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The Surface Plasmon Polaritons at the Metal which is Sandwiched between Two Different Dielectrics (Dielectric 1/ Metal/ Dielectric 2)

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Abstract
Electromagnetic waves that propagated at the interface between metal and dielectrics were widely known as surface plasmon polaritons (SPP). This type of polaritons attracted people to study since the frequency was in the terahertz region. Hence, it could be utilized in the terahertz technology. The properties of polaritons were represented by dispersion relation. The method to derive the formulation of surface polaritons was by solving Maxwell's equation, then it was followed by analysing continuity of the fields at the involved interfaces. The derived dispersion relation was solved numerically using finding root technique. In this study, we analyse surface polaritons in the dielectric 1/ metal/ dielectric 2 geometry. Here dielectric 1 and dielectric 2 were different dielectrics with the different values of permittivity. It was found that the dispersion relation curve of surface plasmon polaritons consisted of two branches. One branch represented SPP that generated and propagated at the top surface. The other branch was SPP at the bottom surface of metal film. We also found if the usage of two different dielectrics with the different values of permittivities were large, then the difference of the two curves were also significant.

Keyword: dispersion relation, surface plasmon polaritons, dielectric/metal/dielectric

Introduction

The electromagnetic waves that propagated at the interfaces between metal and dielectrics or ferroelectrics were widely known as surface plasmon polaritons (SPP) [1]. The generation of the SPP involved photon from incident electromagnetic waves and free electrons from the metals. Here, the permittivities of both metals and dielectric is very important, since the permittivity of metals and dielectrics should be in the opposite signs in generating the surface plasmon polaritons. In the certain frequency range, the real permittivity of metals had negative signs. Hence, with the positive permittivity of dielectrics, these metals can propagate the surface plasmons at the interface.

There was many studies about SPP which propagated along metal-dielectrics due to its potential applications in medicine[2], energy[3] and information system[4]. The generation of SPP mostly involved single surface between dielectrics and metals[5,6]. The studies developed to also include the double interfaces[7]. This case was found when metal or photonic material was sandwiched between two dielectric medium. The generation of SPP at the top and bottom interfaces require that the thickness of metal was thinner than the screening thickness of that metal.

It was expected that the surface plasmon polaritons comprised of two modes since there was two involved interfaces. One modes was generated at the top interface while the other was excited at the bottom interface. In this paper, we wanted to study the characteristic of SPP. The behavior of the SPP can be obtained by deriving the dispersion relation of the system. In surface polaritons, it was also required to analyze the continuity of all the fields at the involved interfaces. We predicted to obtain two branches of the dispersion relation curves that represent two modes of surface polaritons.

The method and formulation

As illustrated in Fig.(1), the geometry of this work was explained as follow. A metal with the thickness d was sandwiched between two semi-infinite dielectrics. The dielectric above metal had permittivity ϵ_1, while dielectric below metal had permittivity ε_2. The planes of interfaces were located in *x-y* plane with the top interface was set at $z = d/2$ and the bottom interfaces was placed at $z = -d/2$. Here we used the electromagnetic waves in TM mode. Here, the magnetic component of electromagnetic waves is directed parallel to the *y* axis (perpendicular to the plane of incident, *x-z* plane). It was assumed that surface modes propagated in x direction. Hence, the fields components involved in this mode were $\{H_y;\ E_x;\ E_z\}$.

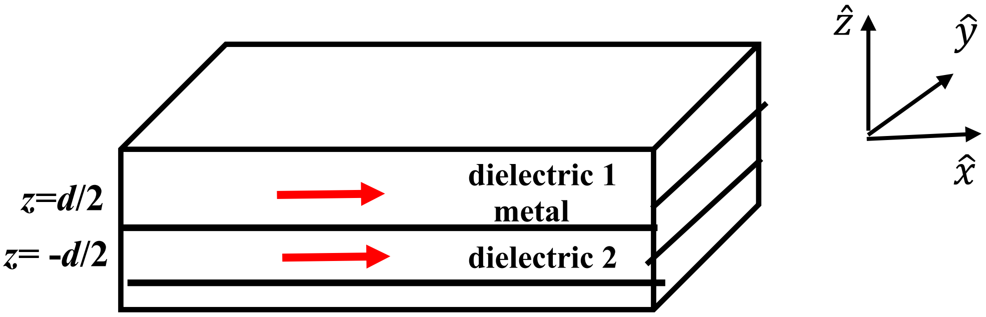


Figure 1. Geometry of the study. The metal was sandwiched between dielectric 1 and dielectric 2. Interface was located *at x-y* plane, one at $z = d/2$ and the other at $z = -d/2$. The surface modes propagated in *x* direction.

We set the magnetic component as

$$\vec{H} = \hat{y}H_0 e^{\beta_1\left(z-\frac{1}{2}d\right)} e^{i(k_x x-\omega t)} \quad \text{for } z > \tfrac{1}{2}d, \tag{1a}$$

$$\vec{H} = \hat{y}\left[H_m e^{\beta_m\left(z-\frac{1}{2}d\right)} + \tilde{H}_m e^{-\beta_m\left(z-\frac{1}{2}d\right)}\right] e^{i(k_x x-\omega t)} \quad \text{for } -\tfrac{1}{2}d < z < \tfrac{1}{2}d, \tag{1b}$$

$$\vec{H} = \hat{y}\tilde{H}_0 e^{\beta_2\left(z+\frac{1}{2}d\right)y} e^{i(k_x x-\omega t)} \quad \text{for } z < -\tfrac{1}{2}d. \tag{1c}$$

Here, the $H_0, H_m, \tilde{H}_m$ and $\tilde{H}_0$ represented the related waves. The variables β_1 and β_2 were the attenuation constants of the dielectrics, while β_m determined an attenuation constant for metal. The attenuation constant was generally formulated as

$$\beta = \left(k_x^2 - \varepsilon\frac{\omega^2}{c^2}\right)^{1/2} \tag{2}$$

where the permittivity for the dielectrics was given in the form: $\varepsilon = \varepsilon^{\infty}\left(\frac{\omega_{L,O}^2-\omega^2}{\omega_{T,O}^2-\omega^2}\right)$. The variable ω_{LO} was optical longitudinal frequency, while ω_{TO} represented optical transverse frequency. Here, ε^{∞} was high frequency dielectric constant. We also used Drude model to determine the permittivity for the metal as

$$\varepsilon_m = \left(1 - \frac{\omega_p^2}{\omega^2}\right) \tag{3}$$

where ω_p was plasma frequency. Here, we assumed that the thickness of the metal was smaller than the skin depth of the metal. This would guarantee that the surface mode localized at the bottom interface could be generated.

In order to derive dispersion relation of surface mode, we had to determine all the involved fields in each region. The electric components (E_x and E_z) could be obtain by exploiting Faraday law in Maxwell equation: $\nabla \times \vec{H} = -\frac{\omega}{c}\varepsilon\vec{E}$. The displacement fields could be derived using $\vec{D} = \varepsilon\vec{E}$, while magnetic fields $\vec{B}$ was determined by $\vec{B}$=$\vec{H}$ since we did not use magnetic material.

The next step was employing continuity of the fields at the all interfaces (at $z = \frac{1}{2}d$ and $z = -\frac{1}{2}d$). The required continuity conditions were: tangential component of $\vec{H}$ (H_y), tangential component of $\vec{E}$ (E_x) and the normal component of $\vec{D}$ (D_z). Then, by analyzing the resulted equations from that continuity conditions, we obtained the dispersion relation in the form as:

$$\left(\frac{\beta_m}{\varepsilon_m} + \frac{\beta_1}{\varepsilon_1}\right)\left(\frac{\beta_m}{\varepsilon_m} + \frac{\beta_2}{\varepsilon_2}\right) = \left(\frac{\beta_m}{\varepsilon_m} - \frac{\beta_1}{\varepsilon_1}\right)\left(\frac{\beta_m}{\varepsilon_m} - \frac{\beta_2}{\varepsilon_2}\right)e^{-2\beta_m d}. \tag{4}$$

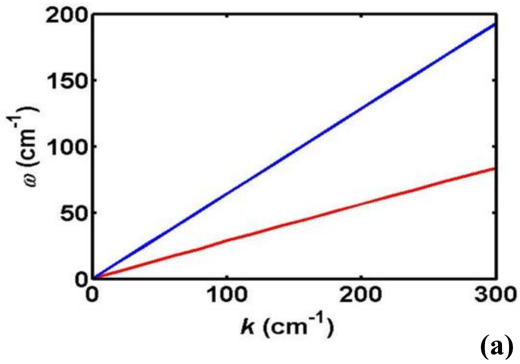
In the case where there was only one dielectric surrounding metal, the dispersion relation in Eq.(4) above became

$$\left(\frac{\beta_m}{\varepsilon_m}+\frac{\beta_d}{\varepsilon_d}\right)=\left(\frac{\beta_m}{\varepsilon_m}-\frac{\beta_d}{\varepsilon_d}\right)e^{-\beta_m d} \quad (5)$$

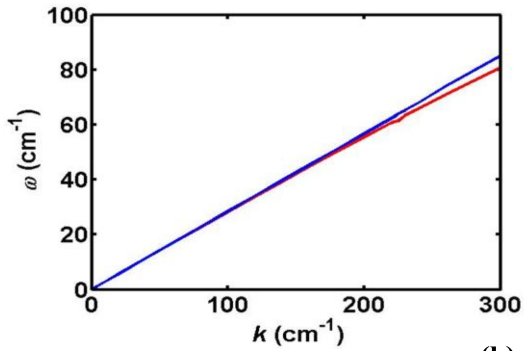
where β_d and ε_d represented attenuation constant and permittivity of the dielectric.

Results and Discussion

In this study, we used frequency plasma, $\omega_p = 3.01 \times 10^4 \mathrm{cm}^{-1}$,which was illustrated as silver. Above metal, we set the parameter for dielectric S_iO_2 with $\omega_{TO} = 903$ cm^{-1}, $\omega_{LO} = 907$ cm^{-1} and ε^{∞}= 2.4. The parameters for dielectric below the metal represented InP with $\omega_{TO} = 903$ cm^{-1}, ω_{LO} =907 cm^{-1} and ε^{∞}= 9.52. Here, we considered that the involved dielectric permittivities were isotropic. The numerical solution of Eq.(5) was illustrated in Fig.(2) below. The Fig.(2a) was the case where the dielectric above metal was S_iO_2, while the dielectric below metal was InP. The result for the case where the dielectric above metal and dielectric below metal were the same (InP) was iilustrated in Fig.(2b).



(a)



(b)

Figure 2. The dispersion relation of surface plasmon polaritons. (a) The case with the top dielectric was S_iO_2. (b) the case with both top and bottom dielectrics were similar, using InP.

In Fig.2, the results were presented for the frequency range between 0 to 300 cm^{-1}. The surface polaritons were having two branches. The blue branch related to the polariton which was generated at the top surface of the metal film. The other branch (red curve) represented the surface polaritons at the bottom of the metal. This result was also reported in the previous work [8] for magnetoelectric multiferroics. It was also stated that the propagation of the surface polaritons at the bottom of the film was in the opposite of the propagation of surface polaritons at the top of the film.

It can also be seen that the difference between top and bottom branches of surface polaritons in the case of two different dielectrics was much wider than that in the case of the same dielectrics compare Fig.(2a) and Fig (2b). We argued that the difference between top and bottom branches was contributed mainly by two things. The first cause was the different permittivity of the involved dielectrics (above and below metal). The thickness of the metal also gave contribution to the difference between top and bottom branches. Hence, it was clear that in the case of single dielectric, the difference between branches was narrow (see Fig.(2b)).

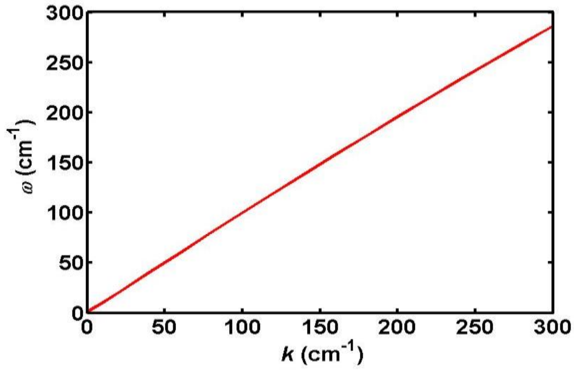


Figure 3. The dispersion relation in free space. Here, the metal film was placed in the free space. The dielectrics were not use in this case.

The case where a metal film was placed in the free space was also presented in this paper. Here, dielectric was not involved. The surface plasmon polaritons were generated at the interface between metal and free space (vacuum). The dispersion relation was shown in Fig.(3). Here, we only found a branch of curve (see Fig.(3). We predicted that this branch was related to the localization of SPP at the top surface. In our opinion, this result appeared because of the free space below metal could not provide enough electric field to maintain the localization of the SPP at the bottom surface. Hence, we only obtained single mode if dielectric was not involved.

Conclusion

The appearance of the two modes of surface plasmon polaritons was highly depended on the permittivites of the involved dielectrics. The difference between two modes was wide when the values of permittivity of those dielectrics were significantly different. However, in the case when we used free space instead of dielectrics, we only got one branch of SPP.

Acknowledgment

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