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Numerical study of vegetable oil as dielectric in the generation of surface plasmon polaritons in metal: The case of double interfaces

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Abstract

Modified electromagnetic waves which is resulted from coupling of surface plasmon and initial electromagnetic waves are called surface plasmon polaritons (SPP). These type of polaritons are generated at the interface between metal and dielectric. Many studies are performed since SPP have potential application in many fields. The process of generating SPP was usually using dielectrics in the form of solid. However, the usage of liquid dielectric in generating SPP is very rare. In this study, we predict numerically the usage of liquid dielectrics by solving the dispersion relation of the SPP. The dispersion relation was derived using Maxwell equations and the continuity of the fields at the interfaces. The metal was immersed in the liquid dielectrics. We used parameters of castor oil as liquid dielectric in the numerical calculation. We found that the dispersion relation had two branches. One branch represented in phase condition while the other branch illustrated out of phase condition. This result agree with the previous research using solid dielectric.

Keyword: surface plasmon polaritons, double interfaces, vegetable oils

Introduction

Coupled state between quantization of surface charge oscillation and photon which traveled parallel to the interface metal-dielectrics was called surface plasmon polaritons (SPPs) (Cunningham et al., 1974). Two well known methods in generating SPP were gratings at metal surface (Ritchie et al., 1968) and optical method using ATR (attenuated total reflection) (Otto, 1968; Kretchmann et al., 1968). Recently, SPPs attracted many attentions due to its potential application, especially for designing nano-structure based devices such as band pass filters (Liu et al, 2021), amplitude modulator (Khani et al., 2021), nano-photonic devices (Shi et al., 2021) and also for tera-hertz technology (Wang et al., 2022). Many studies focused on metals which were used in generating SPPs and also in manipulating SPP (Welford, 1991; Pitarke et al., 2007).

The dielectric materials were one of the key elements in generating SPPs. The dielectrics as passive medium supported the existence of electric field which then provided the polarization at the interface leading to the generation of collective oscillation of the surface plasmon. The usage of non-linear dielectrics was investigated to generate transverse electric (TE) modes of SPPs (Baher et al., 2018). The non-linear dielectric was also used to study spatial instability in the structure where metal was sandwiched between two dielectrics (Kumar et al., 2017). Dielectrics which were implanted by metal ions were also studied for the sensor applications (Wang et al., 2021). Even though liquid dielectrics were widely known in the capacitor (Albishi et al., 2021) and transformer technology (Sarpataky et al., 2021), however the studies of dielectric fluids related to the SPPs, especially in the generation of SPPs, were very limited. We could only find the used of liquid dielectrics to study SPPs application in laser nano-patterning of Si surfaces (Kudryashov et al., 2020).

In this preliminary study, we investigate numerically the possibility to use dielectric fluids in the generation of SPPs. We only consider the dielectric constant of the dielectric fluids as a key parameter in the derivation of SPPs dispersion relation. We consider to use vegetable oils as fluid dielectrics since organic oils are environment friendly and also renewable.

The geometry and method

We consider a metal film with permittivity ε_m and thickness d was immersed into fluid dielectric with permittivity ε_d, as illustrated in Fig.1. Here, there were two interfaces which were involved. The top interface was placed on *x-y* plane at $z = {}^{d}/_{2}$ while the bottom surface was located at $-{}^{1}/_{2}\, d$. The geometry of the study is sketched in Fig.1. In this study, we considered that the reflection plane was located at *x-z* plane. The surfaces modes travelled along *x* direction.

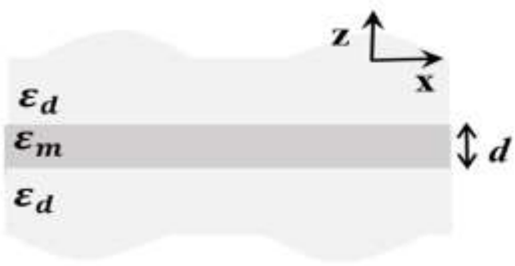

Figure 1. The sketch of metal film with permittivity ε_m was placed inside dielectric fluids with permittivity ε_d. The interfaces were located at *x-y* plane.

The existence of SPPs can be represented by dispersion relation, In the classical approximation, The dispersion relation was obtained by firstly determining the field components of electromagnetic waves for each involved region. Since we needed charges at the metal surfaces from the discontinuity of the normal component of the electric fields (E_z) to support surface charges, then we considered the transverse magnetic (TM) electromagnetic waves where the magnetic fields perpendicular to the reflection plane. Here, the TM modes provided the required normal component of the electric fields E_z. The all involved fields components in TM modes were H_y, E_x and E_Z. In these modes, the magnetic components in dielectrics were represented by

$$\vec{H} = \begin{cases} \hat{j} H_d e^{-\beta_d\left(z-\frac{1}{2}d\right)}\, e^{i(k_x x-\omega t)} & \text{for} \quad z > \frac{1}{2}d \\ \hat{j}\widetilde{H}_d e^{\beta_d\left(z+\frac{1}{2}d\right)}\, e^{i(k_x x-\omega t)} & \text{for} \quad z < -\frac{1}{2}d \end{cases} \qquad (1)$$

with β_d was attenuation constant for dielectric materials. The magnetic components in metal were assumed as

$$\vec{H} = \hat{j}\left[H_m e^{\beta_m\left(z-\frac{1}{2}d\right)} \pm \widetilde{H}_m e^{-\beta_m\left(z+\frac{1}{2}d\right)}\right] e^{i(k_x x-\omega t)} \quad \text{for} \quad \tfrac{1}{2}d > z > -\tfrac{1}{2}d \qquad (2)$$

with β_m represented attenuation constant for metal. Here, the solution was superposition of the top and bottom surface modes. The positive sign in Eq.2 illustrated that the two surface modes were in phase while the negative sign represented the out of phase condition.

The next step, the field components E_x and E_z determined by employing Maxwell equation $\nabla \times \vec{H} = \frac{1}{c}\frac{\partial \vec{D}}{\partial t}$. The electric displacement field $\vec{D}$ and magnetic induction field $\vec{B}$ were derived using consecutive equations $\vec{D} = \varepsilon\vec{E}$ and $\vec{B} = \mu\vec{H}$. Then we analyze the continuity of the fields at the top and bottom interfaces.

In the condition where the surface waves at the top and bottom interfaces were out of phase, the continuity of $\vec{H}$, continuity of tangential $\vec{E}$ and continuity of normal $\vec{D}$ were analyzed in the top interface result in

$$H_d = H_m - \widetilde{H}_m e^{-\beta_m d} \qquad (3)$$

and

$$\frac{\beta_d}{\varepsilon_d} H_d = \frac{\beta_m}{\varepsilon_m}\left(H_m + \widetilde{H}_m e^{-\beta_m d}\right). \qquad (4)$$

Then, the similar continuities were applied for the bottom interface leading to the equations

$$\widetilde{H}_d = H_m e^{-\beta_m d} - \widetilde{H}_m \qquad (5)$$

and

$$-\frac{\beta_d}{\varepsilon_d}\widetilde{H}_d = \frac{\beta_m}{\varepsilon_m}\left(\widetilde{H}_m + H_m e^{-\beta_m d}\right). \quad (6)$$

The dispersion relation for the out of phase can be obtained by employing Eq.(3)-(6) as

$$\frac{\varepsilon_m}{\beta_m}\frac{1}{\coth(\beta_m d/2)} + \frac{\varepsilon_d}{\beta_d} = 0. \quad (7)$$

The similar procedure was performed for in phase case using positive sign in magnetic field in Eq.(2) resulted dispersion relation in the form

$$\frac{\varepsilon_m}{\beta_m}\frac{1}{\tanh(\beta_m d/2)} + \frac{\varepsilon_d}{\beta_d} = 0. \quad (8)$$

Hence, there were two curves in graphic of dispersion relation.

Results and Discussion

The solution for dispersion relations Eq.(7) and Eq.(8) were solved numerically. In the permittivity of metal, $\varepsilon_m = \left(1 - \frac{\omega_p^2}{\omega^2}\right)$, we set the metal was gold with $\omega_p = 5.8$ eV as plasma frequency. We also used castor oil as liquid dielectric with the permittivity $\varepsilon_d = 14.78$ (Roslan et al., 2021). We set the thickness of gold to be 0.1 mm. The results of numerical calculation for the dispersion relations were obtained using root finding technique. The results were presented in Figure 2

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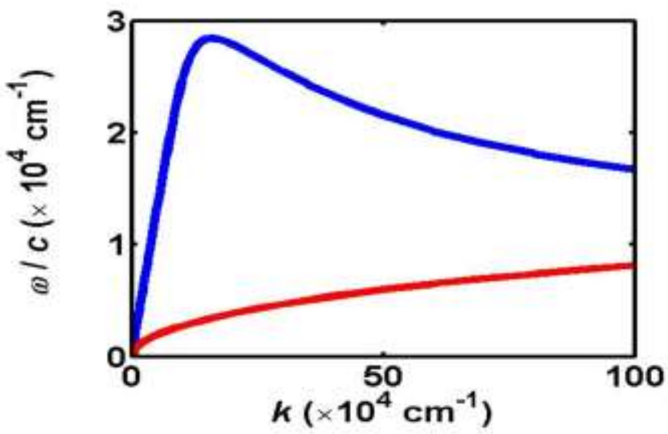

Figure 2. The dispersion relation of SPP at gold-castor oil interfaces with the thickness of gold was 0.1 mm. The red line represented in phase condition while blue line was illustrated for out phase condition.

It can be noticed that the relation between frequency ω and propagation vector k_x was not linear. In our calculation, we obtained two curves. One with the blue line represented the superposition with in phase condition while the other with the red line illustrated out of phase condition. The appearance of these two shapes was similar to the curves from the previous report for aluminum film (Petit et al., 1975). These two curves were obtained from the interaction between two surface modes on metal interfaces. In the condition when the thickness of metal was very thick, then $\tanh(\beta d/2) \cong \coth(\beta d/2) \cong 1$ resulted in the condition where the dispersion relation in Eq.(7) for out of phase and in Eq.(8) for in phase had similar relation as

$$\frac{\varepsilon_m}{\beta_m} + \frac{\varepsilon_d}{\beta_d} = 0. \quad (9)$$

It illustrated that when the thickness is very thick, then the surface modes at the top and bottom of the film cannot interact. Hence, the superposition as indicated in Eq.(2) did not happen. The surface modes at each interface of the metal slab act as a surface mode on the single surface in semi-infinite geometry.

Conclusion

In this work, we presented that it was possible to generate surface plasmon polariton on metal-liquid dielectrics interfaces. We showed that our result was in good agreement with the previous work using metal-solid dielectrics. However, here we only consider the dielectric constant of the liquid dielectric. In our future work, we will include the additional parameters which illustrated the liquid phase of dielectric to make the numerical study closed to reality.

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