulation result of SP order n with effective permittivity in the range of $1.25 < \varepsilon_{eff} < 3.25$. SPs are excited when $\varepsilon_p = -3.35$.

Our simulation is qualitative, and we can see that when effective permittivity ε_{eff} is in this range, the coupling order n has the opportunity to become integer. However, we have not obtained the exact order quantitatively. In our future work, we will take up the challenge from this study and further investigate the quantitative influence of the layer between air and plasma on the excitation of SPs at the boundary of an overdense plasma.

5. Conclusions

In this paper, we have investigated the excitation of SPs at the boundary of an unmagnetized overdense plasma with a strip grating theoretically and experimentally. The incident electromagnetic radiation was p-polarized at the frequency of 5 GHz. Experiments showed that when the plasma density was four times higher than the critical density with the grating present, SPs would be excited at the boundary of the overdense plasma. We also have examined the contribution of the glass layer in the formation of the SP dispersion relation, and qualitatively simulated the coupling order with the effective permittivity from the incident electromagnetic radiation into SPs. The exhibition of SPs at the boundary of the overdense plasma indicates that the reflection coefficient of the incident electromagnetic radiation reaches its minimum and even becomes total absorption.

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