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# Hybridized surface plasmon polaritons at an interface between a metal and a uniaxial crystal

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The surface plasmon polariton (SPP) at an interface between a metal and a uniaxial crystal is studied. A new class of hybridized SPP found in this work is quite different from the traditional SPP at the interface between a metal and an isotropic dielectric. In contrast to the two evanescent fields for the traditional SPP, the hybridized SPP involves four evanescent fields: transverse-electric-like and transverse-magnetic-like waves in the metal, and ordinary-light-like and extraordinary-light-like waves in the uniaxial crystal. The necessary conditions and the regimes for the existence of the hybridized SPP are presented. Some potential applications are also discussed. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2908920]

An electromagnetic surface wave propagates along an interface with its amplitude exponentially decaying away from the interface. It has many potential applications, such as in enhanced second harmonic generation,[1] surface enhanced Raman scattering,[2] and tissular detection.[3] Depending on the type of interfaces, different electromagnetic surface waves can be supported. In general, the electromagnetic surface wave can be classified into Dyakonov surface wave,[4,5] photonic crystal surface wave,[6] surface plasmon polariton (SPP),[7] and so on. Up until now, only limited effort has been devoted to investigating SPP at the interface between an isotropic metal and an anisotropic dielectric.[8,9] Jen *et al.* developed a SPP-based method in determining the principal values of the permittivity tensor of the uniaxial crystal.[8] Krokhin *et al.* showed that long-range propagating SPP mode can be achieved by using large-birefringence materials.[9] In the present letter, we show that SPP at the interface between a metal and a uniaxial crystal has some unique properties; for instance, it has the polarization-hybridized nature and can only exist in some special situations and regimes. Some potential applications are also discussed.

The interface structure and the coordinate system are shown in the inset of Fig. 2, where the $x$ axis is normal to the interface, and the $y$ and $z$ axes are within the interface. The *uniaxial* crystal with a permittivity tensor $\boldsymbol{\varepsilon_c}$ and the *isotropic* metal with a permittivity $\varepsilon_m<0$ occupy the upper $(x>0)$ and lower $(x<0)$ spaces, respectively. The principal values of $\boldsymbol{\varepsilon_c}$ are $\varepsilon_o$, $\varepsilon_o$, and $\varepsilon_e$, respectively. Without loss of universality, we assume that the optic axis (OA) of the uniaxial crystal is within the interface and forms an angle $\varphi$ with the propagation direction of SPP ($z$ axis), and one of the other two principal axes is along the $x$ direction. Throughout this letter, all the wavevectors are scaled by the wavevector $k_0$ in vacuum. As is well-known, a traditional SPP at the interface between a metal and a dielectric (both are isotropic) can only be launched by the transverse-magnetic (TM) wave. However, for the interface structure shown in the inset of Fig. 2, SPP cannot be launched either by the pure TM or by the TE (transverse-electric) wave due to the anisotropy of the uniaxial crystal. In contrast to the two evanescent fields for the traditional SPP, the SPP for this particular interface structure has a polarization-hybridized nature and involves four evanescent fields (two field modes each in both the metal and the uniaxial crystal) with a common wavevector $\beta$ in the $z$ direction. The isotropic metal ensures that the two evanescent fields in the metal have an identical wavevector $\boldsymbol{k}_m=(-iq_m,0,\beta)$; they can be classified as TE-like and TM-like waves according to their polarizations. Similar to the ordinary-light (OL) and extraordinary-light (EL) waves in a bulk uniaxial crystal, the two evanescent fields in the uniaxial crystal can be classified as the OL-like and EL-like waves with wavevectors $\mathbf{k}_o=(iq_o,0,\beta)$ and $\mathbf{k}_e=(iq_e,0,\beta)$. Here, $q_m$, $q_o$, and $q_e$ must be positive and real, $q_m$ and $q_o$ are independent of $\varphi$, while $q_e$ is a function of $\varphi$; they are determined by the following conservation laws:

$$(\beta^2-q_m^2)/\varepsilon_m=1, \quad (1)$$

$$(\beta^2-q_o^2)/\varepsilon_o=1, \quad (2)$$

$$(\beta^2\sin^2\varphi-q_e^2)/\varepsilon_e+(\beta^2\cos^2\varphi)/\varepsilon_o=1. \quad (3)$$

Inasmuch as the four cases of $\varphi$, $-\varphi$, $\pi-\varphi$, and $\pi+\varphi$ are, in fact, indistinguishable, the discussions below will only focus on the regime of $0\leqslant\varphi\leqslant\pi/2$. Based on the electromagnetic boundary conditions at the interface, one can easily obtain the following relationship:

$$(q_m+q_o)(q_m+q_e)(\varepsilon_o q_e+\varepsilon_m q_o)=(\varepsilon_e-\varepsilon_m)(\varepsilon_m-\varepsilon_o)q_o. \quad (4)$$

For Eq. (4) to be valid, $\varepsilon_o q_e+\varepsilon_m q_o<0$ must be satisfied. Together with Eqs. (2) and (3), this yields the condition $|\varepsilon_m|>\min[\varepsilon_e,\varepsilon_o]$.

Due to the anisotropy of the uniaxial crystal, the hybridized SPP does not exist for all angle $\varphi$ and it disappears in the following two cases: (I) one of $q_m$, $q_o$, and $q_e$ becomes 0 and (II) $\beta=\infty$.

Case I: Equation (1) shows that $q_m$ can never be 0, otherwise $\beta$ will be imaginary due to $\varepsilon_m<0$. Assuming $q_o=0$,

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Eq. (4) indicates that $q_e$ must also be 0 because of $q_m \neq 0$. Thereby, we only need to discuss the situation of $q_e=0$. With Eqs. (1)–(4), one can define a function

$$f'(\varepsilon_e,\varepsilon_o,\varepsilon_m) = \frac{\varepsilon_e^3(\varepsilon_o - \varepsilon_m)}{[\varepsilon_o(\varepsilon_m - \varepsilon_e)^2 - \varepsilon_e^2\varepsilon_m](\varepsilon_e - \varepsilon_o)}. \quad (5)$$

A critical angle $\varphi'$ (corresponding to $q_e=0$), if it exists, can be found by the equation $\sin^2\varphi' = f'(\varepsilon_e,\varepsilon_o,\varepsilon_m)$.

Case II: When $\beta=\infty$, Eqs. (1)–(3) suggest that $q_m$, $q_o$, and $q_e$ all simultaneously approach infinity, and Eq. (4) reduces to $q_o = -(\varepsilon_o/\varepsilon_m)q_e$. Together with Eqs. (1)–(3), the other critical angle $\varphi''$, if it exists, can be determined by $\sin^2\varphi'' = f''(\varepsilon_e,\varepsilon_o,\varepsilon_m)$, where

$$f''(\varepsilon_e,\varepsilon_o,\varepsilon_m) = (\varepsilon_e\varepsilon_o - \varepsilon_m^2)/[(\varepsilon_e - \varepsilon_o)\varepsilon_o]. \quad (6)$$

Of course, whether the critical angles ($\varphi'$ and $\varphi''$) exist or not depends on the values of $f'$ and $f''$. With the requirements of $q_e > 0 \cap \beta < \infty$ in mind, we can now discuss the necessary conditions and regimes for the existence of the hybridized SPP for positive and negative uniaxial crystals, respectively.

Positive uniaxial crystal ($\varepsilon_e > \varepsilon_o$): As $f'$ in Eq. (5) is always positive. For $f'$, we only need to discuss two cases: $0 < f' \leq 1$ and $f' > 1$. Also, since $f'' > 1$ implies $|\varepsilon_m| < \varepsilon_o$, SPP can never exist. Hence, only two situations $f'' < 0$ and $0 < f'' \leq 1$ need to be discussed.

For the first case, $0 \leq f' \leq 1$, Eq. (5) requires

$$|\varepsilon_m| \geq \varepsilon_e\varepsilon_o/(\varepsilon_e - \varepsilon_o). \quad (7)$$

To ensure that the hybridized SPP does exist within the regime of $\varphi < \varphi'$, the two subcases $f'' < 0$ and $0 \leq f'' \leq 1$ must be further examined.

It follows from Eq. (6) that if $f'' < 0$, then

$$|\varepsilon_m| > \sqrt{\varepsilon_e\varepsilon_o}. \quad (8a)$$

$\beta < \infty$ is always valid for all angles $\varphi$. By combining Eqs. (7) and (8a), one finds that the hybridized SPP does exist within the regime of $0 \leq \varphi < \varphi'$, with the following condition:

$$|\varepsilon_m| > \max[\sqrt{\varepsilon_e\varepsilon_o}, \varepsilon_e\varepsilon_o/(\varepsilon_e - \varepsilon_o)], \quad (8b)$$

Similarly, $0 \leq f'' \leq 1$ (implying that $\varphi''$ exists) requires the following condition:

$$\sqrt{\varepsilon_e\varepsilon_o} \geq |\varepsilon_m| \geq \varepsilon_o. \quad (9a)$$

The existence of the hybridized SPP is permissible within the regime of $\varphi > \varphi''$. Inasmuch as $\varepsilon_e\varepsilon_o/(\varepsilon_e - \varepsilon_o) > \varepsilon_o$, by combining Eqs. (7) and (9a), we obtain

$$\sqrt{\varepsilon_e\varepsilon_o} \geq |\varepsilon_m| \geq \varepsilon_e\varepsilon_o/(\varepsilon_e - \varepsilon_o). \quad (9b)$$

We can further prove that $\varphi'' < \varphi'$. Therefore, the hybridized SPP exists within the regime of $\varphi'' < \varphi < \varphi'$, under the condition of Eq. (9b).

For the second case, $f' > 1$, Eq. (5) requires

$$|\varepsilon_m| < \varepsilon_e\varepsilon_o/(\varepsilon_e - \varepsilon_o). \quad (10)$$

The hybridized SPP exists for all angles $\varphi$, but further restriction from $f''$ has to be considered, which can be divide into two subcases.

TABLE I. A summary of the necessary conditions and the regimes for the existence of the hybridized SPP supported at an interface between an isotropic metal and a uniaxial crystal. There are only four possible cases, (a)–(d), when the uniaxial crystal is positive uniaxial ($\varepsilon_e > \varepsilon_o$), while there are only two cases, (e) and (f), when the uniaxial crystal is negative uniaxial ($\varepsilon_e < \varepsilon_o$).

| Case | Regime | Condition |
|---|---|---|
| (a) | $0 \leq \varphi < \varphi'$ | $\|\varepsilon_m\| > \max[\sqrt{\varepsilon_e\varepsilon_o}, \varepsilon_e\varepsilon_o/(\varepsilon_e-\varepsilon_o)]$ |
| (b) | $\varphi'' < \varphi \leq \pi/2$ | $\varepsilon_o \leq \|\varepsilon_m\| < \min[\sqrt{\varepsilon_e\varepsilon_o}, \varepsilon_e\varepsilon_o/(\varepsilon_e-\varepsilon_o)]$ |
| (c) | $\varphi'' < \varphi < \varphi'$ | $\sqrt{\varepsilon_e\varepsilon_o} \geq \|\varepsilon_m\| \geq \varepsilon_e\varepsilon_o/(\varepsilon_e-\varepsilon_o)$ |
| (d) | $0 \leq \varphi \leq \pi/2$ | $\sqrt{\varepsilon_e\varepsilon_o} < \|\varepsilon_m\| < \varepsilon_e\varepsilon_o/(\varepsilon_e-\varepsilon_o)$ |
| (e) | $0 \leq \varphi < \varphi''$ | $\sqrt{\varepsilon_e\varepsilon_o} \leq \|\varepsilon_m\| \leq \varepsilon_o$ |
| (f) | $0 \leq \varphi \leq \pi/2$ | $\|\varepsilon_m\| > \varepsilon_o$ |

For $f'' < 0$ ($\varphi''$ does not exist), one arrives at Eq. (8a). Equations (8a) and (10) suggest that $\beta < \infty$ is always valid, the hybridized SPP can be supported at any angle $\varphi$ under the condition

$$\sqrt{\varepsilon_e\varepsilon_o} < |\varepsilon_m| < \varepsilon_e\varepsilon_o/(\varepsilon_e - \varepsilon_o). \quad (11)$$

For $0 \leq f'' \leq 1$, Eqs. (9a) and (10) show that the hybridized SPP exists within the regime of $\varphi'' < \varphi \leq \pi/2$, under the condition

$$\varepsilon_o \leq |\varepsilon_m| < \min[\sqrt{\varepsilon_e\varepsilon_o}, \varepsilon_e\varepsilon_o/(\varepsilon_e - \varepsilon_o)]. \quad (12)$$

Negative uniaxial crystal ($\varepsilon_e < \varepsilon_o$): In this case, $f'$ is always negative; thus, the existence of the hybridized SPP is possible at any angle $\varphi$. However, we have to further examine three subcases of $f'' < 0$, $0 \leq f'' \leq 1$, and $f'' > 1$.

For $f'' < 0$, Eq. (6) requires $|\varepsilon_m| < \sqrt{\varepsilon_o\varepsilon_e}$. Since $\beta$ is infinity in this subcase, the hybridized SPP could never be supported.

For $0 \leq f'' \leq 1$, Eq. (6) requires

$$\sqrt{\varepsilon_e\varepsilon_o} \leq |\varepsilon_m| \leq \varepsilon_o. \quad (13)$$

The hybridized SPP could be allowed within the regime of $0 \leq \varphi < \varphi''$.

Finally, for $f'' > 1$, Eq. (6) implies that

$$|\varepsilon_m| > \varepsilon_o. \quad (14)$$

The hybridized SPP could be supported for all angles $\varphi$ under the condition of Eq. (14).

For the sake of clarity, Table I summarizes the necessary conditions and the regimes for existence of the hybridized SPP supported at the interface between the metal and the uniaxial crystal.

We now present the numerical simulation results for visually understanding the necessary conditions and the regimes for existence of the hybridized SPP, as well as the polarization characteristics and the dispersion relations of the hybridized SPP. Figures 1(a)–1(f) show the dependence of $q_m$, $q_e$, $q_o$, and $\beta$ on $\varphi$, corresponding to the six cases (a)–(f) in Table I, respectively. One explicitly sees that the simulation results agree with our analysis very well. To distinguish the polarization characteristic of the hybridized SPP, we define two quantities, $P_{O/E}$ and $P_{E/M}$, which stand for the amplitude ratios of the OL-like wave to the EL-like one and of the TE-like wave to the TM-like one, respectively. As shown in Fig. 1, $P_{O/E}$ and $P_{E/M}$ strongly depend on $\varphi$, which indeed validates the hybridity of SPP. When $\varphi=0$ or $0.5\pi$ (implying that the light wave propagates along or perpendicular to the

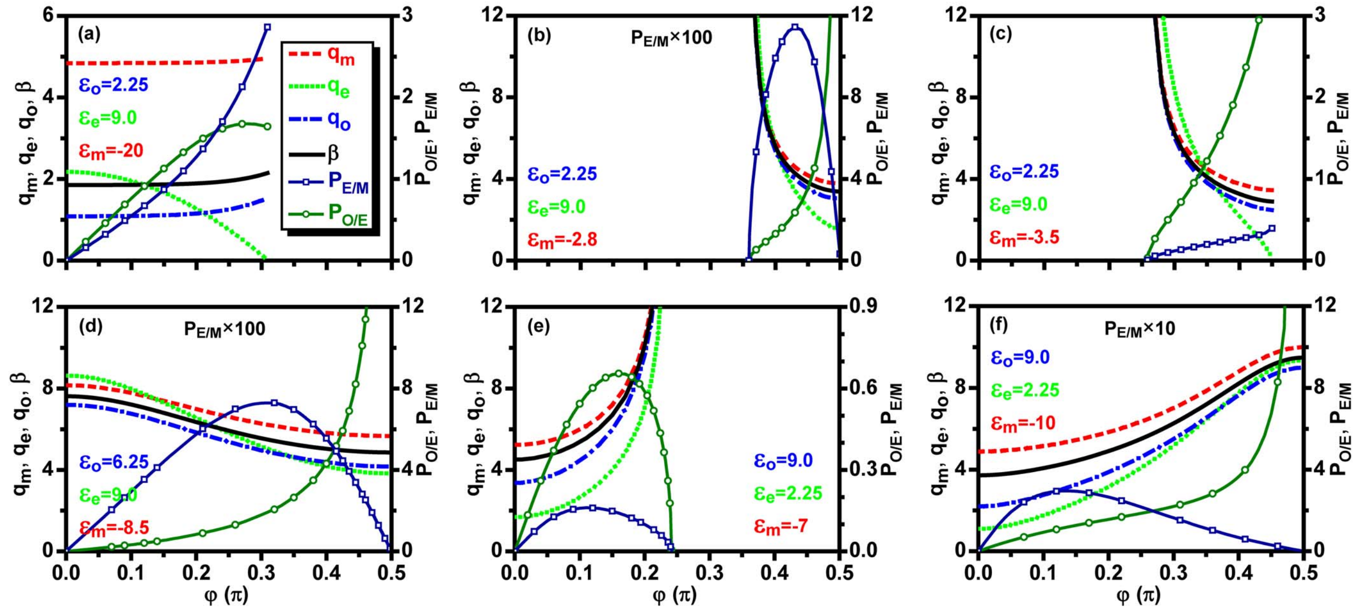

FIG. 1. (Color online) Dependences of $q_m$, $q_e$, $q_o$, and $\beta$, as well as $P_{O/E}$ and $P_{E/M}$, on $\varphi$.

direction of OA), the hybridized SPP merges into the traditional SPP. In the case of $\varphi=\varphi''$, SPP also merges into the traditional SPP. In contrast, in the case of $\varphi=\varphi'$, SPP still exhibits the hybridity.

Due to the intrinsic azimuth dependence of the hybridized SPP, we should also explore the dispersion relations at different azimuth angles $\varphi$. For the dispersion of the metal, we choose the widely adopted Drude model, $\varepsilon_m=1-\omega_p^2/\omega^2$, where $\omega_p$ and $\omega$ are the angular frequencies of the plasma and the electromagnetic radiation, respectively. Figure 2 explicitly depicts that SPPs at different azimuth angles obey different dispersions, in particular, with different cutoff frequencies, which originate from the anisotropy of the uniaxial crystal. Therefore, the frequency of the hybridized SPP can be tuned by choosing the orientation of OA.

The hybridized SPP can find some potential applications such as in anisotropic detection, tunable SPP resonance, and directional signal transportation. For instance, for application of the tunable hybridized SPP resonance on enhanced spontaneous emission,[10] if the traditional SPP at the interface between two isotropic media is utilized, only a half of spontaneous emission can be enhanced because only the TM-polarized component can launch SPP. In contrast, if in using the hybridized SPP, the spontaneous emission efficiency can be significantly enhanced, since the TE-polarized component can also be utilized. Inasmuch as the hybridized SPP has different resonance frequencies and different polarization fractions in different propagation directions, the hybridized SPP can be used to achieve directional signal transportation or directional electromagnetic antenna.

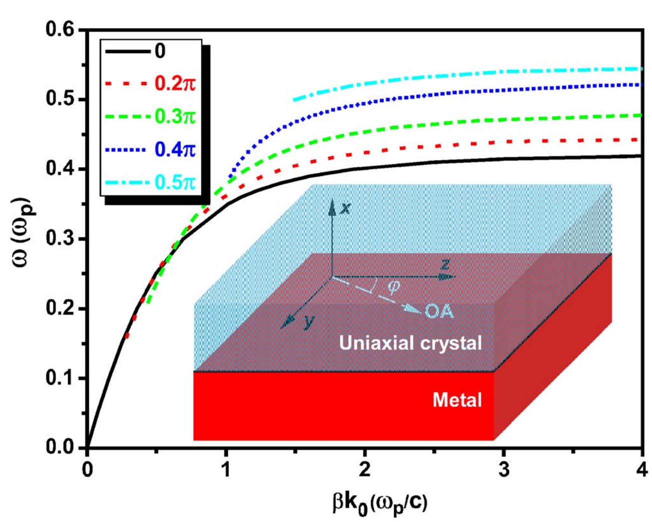


FIG. 2. (Color online) Dispersion curves of the hybridized SPP at different azimuth angles. The inset depicts the interface structure and the coordinate system.

In summary, we explore the properties of SPP supported at an interface between an isotropic metal and a uniaxial crystal. Such SPP belongs to the hybridized SPP in polarization, which is quite different from the traditional SPP at the interface between two isotropic media (metal and dielectric). The necessary conditions and the regimes for the existence of such a kind of hybridized SPP are derived. Some potential applications of the hybridized SPP are briefly discussed.

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