The Refraction of Surface Plasmon Polaritons

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Abstract

We show how a complex Snell’s law can be used to describe the refraction of surface plasmon polaritons (SPPs) at an interface between two metals, validating its predictions with 3-D electro-dynamics simulations. Refraction gives rise to peculiar SPP features including inhomogeneities in the waveform and dispersion relations that depend on the incident wave and associated material. These features make it possible to generate SPPs propagating away from the interface with significant confinement normal to the propagation direction. We also show that it is possible to encode optical properties of the incident material into the refracted SPP. These consequences of metal-metal SPP refraction provide new avenues for the design of plasmonics-based devices.
Surface plasmon polaritons (SPPs), surface waves created by coupling light into charge-density oscillations at a metal–dielectric interface, continue to be of current interest \[1\]–\[7\]. Systems that permit the excitation of SPPs can exhibit interesting and unexpected optical properties, including extraordinary optical transmission \[8\] and super-lensing \[9\]–\[11\]. Such properties are also relevant to a wide range of applications including imaging and sensing \[12\]–\[16\] and optoelectronics \[17\]–\[20\]. Therefore, learning how to control and manipulate SPPs as they propagate along a metal surface is a major goal of nanophotonics research. A particular goal for optoelectronics applications involves introducing lateral confinement of the SPPs without sacrificing the propagation length \[19\]–\[21\]–\[23\]. For sensing applications, sensitivity figures of merit depend not on the features of the SPP wave itself, but on the SPP dispersion relations, where a desirable feature is a strong dependence of the SPP dispersion on the dielectric environment \[15\]–\[16\].

SPPs propagate on a 2-D metal surface, and are exponentially confined both above and below this surface, suggesting that one can attempt to describe and manipulate their motion using ideas from classical optics applied to the 2-D propagation plane. Successful examples include the focusing of SPPs created by an array of holes or slits in metal films \[24\]–\[25\] and the generation of Talbot effect intensity patterns \[26\]–\[28\]. SPPs have also been shown experimentally to exhibit refraction behavior when they propagate across an interface between two metal/dielectric interfaces with differing optical properties \[29\]–\[30\]. Negative refraction of SPP-dominated waveguide modes has also been achieved \[31\]. In this Letter, we analyze SPP refraction, presenting and discussing the implications of a complex generalization of Snell’s law (CSL). The CSL predicts that refracted SPPs will be inhomogeneous and will obey dispersion relations that depend not only on the medium supporting the refracted SPP, but on the incident wave and medium. The inhomogeneous character of the refracted wave can be exploited to introduce significant confinement of the SPP without sacrificing propagation length. The dependence of the dispersion of the refracted SPP on the details of the incident wave introduces the possibility of encoding or imprinting the plasmonic properties of one material onto another, including anomalous dispersion phenomena (back-bending) and ‘slow-light’ \[32\]. Dispersion encoding imparts an unexpected environmental sensitivity to the refracted SPP, which may be useful for sensing applications.\[15\]–\[16\]–\[18\]

Refraction of 3-D plane waves from a dielectric medium into an absorbing medium is a well-known problem \[33\]–\[35\] and there are also treatments of refraction that allow for
the medium of the incident wave to be absorbing \[36–38\]. Here we adapt the particularly transparent treatment of Chang, Walker and Hopcraft\[38\] to the case of 2-D SPP refraction at the boundary between different metal surfaces and discuss several consequences. The system of interest involves an SPP, generated by conventional means, propagating on top of a metal surface 1 that has dielectric material 1 above it; it is reflected and refracted at the interface with a different metal surface 2 with possibly different dielectric 2 above it (Fig. 1). The refracted SPP propagates on the surface of metal 2. The propagation of the SPPs on each surface can be described with 2-D waveforms moving in the \( x - y \) plane of Fig. 1,

\[
E_j = E_{0,j} \exp (i \mathbf{k}_j \cdot \mathbf{r} - i \omega t),
\]

where \( \mathbf{k}_j \) is a complex SPP wavevector associated with incident (\( j = 1 \)) or refracted (\( j = 2 \)) waves. (For the present purposes reflection is not of relevance.) A 2-D medium refractive index may be defined based on the standard SPP dispersion relation:

\[
\eta_j + i \kappa_j = \left( \frac{\epsilon_j \epsilon_j^D}{\epsilon_j + \epsilon_j^D} \right)^{1/2},
\]

where \( \epsilon_j = \epsilon_j(\omega) \) is the frequency-dependent permittivity of metal \( j \) and \( \epsilon_j^D \) is the permittivity of the dielectric material above it. The incident SPP wavevector is

\[
\mathbf{k}_1 = \frac{\omega}{c} (\eta_1 + i \kappa_1) \hat{e},
\]

where \( \hat{e} = \sin(\theta_1) \hat{x} + \cos(\theta_1) \hat{y} \) is a unit vector indicating the direction of propagation. The lines of constant phase and constant amplitude for \( \mathbf{E}_1 \) are parallel and \( \hat{e} \) is the direction normal to both these types of lines. \( \mathbf{E}_1 \) is therefore homogeneous. In contrast, the refracted SPP is allowed to be inhomogeneous; its lines of constant phase and amplitude are not necessarily parallel. The wavevector for the refracted SPP is thus taken to be

\[
\mathbf{k}_2 = \frac{\omega}{c} \left( N_2 \hat{a} + i K_2 \hat{b} \right),
\]

where \( \hat{a} = \sin(\theta_2) \hat{x} + \cos(\theta_2) \hat{y} \) is a unit vector normal to the lines of constant phase, \( \hat{b} = \sin(\phi_2) \hat{x} + \cos(\phi_2) \hat{y} \) is a unit vector normal to the lines of constant amplitude, and the effective indices \( N_2 \) and \( K_2 \) depend on the medium refractive indices \( \eta_2, \kappa_2, \eta_1, \kappa_1 \) and incident angle, \( \theta_1 \). The boundary conditions and wave equation determine \( N_2 \) and \( K_2 \) in terms of the known quantities. The SPP phases \( \mathbf{k}_j \cdot \mathbf{r} \) must be continuous at the \( y = 0 \)
FIG. 1. (a) Diagram of SPP refraction at a metal-dielectric/metal-dielectric interface. The incident SPP propagates on the 2-D interface between metal 1 and dielectric 1, with direction \( \hat{e} \) being associated with both the real and imaginary parts of its wavevector. The wavevector of the refracted SPP propagating in the interface region of metal 2 and dielectric 2 has direction \( \hat{a} \) associated with its real part and direction \( \hat{b} \) associated with its imaginary part. (b) 2-D effective medium picture of the refraction in the \( x-y \) plane of (a).

Metal-metal interface, implying

\[
\eta_1 \sin(\theta_1) = N_2 \sin(\theta_2) \\
\kappa_1 \sin(\theta_1) = K_2 \sin(\phi_2).
\]

(5) \hspace{2cm} (6)

We refer to Eqs. (5) and (6) as the complex Snell’s law (CSL) because they determine the angles of refraction of the real and imaginary parts of the complex refracted SPP wavevector. All the quantities involved in these equations are still real and so the complication of complex angles is avoided. To determine \( N_2 \) and \( K_2 \), inserting \( E_2 \) of the form Eq. (1) into the usual second-order electromagnetic wave equation gives

\[
(k_2 \cdot k_2) E_2 = \frac{\omega^2}{c^2} (\eta_2 + i\kappa_2)^2 E_2,
\]

(7)

which is satisfied if

\[
N_2^2 - K_2^2 = \eta_2^2 - \kappa_2^2.
\]

(8)
and
\[ N_2 K_2 \cos(\theta_2 - \phi_2) = \eta_2 \kappa_2. \] (9)

Using Eqs. (5) and (6), Eq. (9) is equivalent to
\[ \eta_2 \kappa_2 - \alpha_1 \beta_1 = \sqrt{N_2^2 - \alpha_1^2} \sqrt{N_2^2 - (\eta_2^2 - \kappa_2^2)} - \beta_1^2, \] (10)

where \( \alpha_1 = \eta_1 \sin(\theta_1) \) and \( \beta_1 = \kappa_1 \sin(\theta_1) \). Squaring both sides of Eq. (10) gives a quartic equation for \( N_2 \), which has the following root of interest
\[ N_2 = \frac{1}{\sqrt{2}} \sqrt{a + \sqrt{b}}, \] (11)

where
\[ a = \alpha_1^2 + \beta_1^2 + \eta_2^2 - \kappa_2^2, \]
\[ b = ((\kappa_2 - \beta_1)^2 + (\eta_2 - \alpha_1)^2) ((\kappa_2 + \beta_1)^2 + (\eta_2 + \alpha_1)^2). \]

Once \( N_2 \) is known, \( K_2 \) may be determined readily using Eq. (8); \( \theta_2 \) and \( \phi_2 \) are then found from form the CSL, Eqs. (5) and (6).

In the case of normal incidence (\( \theta_1 = 0 \)) the CSL leads to \( N_2 = \eta_2, K_2 = \kappa_2, \) and \( \theta_2 = \phi_2 \), i.e. a refracted SPP in medium 2 that is an ordinary medium 2 SPP. Otherwise, there are two new features: (1) \( \theta_2 \neq \phi_2 \), i.e. the waveform is inhomogeneous with its lines of constant phase and constant amplitude no longer being parallel and (2) \( N_2 + iK_2 \neq \eta_2 + i\kappa_2 \), i.e. the complex propagation constant (and dispersion relation) is not the same as that for an ordinary SPP in medium 2.

The propagation length \( (L_P) \) of an SPP is the distance, measured along the propagation direction, that the SPP propagates when the intensity decays to \( |E|^2_0/e \). For an ordinary (homogeneous) SPP in medium 2, \( L_P = 1/(2k_0 \kappa_2) \), where \( k_0 \) is the free-space wavevector of the exciting light, \( k_0 = 2\pi/\lambda_0 \). For a refracted SPP in medium 2, this distance is measured along \( \hat{a} \) and is given by \( L_P = 1/(2k_0 K_2 \cos(\theta_2 - \phi_2)) \). Utilizing Eq. (9), the ratio of the refracted SPP propagation length to an ordinary SPP propagation length is simply \( N_2/\eta_2 \) and so if \( N_2 > \eta_2 \) there will be propagation length enhancement. We define a confinement length \( (L_C) \) as the distance in the direction perpendicular to propagation over which the SPP intensity decays to \( |E|^2_0/e \). The confinement length of an inhomogeneous SPP is given by \( L_C = 1/(2k_0 K_2 \sin(\theta_2 - \phi_2)) \), where a more strongly confined SPP has a shorter confinement
FIG. 2. Field profiles of incoming SPP (below white dashed line) excited on an Au surface by 532 nm light with incident angle 25° refracting onto an Ag surface (above white dashed line). Air is assumed to be above both surfaces. (a) and (b): Analytical CSL and FDTD electric field intensities, respectively. (c) and (d): Analytical and FDTD instantaneous electric field components, respectively. The FDTD results are $x - y$ cuts taken at a $z$ level 120 nm above metal surfaces and are associated with the $z$ component of the electric field.

length. In the event of propagation length enhancement, $K_2$ itself will be larger than $\kappa_2$; hence propagation length enhancement is also associated with strong confinement of the refracted SPP.

We first consider Au for metal 1 and Ag for metal 2 with air as the dielectric above each metal, and an incident SPP on Ag excited with $\lambda_0 = 532$ nm light. We take $\epsilon_1 = -4.762 + 2.378 \ i$ and $\epsilon_2 = -11.825 + 0.374 \ i$[39] which gives medium refractive indices $\eta_1 = 1.092$, $\kappa_1 = 0.057$, $\eta_2 = 1.045$, and $\kappa_2 = 0.0015$. While $\eta_1$ and $\eta_2$ are similar in magnitude, $\kappa_1$ is significantly larger than $\kappa_2$ and so $\phi_2$ rises very rapidly with $\theta_1$ (see Fig. S3). When an incident angle of 25° is considered, the CSL predicts $\theta_2$ to be 26° and $\phi_2$
to be $112^\circ$ (see Fig. S3). ($\phi_2$ can be larger than $90^\circ$ because the arcsine has two unique values, a principal value between 0 and $\pi/2$ and a secondary value between $\pi/2$ and $\pi$; one or the other of these values is the physically correct one. See the Supporting Material) The analytical CSL electric field intensity ($|E_z|^2$) and instantaneous field map, Re($E_z$), are shown in Fig. 2 (a) and (c), respectively. To validate these predictions, we use rigorous 3-D finite-difference time-domain (FDTD) calculations ([40, 41]) (see Supporting Material) to simulate the refraction phenomena and plot $|E_z|^2$ and Re($E_z$) in Fig. 2 (b) and (d), respectively. (Other FDTD field components give similar results.) The FDTD results show a high degree of similarity in the SPP wavelength, propagation direction, and attenuation behavior with that predicted by CSL. Values of the simulated electric field intensity are sampled along the propagation direction ($\hat{a}$) and fit an exponential to allow accurate inference of $L_P$ (see Fig. S1). The FDTD fields do differ from the CSL ones in that there is a fast decay of the FDTD field in the upper left region of Figs. 2 (b) and (d). This is simply due to the finite size of the excitation source used in the simulations (see Supplementary Material). One can also see slight interference fringes in the FDTD results due to interference of incident and reflected waves.

We find that the propagation length of the refracted SPP as determined by rigorous 3-D electrodynamics calculation is approximately 28 $\mu$m, compared to 27 $\mu$m from analytical predictions using CSL. The FDTD instantaneous field allows us to infer a propagation direction of $27^\circ$, compared to the CSL prediction of $26^\circ$. The simulated propagation length thus closely matches the propagation length predicted for a normal SPP excited on a silver surface, but the refracted SPP has significant lateral confinement compared to an ordinary SPP. We follow a similar procedure to extract $L_C$, this time sampling the electric field intensity along the direction perpendicular to $\hat{a}$, and nearly parallel to $\hat{b}$. We find $L_C$ of the refracted SPP is 1.1 $\mu$m as determined by FDTD calculation, which agrees closely to the CSL prediction of 1.7 $\mu$m (see Fig. S1). Note that an ordinary SPP in this medium would propagate with no such confinement lateral to the propagation direction. Analysis of the FDTD lines of constant amplitude allows us to infer an attenuation direction of $115^\circ$, similar to the CSL prediction of $112^\circ$. In this first example, $\phi_2$ is relatively large relative to $\theta_2$, i.e., the direction of the amplitude decay is nearly normal to the propagation direction, a dramatic change relative to the incident wave that had amplitude decay in the same direction as the propagation direction. Regarding the effective indices in medium 2,
FIG. 3. Field profiles of the refracted SPP on an Al surface arising from refraction of an incident SPP on a Au surface. An $\epsilon^D_1 = 4$ material is assumed to be above the Au surface and glass, $\epsilon^D_2 = 2.25$, is assumed to be above the Al surface. The incident SPP was excited with 780 nm light and had incident angle $50^\circ$. (a) and (b): Analytical CSL and FDTD electric field intensities, respectively. (c) and (d): Analytical and FDTD instantaneous electric field components, respectively. (e) Dispersion relation for the SPP generated on Al (solid red) showing how refraction imparts strong features of Au’s SPP dispersion (dashed blue) onto the refracted wave.

it turns out that $K_2 = 0.0252$, which is significantly larger that the medium value of $\kappa_2 = 0.0015$, but that $N_2 \approx \eta_2 = 1.045$. The next example will involve more significant changes in $N_2$, which is proportionate to the real part of the propagation vector and determines the dispersion relation.

As a second example consider $\lambda_0 = 780$ nm excitation of SPPs on Au as metal 1 ($\epsilon_1 = -22.660 + 1.411 i$[39]), with a high refractive index material ($\epsilon^D_1 = 4$, e.g. TiO$_2$) above.
These SPPs refract at an interface with aluminum as metal 2 ($\epsilon_2 = -66.263 + 45.719 i$) with glass ($\epsilon_D = 2.25$) above. These result in medium refractive indices of $\eta_1 = 2.202$, $\kappa_1 = 0.014$, $\eta_2 = 1.517$, and $\kappa_2 = 0.012$. In this example, when $\theta_1 = 50^\circ$ $\theta_2 \approx 90^\circ$ while $\phi_2 \approx 1.5^\circ$, making this akin to total internal reflection (TIR) (see Fig. S4). FDTD results again show a high degree of similarity in propagation direction and attenuation behavior (see Fig. 3 (a)-(d)) and a strong quantitative agreement in the predicted propagation and confinement lengths (see Fig. S2). We focus only on the fields in medium 2, but again interference patterns can be seen in the FDTD fields (Figs. 4 (c) and (e)) resulting from interference of the reflected and incident SPP in medium 1. Analysis of the lines of constant phase and amplitude from FDTD simulations gives a propagation direction of $90^\circ$ and an attenuation direction of approximately $0.5^\circ$, respectively, in excellent agreement with CSL predictions. Interestingly, some experimental evidence for this particular consequence of Snell’s law (TIR plasmons) has already been reported [30].

The FDTD propagation length of the refracted SPP is approximately $5.6 \mu m$, and CSL also predicts $5.6 \mu m$ (see Fig. S2). The corresponding ordinary SPP on an Al/glass surface would have a propagation length of $5.0 \mu m$, so this provides an example of modest propagation length enhancement. The refraction also produces an extremely confined mode: FDTD $L_C \approx 0.1 \mu m$; CSL $L_C = 0.08 \mu m$ (see Fig. S2). $L_P$ may be enhanced proportionally to $N_2/\eta_2$, so it is expected the refracted SPP will have a shorter wavelength than an ordinary SPP propagating in medium 2. Indeed, we find the refracted FDTD $\lambda_{SPP}$ to be 486 nm compared to a wavelength of 462 nm predicted by CSL. An ordinary SPP propagating in medium 2 would have a wavelength of 514 nm. In this example both the real and imaginary parts of the effective index of the refracted SPP are different from the medium 2 values: $N_2 = 1.688$ compared to $\eta_2 = 1.517$ and $K_2 = 0.738$ compared to $\kappa_2 = 0.012$.

It is also interesting for this example to consider the behavior of the refracted SPP in Al/glass across a spectrum of incident frequencies, i.e. its dispersion. Unlike an ordinary SPP dispersion in an Al/glass system, the refracted SPP dispersion also has information about the refractive index, $\eta_1 + i\kappa_1$ and the angle of incidence, $\theta_1$, in the Au/$\epsilon_D = 4$ medium. Mapping out the real part of the propagation vector, $(\omega/c)N_2$, with $\theta_1 = 50^\circ$ shows a startling departure from the ordinary Al/glass result (Fig. 3 (e)). The ordinary Al/glass dispersion is relatively featureless, the wavevector increases uniformly with $\omega$ so that the SPP group velocity is approximately independent of frequency. The dispersion of the refracted SPP
shows markedly different features, including a dramatic slowing of group velocity in the frequency range between 1.5 and 2 eV and a back-bending region between 2 and 3 eV. These features mirror dispersion characteristics of SPPs on the gold/$\epsilon_D^2 = 4$ medium (see Fig. 3(e)). To see the relationship between the details of the incident SPP and the dispersion of the refracted SPP more clearly, we note that $\eta_2^4$ can be factored out of b Eq. 11 so the root can be written $N_2 = \frac{1}{2} \sqrt{a + \eta_2^2 \sqrt{1 + f}}$. We can then expand $\sqrt{1 + f}$ to first order in $f$, yielding the following approximation of $N_2^2$,

$$N_2^2 \approx \eta_2^2 + \beta_1^2 - \frac{2}{\eta_2} \alpha_1 \beta_1 \kappa_2 + \frac{1}{4 \eta_2^2} (\alpha_4^4 + \beta_1^4 + \kappa_2^4 + 2 (\kappa_2^2 \alpha_1^2 - \kappa_2^2 \beta_1^2 + \beta_1^2 \alpha_1^2)).$$

(12)

$\eta_2$ makes a strong contribution to $N_2$, which is to be expected as the dispersion of the refracted SPP should depend on the material properties of the metal/dielectric supporting its propagation. What is interesting to note is the fact the terms involving $\alpha_1$ ($\beta_1$) can make strong contributions to $N_2$ when $\theta_1$ is large and $\eta_1$ ($\kappa_1$) is large. Both $\eta_1$ and $\kappa_1$ tend to be large in the vicinity of the surface plasmon resonance (SPR) of material 1, which in terms of the SPP dispersion, is associated with the back-bending or anomalous dispersion region [32, 43–45]. Back-bending features can be encoded from material 1 to material 2 in general, but they will often be associated with high loss. Recalling the definitions of $L_P$ and $L_C$, we observe that the any additional loss imparted by refraction leads to greater confinement of the SPP and not additional attenuation in the propagation direction.

In this Letter, we presented a complex generalization of Snell’s law (CSL) to be applied to the refraction of SPPs propagating across a metal-metal interface. This theory predicts several surprising features of the refracted SPPs which were validated using 3-D electrodynamics simulations. In particular, we demonstrated that refraction can generate SPPs that are inhomogeneous in the plane of propagation. It is possible to introduce significant confinement and, in certain cases, propagation length enhancement to the refracted modes. A further consequence is that the refracted SPPs obey unique dispersion relations that depend on the supporting medium as well as the incident medium. The theory should also be applicable to more complicated structures such as the layered waveguide modes described by Atwater and co-workers for the measurement of negative refraction in the visible spectrum [31], and indeed such structures might provide experimentally realizable systems for the peculiar predictions that result from the CSL discussed here. The theoretical and numerical results presented suggest that simple geometric principles such as the CSL discussed here can
offer novel and powerful strategies for engineering SPPs, which could be particularly useful for optoelectronics and sensing applications. For example, although we do not discuss this application in detail, FDTD simulations demonstrate SPP focusing can be achieved using a metal region acting as a plasmonic lens (see Fig. S6). The focusing through refraction of such a lens could allow the generation of tightly confined and controlled SPP modes without loss of propagation length. Optical switching devices could also be constructed using incident angle or superstrate dielectric constant as noxes to induce a dramatic change in the propagation behavior of the refracted SPP. Similarly, the dependence of the refracted wave on the dielectric properties of the incident medium may also prove useful in chemical and biological sensing applications.

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