J. Opt. A: Pure Appl. Opt. **8** (2006) S87–S93 doi:10.1088/1464-4258/8/4/S06

REVIEW ARTICLE

Surface plasmon–polariton length scales: a route to sub-wavelength optics

William L Barnes

School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK

Received 21 December 2005, accepted for publication 27 January 2006
Published 21 March 2006
Online at stacks.iop.org/JOptA/8/S87

Abstract
We look at four length scales associated with the surface plasmon–polariton (SPP) modes in the visible and near-infrared. We examine some of the consequences of these length scales for exploiting surface plasmon–polariton modes as a means to provide sub-wavelength optics. The four length scales discussed are the SPP wavelength, the SPP propagation distance, and the penetration depths of the field associated with the SPP into the dielectric and metal media that bound the interface that supports the SPP. Length scales spanning seven orders of magnitude, from nanometres to centimetres, are of relevance to SPPs. This paper concludes by identifying some of the challenges that lie ahead.

Keywords: surface plasmon, nano optics, nanophotonics

1. Introduction

Understanding and controlling the interaction between light and matter is of fundamental importance to a wide range of science and technology. More that a century ago puzzles over blackbody radiation and atomic line spectra led to the birth of quantum mechanics and there have been innumerable developments since, not least the laser. We can also use light to control matter, as for example in the use of optical tweezers to manipulate cells. When it comes to light, metals are usually thought of as just mirrors; however, there is a fascinating light–matter interaction involving metals—the surface plasmon–polariton—that enables us to use metals as much more than just mirrors. Surface plasmon–polaritons (SPPs) are electromagnetic modes that arise from the interaction between light and mobile surface charges, typically the conduction electrons in metals. This light–matter interaction leads to SPP modes having greater momentum than light of the same frequency; consequently the electromagnetic fields associated with them cannot propagate away from the surface: rather, the field decays exponentially in strength with distance away from the surface. SPP modes on a planar metal surface are thus bound to that surface and guided by it, propagating until their energy is dissipated as heat in the metal.

The topic of surface plasmon–polaritons has a history going back more than a hundred years, but it has recently attracted renewed interest for a variety of reasons. In part this is because there are now a variety of routine nanoscale fabrication technologies that allow suitable sized structures to be made and explored as a way of harnessing SPPs. Surface plasmon–polaritons are also being developed as bio-molecule sensors [1], they can help us to characterize the optical properties of complex structures such as liquid crystals [2], and they are seen as one possible route in the development of sub-wavelength optics [3]; they are also quite simply fascinating. In the context of sub-wavelength optics it is designed nanoscale structuring of the metal surface that is opening up ways to control surface plasmon–polaritons with unprecedented finesse. It is the convergence of an understanding of how nanoscale features change surface plasmon–polariton properties together with the use of fabrication tools based on nanotechnology that makes this a topical and dynamic research area.

The aim of this paper is to give a didactic introduction to the properties of surface plasmon–polaritons with an emphasis on those aspects that underlie the recent surge in activity. Attention will be focused on the different length scales that are important for surface plasmon–polaritons; as we will see, these length scales span seven orders of magnitude. These length scales are the SPP propagation length, δ_{SPP}, the SPP wavelength, λ_{SPP}, the penetration depth of the electromagnetic field associated with the SPP mode into the dielectric medium, δ_d, and the penetration depth of the field into the metal, δ_m. These different length scales are indicated schematically in

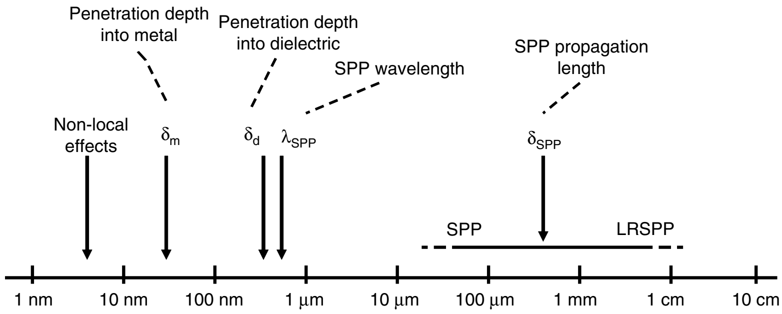

Figure 1. The different length scales of importance for surface plasmon–polaritons in the visible and near-infrared are indicated on a logarithmic scale. At the single nanometre end the non-local (spatially dispersive) response of real metals provides a lower limit. At the other end, the propagation length of long-range surface plasmon–polaritons (LRSPPs) has so far reached centimetres. The important length scales thus span seven orders of magnitude.

figure 1; in what follows we show where these length scales come from and examine their implications. Even though the approach adopted is an approximate one, making many simplifying assumptions, it is enough to allow us to appreciate the potential that SPPs offer for sub-wavelength optics.

1.1. Structure of paper

This paper is organized as follows. We begin by developing the concept of the surface plasmon–polariton dispersion diagram, an understanding of which greatly helps in exploring many aspects of SPP physics. The four different length scales associated with SPPs are then explored in detail and their physical implications discussed. This paper concludes by looking at some of the challenges that lie ahead. We should point out that we have considered only silver as the metal, and only air as the overlying dielectric medium. However, for our purposes here, that of investigating the different length scales, this restricted analysis is sufficient to give us considerable insight.

2. The surface plasmon–polariton dispersion relation

Much can be understood about SPPs by examining their dispersion relation, the relationship between the angular frequency (ω) and in-plane wavevector ($k_{\parallel}$) of SPP modes. The in-plane wavevector is the wavevector of the mode in the plane of the surface along which it propagates. For light in free space the wavevector (k_0) is simply given by $k_0 = 2\pi/\lambda_0$. In a quantum picture the momentum of the associated photon is $\hbar k_0$, and the dispersion relationship between frequency and wavevector of the photon is simply $k_0 = \omega/c$, c being the speed of light. In a medium of relative permittivity ε_d (and thus refractive index $n_d = \sqrt{\varepsilon_d}$), the dispersion relation for the photon becomes $k = n_d k_0 = \sqrt{\varepsilon_d} k_0$. The dispersion relationship between the frequency and in-plane wavevector for SPPs propagating along the interface between a metal and a dielectric can be found in a number of ways; for example, by looking for surface mode solutions of Maxwell's equations under appropriate boundary conditions, the dispersion relation is [4]

$$k_{SPP} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \tag{1}$$

where the metal and dielectric are characterized by relative permittivities (dielectric functions) ε_m and ε_d respectively. The relative permittivity of the dielectric is usually only weakly dispersive so that most of the interesting physics arises from the intriguing behaviour of the relative permittivity of metals.

The central role of the relative permittivity of the metal, ε_m, can be seen by considering what requirements are placed on the possible values that ε_m can take if SPPs are to be supported by the interface. SPPs involve charges at the surface of the metal and for such charges to be sustained the electric field normal to the interface (E_z) must change sign across the interface. Since the displacement field in the surface normal direction (D_z) has to be conserved and D_z and E_z are related by $D_z = \varepsilon E_z$, it follows that ε_m and ε_d must be of opposite sign if the interface is to support SPPs. Since dielectrics have a positive (and real) ε_d, this means that ε_m must be real and negative. This condition is largely fulfilled by several metals in the visible and near-infrared (near-IR) parts of the spectrum for which ε_m has a large negative real part (the small positive imaginary part being largely associated with absorption and scattering losses in the metal). For example, gold at a wavelength of 830 nm has a relative permittivity of $\varepsilon_m \approx -29 + 2.1i$. The relative permittivities of many metals have been measured and tabulated [5] but at this stage in our discussion it is useful to look at a simple conceptual model for a metal, the Drude model, in which the relative permittivity is given by

$$\varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - i\Gamma\omega} \tag{2}$$

where ω_p is the plasma frequency and Γ the scattering rate that is used to account for dissipation (through scattering) of the electron motion. Substituting this expression for ε_m into the dispersion relation (equation (1)), and by making the assumption for the moment that only the real part of ε_m is important, we can plot the SPP dispersion relation, figure 2, where we have taken ω_p and Γ for silver to be $\omega_p = 1.2 \times 10^{16}$ rad s^{-1} ($\equiv$7.9 eV) and $\Gamma = 1.45 \times 10^{13}$ s^{-1} ($\equiv$0.06 eV) respectively. This choice of ω_p and Γ gives a reasonable match to the experimentally determined relative permittivity of silver in the visible part of the spectrum [5].

The dispersion curve, figure 2, shows that at low frequencies the surface mode lies close to the light line and is predominantly light-like; it is in this region that it is best

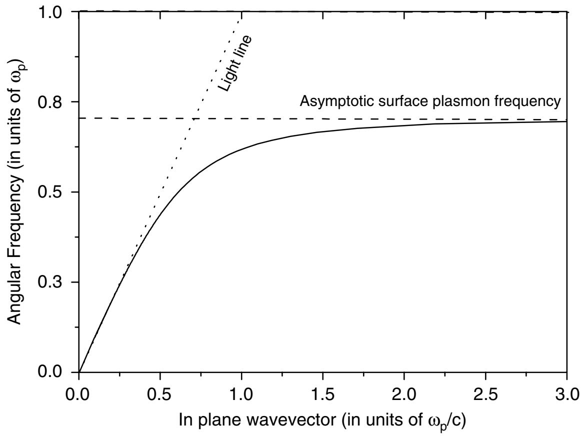

Figure 2. The dispersion relation, found by taking the real part of equation (1) with the relative permittivity of the metal based on the Drude approximation, equation (2), with ω_p and Γ for silver taken to be $\omega_p = 1.2 \times 10^{16}$ rad s^{-1} ($\equiv$7.9 eV) and $\Gamma = 1.45 \times 10^{13}$ s^{-1} ($\equiv$0.06 eV) respectively. The data are plotted in terms of the plasma frequency, and the light line is simply the dispersion line for light in free space.

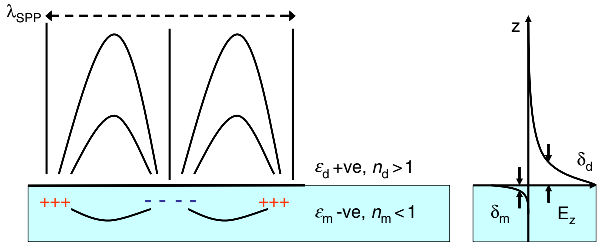

Figure 3. Sketches of the surface charge and electric field distributions associated with the surface plasmon–polariton mode. The right-hand section indicates how the z-component of the electric field strength falls with distance away from the interface. Three of the length scales are indicated: the SPP wavelength, λ_{SPP}, and the penetration depth of the field into the dielectric, δ_{d}, and into the metal, δ_{m}.

(This figure is in colour only in the electronic version)

described as a polariton. As the frequency rises the mode moves further away from the light line, gradually approaching an asymptotic limit, the surface plasmon resonant frequency. This occurs when the relative permittivity of the metal and dielectric are of the same magnitude but opposite sign, thus producing a pole in the dispersion relation, equation (1). Note that for the case considered here, the visible and near-IR regime, the SPP is in general close to the light line [6], implying that the wavelength associated with the SPP is in this regime only slightly shorter than that of light of the same frequency.

The oscillating nature of the SPP mode surface charge density and associated fields is shown schematically in figure 3. From this figure we can see three of the length scales that are important to SPPs. Perhaps the most obvious length scale is the wavelength or period of the SPP, λ_{SPP}, the separation of positions of equal charge/field on the surface. There are two other important length scales here: the penetration depths of the fields into the dielectric and the metal, δ_{d} and δ_{m} respectively. The remaining length scale we wish to discuss is the SPP propagation length, δ_{SPP}, the distance the surface plasmon–polariton travels before its intensity is diminished by $1/\mathrm{e}$. These four length scales are the focus of most of what follows; before looking at them in detail we first take another look at the dispersion relation since information about all four length scales can be obtained from it [4].

From the dispersion relation (equation (1)) we can see that as a result of the complex nature of ε_{m}, k_{SPP} is also a complex quantity. Writing the complex relative permittivity of the metal as $\varepsilon_{\mathrm{m}} = \varepsilon'_{\mathrm{m}} + \mathrm{i}\varepsilon''_{\mathrm{m}}$, we can write the complex surface plasmon–polariton wavevector as $k_{\mathrm{SPP}} = k'_{\mathrm{SPP}} + \mathrm{i}k''_{\mathrm{SPP}}$. For the case considered here, two semi-infinite media separated by a planar interface, this complex wavevector arises from the absorbing nature of the metal; SPPs attenuate as they propagate and have a finite lifetime [7]. Where the coupling of the SPP to radiation (freely propagating light) is possible, for example because of the presence of a grating on the surface or proximity of a high index layer to the metal dielectric interface, then this radiative loss also contributes to the complex nature of the SPP wavevector [8]. As we will see, all of the four length scales we are interested in can be obtained from the (complex) SPP dispersion relation.

If for the moment we ignore the complex nature of this expression, we can see that the magnitude of the surface plasmon–polariton wavevector (momentum), k_{SPP}, is always more than that of a photon in the dielectric medium bounding the metal, $\sqrt{\varepsilon_{\mathrm{d}}}k_0$. and this represents the non-radiative or bound nature of the SPP mode. The fact that $k_{\mathrm{SPP}} > \sqrt{\varepsilon_{\mathrm{d}}}k_0$ also means that one cannot use incident plane-wave light to couple to these modes—some form of momentum-enhancing scheme is needed. There are various coupling schemes that allow light and SPP modes to be coupled, notably prism coupling [8, 9], grating coupling [10–12] and near-field coupling [13, 14].

3. Surface plasmon–polariton length scales

We next look at the four length scales in turn, looking at their magnitude and the important consequences these have in thinking about using SPPs in the context of sub-wavelength optics.

3.1. The surface plasmon–polariton wavelength

We begin by looking at the wavelength of the surface plasmon–polariton, i.e. the period of the surface charge density oscillation and associated field distribution of the mode. The SPP wavelength and the SPP propagation distance can be found from the complex dispersion relation by taking the real and imaginary parts respectively. The real part of the surface plasmon wavevector is

$$k'_{\mathrm{SPP}} = k_0\sqrt{\frac{\varepsilon_{\mathrm{d}}\varepsilon'_{\mathrm{m}}}{\varepsilon_{\mathrm{d}} + \varepsilon'_{\mathrm{m}}}}. \quad (3)$$

From this the SPP wavelength, λ_{SPP}, given by $\lambda_{\mathrm{SPP}} = 2\pi/k'_{\mathrm{SPP}}$, is

$$\lambda_{\mathrm{SPP}} = \lambda_0\sqrt{\frac{\varepsilon_{\mathrm{d}} + \varepsilon'_{\mathrm{m}}}{\varepsilon_{\mathrm{d}}\varepsilon'_{\mathrm{m}}}}. \quad (4)$$

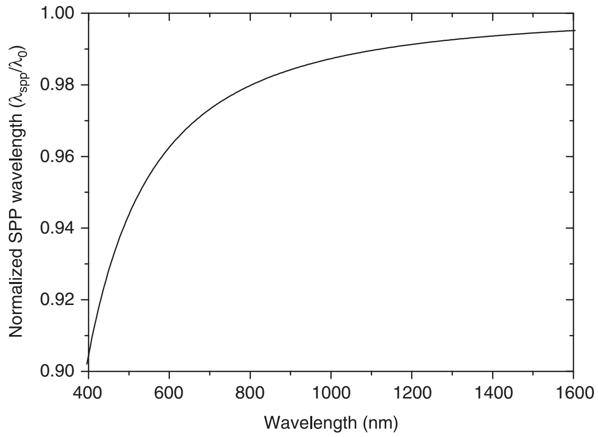

Figure 4. Showing how the normalized surface plasmon–polariton wavelength (i.e. SPP wavelength relative to free space wavelength λ_{SPP}/λ_0) varies with free space wavelength in the visible and near-infrared. The data were computed using the Drude approximation for the relative permittivity of the metal (with ω_p and Γ for silver taken to be $\omega_p = 1.2 \times 10^{16}$ rad s^{-1} ($\equiv$7.9 eV) and $\Gamma = 1.45 \times 10^{13}$ s^{-1} ($\equiv$0.06 eV) respectively). The relative permittivity of the dielectric was taken to be equal to 1. Note that in this spectral range the SPP wavelength is only slightly less than the free space wavelength.

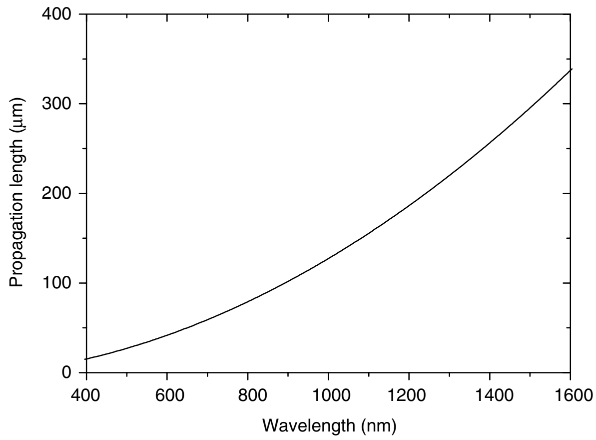

Figure 5. Showing the propagation length of the surface plasmon–polariton. The date were computed using the Drude approximation for the relative permittivity for the metal (with ω_p and Γ for silver taken to be $\omega_p = 1.2 \times 10^{16}$ rad s^{-1} ($\equiv$7.9 eV) and $\Gamma = 1.45 \times 10^{13}$ s^{-1} ($\equiv$0.06 eV) respectively). The relative permittivity of the dielectric was taken to be equal to 1. Note that in calculating these data we have assumed that there is no radiative damping, specifically that there is no mechanism by which SPPs can be converted to light, e.g. by the presence of a prism or grating coupler.

And the normalized SPP wavelength, λ_{SPP}/λ_0, is given by

$$\frac{\lambda_{SPP}}{\lambda_0} = \sqrt{\frac{\varepsilon_d + \varepsilon'_m}{\varepsilon_d \varepsilon'_m}}. \tag{5}$$

Figure 4 shows the SPP wavelength as a function of the free space wavelength, λ_0, for SPPs on a silver surface; the relative permittivity of silver is based on the Drude parameters given above, and the relative permittivity of the dielectric has been taken as equal to 1.

We can see from figure 4 that the SPP wavelength, λ_{SPP}, is very similar to, but always slightly less than, the free space wavelength, λ_0. Again, the fact that $\lambda_{SPP} < \lambda_0$ reflects the bound nature of SPP modes on a planar surface. The important point to draw from these data is that if we are to use surface structure as a means to control SPPs, e.g. through the use of periodic structures that act as Bragg scatterers, then the length scale of such structure needs to be of order the wavelength involved. (Where the overlying dielectric is not air/vacuum but some other medium, for example water, then the SPP wavelength will be reduced in proportion to the refractive index.) In practice, for SPP modes in the visible and near-IR, one therefore needs structures with features of order ~400–1000 nm size, something that is readily achieved with electron-beam lithography [15], focussed ion-beam milling [16], and photolithography [17], and should in principle be possible with structures produced by soft-lithography, e.g. solvent-assisted soft lithography [18]. Using such approaches a whole range of possibilities are opened up (beam splitters, mirrors, etc), both for manipulating SPP modes on the surface, and for coupling them to freely propagating light [19, 20].

In order that such wavelength-scale structure be effective in manipulating SPPs it is important that the SPPs have a propagation (attenuation) length that is at least several times their wavelength. Put another way, the SPP needs to experience several bumps of a grating for grating coupling to be effective.

3.2. The surface plasmon–polariton propagation length

As noted above, the SPP propagation length, δ_{SPP}, is found from the imaginary part of the surface plasmon–polariton wavevector. This is obtained from equation (1) as

$$k''_{SPP} = k_0 \frac{\varepsilon''_m}{2(\varepsilon'_m)^2} \left(\frac{\varepsilon'_m \varepsilon_d}{\varepsilon'_m + \varepsilon_d} \right)^{\frac{3}{2}}. \tag{6}$$

From this the propagation length, δ_{SPP}, the distance over which the power/intensity of the mode falls to $1/e$ of its initial value, is given by $\delta_{SPP} = 1/2k''_{SPP}$, and is found to be

$$\delta_{SPP} = \lambda_0 \frac{(\varepsilon'_m)^2}{2\pi \varepsilon''_m} \left(\frac{\varepsilon'_m + \varepsilon_d}{\varepsilon'_m \varepsilon_d} \right)^{\frac{3}{2}}. \tag{7}$$

When the metal is low loss, and the condition $|\varepsilon'_m| \gg |\varepsilon_d|$ is satisfied, we can approximate the propagation length as

$$\delta_{SPP} \approx \lambda_0 \frac{(\varepsilon'_m)^2}{2\pi \varepsilon''_m}. \tag{8}$$

From equation (8) we see that for a long propagation length we require a large (negative) real part of the relative permittivity of the metal, ε'_m, and a small imaginary part, ε''_m. i.e. we need a low loss metal, as one would expect.

The propagation length calculated using equation (8) and based on the Drude parameters for silver is shown in figure 5 for visible and near-IR wavelengths. Several implications can be drawn from these data. First, if one is thinking of trying to construct photonic components or circuits based on SPPs then the propagation length represents an upper limit on the size of the structures one can contemplate using. The data in figure 5 show that the absorptive nature of metals in the visible and near-IR places considerable restrictions on potential circuit size. One way to extend the length scale of

SPP modes is to make use of the coupled surface plasmon–polariton modes supported by symmetrically clad thin metal films [21]. When the metal is thin enough then the SPP modes associated with the two metal surfaces may interact to form two coupled SPP modes. We will see how thin the metal needs to be below, but note for now that the film thickness needs to be of order 50 nm to see significant coupling. One of these modes propagates in such a way that less of the power is carried in the metal than is the case for the single interface SPP mode, thus reducing the effects of loss. Coupled modes have been investigated in some detail [22, 23] and the longest propagation lengths reported thus far are of the order of centimetres. There is a price to pay for such long propagation lengths: one loses the sub-wavelength character of the SPP mode because these coupled modes have fields that extend further into the dielectric; however, this does facilitate a better match to the spot size of optical fibres.

Second, we see that the SPP propagation length is significantly greater than the SPP wavelength. The fact that $\delta_{\rm SPP} \gg \lambda_{\rm SPP}$ means that, as anticipated above, wavelength-scale gratings and other periodic surface structures can be used to manipulate surface plasmon–polaritons since the modes are able to interact over many periods of such a structure. Note though that, as mentioned above, in the case where such structure can scatter SPP modes into freely propagating light, e.g. a grating coupler, radiative damping acts as an additional loss mechanism that reduces the SPP propagation length. However, optimum coupling is achieved when radiative and non-radiative (internal) losses are equal [24], so that the SPP propagation length is only reduced by a factor of $\sim$2, and is in general still more than adequate to ensure that the mode experiences enough of a periodic structure to undergo coherent scattering.

3.3. The surface plasmon–polariton field penetration depths

The penetration of the fields into the materials bounding the interface, the metal and the dielectric, can be found by again considering the wavevector of the SPP. In a material with a relative permittivity ε_i the total wavevector of light of free-space wavevector k_0 is given by $\varepsilon_i k_0^2$. Setting the z-direction to be the direction perpendicular to the plane in which the SPP propagates, the relationship between the total wavevector and this z-component of the wavevector is

$$\varepsilon_i k_0^2 = k_{\rm SPP}^2 + k_{z,i}^2. \qquad (9)$$

The surface plasmon–polariton wavevector is simply the in-plane component of the wavevector. As we noted above, the surface plasmon–polariton wavevector always exceeds that of a photon freely propagating in the adjacent medium, i.e. $k_{\rm SPP}^2 > \varepsilon_i k_0^2$, so that the z-component of the wavevector in both media is imaginary, representing the exponential fall off of the fields with distance into the two media. Combining the dispersion relation (equation (1) with (9)) above we find for the penetration depths into the dielectric, $\delta_{\rm d}$, and metal, $\delta_{\rm m}$, are

$$\delta_{\rm d} = \frac{1}{k_0}\left|\frac{\varepsilon'_{\rm m} + \varepsilon_{\rm d}}{\varepsilon_{\rm d}^2}\right|^{\frac{1}{2}} \qquad (10)$$

$$\delta_{\rm m} = \frac{1}{k_0}\left|\frac{\varepsilon'_{\rm m} + \varepsilon_{\rm d}}{\varepsilon_{\rm m}'^2}\right|^{\frac{1}{2}} \qquad (11)$$

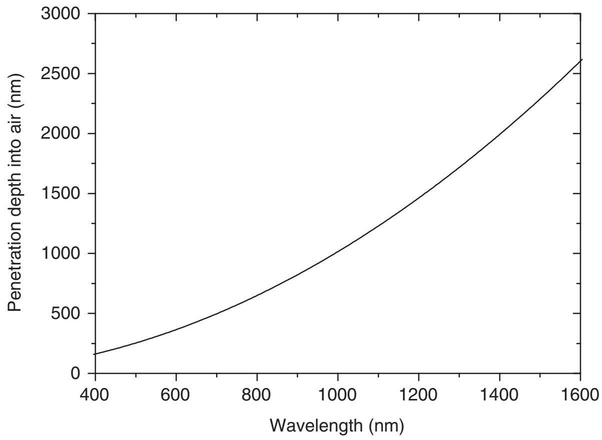

Figure 6. Showing how the penetration depth into the dielectric (here air) varies with free space wavelength in the visible and near-infrared. The data were computed using the Drude approximation for the relative permittivity of the metal (with $\omega_{\rm p}$ and Γ for silver taken to be $\omega_{\rm p} = 1.2 \times 10^{16}$ rad s^{-1} ($\equiv$7.9 eV) and $\Gamma = 1.45 \times 10^{13}$ s^{-1} ($\equiv$0.06 eV) respectively). The relative permittivity of the dielectric was taken to be equal to 1.

where we have again assumed that $|\varepsilon'_{\rm m}| \gg |\varepsilon''_{\rm m}|$. Let us now look at these two penetration depths in turn.

3.3.1. The surface plasmon–polariton penetration depth into the dielectric. Using equation (10) we can plot the penetration depth into the dielectric medium as a function of wavelength, as shown in figure 6. We see from figure 6 that for wavelengths in the visible spectral region the penetration depth into the dielectric is less than the free space wavelength whilst at the infrared end it is more than the free space wavelength. This increase, relative to the free space wavelength, arises because as one moves to longer wavelengths the metal is a better conductor and the mode has a wavevector that is closer to the free space wavevector (the mode is thus more light-like) and is consequently less confined to the surface. Nonetheless, to a first approximation the penetration depth into the dielectric is the same as the free space wavelength. The penetration depth of the field into the dielectric gives us a measure of the length scale over which the SPP mode is sensitive to the presence of changes in refractive index, for example the presence of a prism coupler in the Otto configuration for coupling light to SPPs via attenuated total reflection [9], or the binding of specific bio-molecules in a bio-sensor. In the latter case we see that although the sensitivity of the SPP to changes in the dielectric medium falls of exponentially, the distance over which the fall off takes place is large on a molecular scale. Although we are discussing here the SPP modes associated with continuous planar metal surfaces, albeit perhaps possessing wavelength-scale patterning, it is interesting to note that the penetration depth into the dielectric of the localized surface plasmon mode associated with metallic nanoparticles can be very considerably smaller, of order 10 nm [25], owing to the divergence of the electric field around the tips of such structures.

Finally we note that associated with the localization of the field near the metal there is also a field enhancement, owing to the associated increase in the local photonic mode density [14].

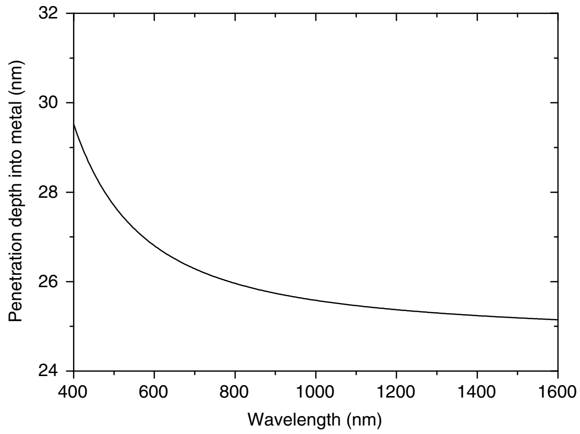

Figure 7. Showing how the penetration depth into the metal varies with free space wavelength in the visible and near-infrared. The data were computed using the Drude approximation for the relative permittivity of the metal (with ω_p and Γ for silver taken to be $\omega_p = 1.2 \times 10^{16}$ rad s^{-1} ($\equiv$7.9 eV) and $\Gamma = 1.45 \times 10^{13}$ s^{-1} ($\equiv$0.06 eV) respectively). The relative permittivity of the dielectric was taken to be equal to 1.

This enhanced field has many important consequences: it is part of the reason that SPPs are sensitive to changes at the surface (in addition to only being sensitive to changes relatively near the surface, as noted above). Further, it also means that fluorescing molecules near a metal surface may predominantly lose their energy to SPP modes; under good conditions such molecules have a 95% probability of losing their energy to an SPP mode [26]. This has important consequences for light sources such as light-emitting diodes where the presence of metallic electrical contacts in a thin-film device can lead to SPPs being an important mechanism that traps light in the device, reducing efficiency, which is something that it is hoped nanostructuring may help us overcome [6, 27, 28].

3.3.2. The surface plasmon–polariton penetration depth into the metal. We come now to the last of our fourth length scales, and in many ways the most interesting, the penetration of the field into the metal, δ_m. In figure 7 we have plotted this parameter as a function of wavelength for silver, using the Drude parameter listed above. A striking feature of these data is that the penetration depth is largely independent of the free space wavelength in this wavelength range, taking a value of $\sim$30 nm. This should not perhaps be a surprise: substituting the Drude expression for the relative permittivity of the metal (equation (2)) into the expression for the penetration depth into the metal (equation (11)) and noting that we are working in the regime well below the plasma frequency, i.e. $\omega \ll \omega_p$, then one finds the penetration depth to be

$$\delta_m = \frac{\lambda_p}{2\pi} \tag{12}$$

where λ_p is the wavelength associated with the plasma frequency. For $\omega_p = 1.2 \times 10^{16}$ rad s^{-1} this gives $\delta_m = 25$ nm. This expression is identical with the usual expression obtained for the skin depth [29]. (Note that in figure 7 the penetration depth rises above this value for short wavelengths because here the assumption that $\omega \ll \omega_p$ begins to fail.)

The penetration depth into the metal gives us a measure of the thickness required of metal films that allow coupling to freely propagating light in the prism coupling (Kretschmann) geometry (typically 50 nm for silver and gold in the visible), the thickness of films in SPP-mediated transmission through metals [30, 31] and using metal films for lensing [32, 33], and of the thickness of metal films where the SPP modes on the two metal surfaces interact [23].

The penetration depth into the metal also gives us at least an idea of the feature sizes needed to control SPPs: as features become much smaller than the penetration depth into the metal they will have a diminishing effect on SPP mode. Thus the small-scale (nm) roughness associated with many of the techniques used to make the metal films used in SPP investigations is usually only sufficient to provide a minor perturbation to the SPP mode.

Does the penetration depth into the metal, 25 nm, represent the shortest length scale of importance to SPPs? The answer is no. There are two related factors to consider: the effect of spatial dispersion and impedance changes at boundaries. In all that we have discussed so far we have assumed that the metal can be described by a relative permittivity that applies to bulk metals or continuous thin films. However, at very short lengths scales, for example when a molecule is adjacent to a metallic surface, such a description no longer holds and one has instead to include a non-local (spatially dispersive) response [13]. Such a response is of relevance for length scales below a few nanometres and defines the lower end of the length scale of interest for surface plasmon–polaritons. The penetration depth into the metal could act as some kind of limiting scale for sub-wavelength structures. Although spatial dispersion means we need to find better ways to describe the optical response of metals on a very short lengths scales, it also has a bearing on how we think about the penetration depth into the metal. If we consider how the field penetrates from the dielectric into the metal, the strength depends not just on the penetration depth but also on the extent of the impedance mismatch at the metal/dielectric interface. This second factor can lead to the field in the metal being very much weaker than in the dielectric over a length scale much less than the penetration depth, something that has very recently been elegantly demonstrated by Hibbins and co-workers [34] in the microwave regime. Whilst it is the impedance mismatch that determines the immediate reduction in the strength of the electric field in the metal, the non-local response determines the length scale over which this impedance mismatch occurs: the boundary between the metal and dielectric is not infinitely sharp.

The final consequence we wish to mention here is that it is the combination of impedance mismatch and penetration depth of the field into the metal limits the extent of the field enhancement that can be achieved. The largest field enhancements are found between metal surfaces [35, 36]. However, the degree to which the field is enhanced by such confinement is ultimately limited by the impedance mismatch and the penetration depth into the metal.

4. Outlook: the challenges

The length scales associated with SPPs are summarized in figure 1. At the longest scale, the pioneering work by Berini and co-workers [22, 23] has shown that circuit elements such as couplers and junctions are possible, and that losses can be kept low enough to allow propagation over many centimetres. More complex components such as interferometers and modulators need to be better explored if the idea of SPP-based photonic circuits is to be properly assessed.

SPPs are also being pursued as a means to develop sub-wavelength optical components. In this area we need to make use of significantly sub-wavelength sized metallic objects, e.g. particles or holes, possibly in conjunction with larger structures to allow more efficient coupling to freely propagating light.

One of the more topical areas in the plasmonics community is that of sub-wavelength optics. The work of Hibbins *et al* [34], among others, shows that in the microwave regime $\lambda/1000$ is possible. There is a fascinating topic of study emerging as designs that work at microwave frequencies are explored at optical frequencies: what can and cannot be achieved are not immediately obvious owing to the different properties of metals in these different spectral regions. We are already seeing a surge of activity in pursuing sub-wavelength plasmonics, and it will be fascinating to see how this develops over the next few years.

Another area of active investigation is that of field enhancement in phenomena such as surface-enhanced fluorescence and SPP-mediated energy transfer [37–39]. As we have seen above, the wavelength and propagation length of SPP modes are such that we can exert good control over them; in particular we may efficiently couple them to freely propagating light. Thus, when we combine this fact with the high efficiency with which excited molecules may lose their energy to SPP modes we see that SPPs offer an attractive route to control the optical properties of molecules; we thus expect SPPs to be important in the development of molecular photonics.

Finally, we might perhaps note that whilst the length scale for features we wish to control SPPs with are identified as being roughly that of the associated wavelength of light there is at least one important exception, and that is when we are working near the asymptotic surface plasmon frequency; see figure 2. Here the wavevector of the mode is very significantly enhanced over the free space wavevector and the mode consequently has a much reduced wavelength. As has been pointed out by others, the density of states associated with such modes is high (the density of states varies as the inverse of the slope of the dispersion curve). This has important consequences for light-emitting structures where the emission is mediated by surface plasmons [6, 27, 40].

In conclusion, we have seen that length scales from nanometres to centimetres are important for surface plasmon–polaritons in the visible and near-infrared. Exciting times lie ahead as we learn more about how to harness surface plasmon–polaritons with nanoscale structure.

Acknowledgments

This paper emerged as a result of an invitation to attend a workshop at Donostia, San Sebastian in 2003 and I would like to thank Professor P Echenique and Professor J Garc ía de Abajo for their support and encouragement. I am also indebted to many other colleagues for suggestions. The support of the EC through funding the project 'Surface Plasmon Photonics' FP6 NMP4-CT-2003-505699 is gratefully acknowledged.

References

[1] Homola J 2003 *Anal. Bioanal. Chem.* **377** 528
[2] Welford K 1991 *Opt. Quantum Electron.* **23** 1
[3] Barnes W L, Dereux A and Ebbesen T W 2003 *Nature* **424** 824
[4] Raether H 1988 *Surface Plasmons* (Berlin: Springer)
[5] Lynch D W and Huttner W R 1985 *Handbook of Optical Constants of Solids* ed Palik (New York: Academic)
[6] Barnes W L 2004 *Nat. Mater.* **3** 588
[7] van Exter M and Lagendijk A 1988 *Phys. Rev. Lett.* **60** 49
[8] Kretschmann E and Raether H 1968 *Z. Naturf.* a **23** 2135
[9] Otto A 1968 *Z. Phys.* **216** 398
[10] Wood R W 1902 *Phil. Mag.* **4** 396
[11] Fano U 1941 *J. Opt. Soc. Am.* **31** 213
[12] Ritchie R H *et al* 1968 *Phys. Rev. Lett.* **21** 1530
[13] Ford G W and Weber W H 1984 *Phys. Rep.* **113** 195
[14] Barnes W L 1998 *J. Mod. Opt.* **45** 661
[15] Ditlbacher H *et al* 2002 *Appl. Phys. Lett.* **81** 1762
[16] Ebbesen T W *et al* 1998 *Nature* **391** 667
[17] Kitson S C, Barnes W L and Sambles J R 1996 *Phys. Rev. Lett.* **77** 2670
[18] Yates C *et al* 2005 at press
[19] Moreland J, Adams A and Hansma P K 1982 *Phys. Rev.* B **25** 2297
[20] Giannattasio A and Barnes W L 2006 *J. Mod. Opt.* **53** 429–36
[21] Sarid D 1981 *Phys. Rev. Lett.* **47** 1927
[22] Berini P *et al* 2005 *J. Appl. Phys.* **98** 043109
[23] Berini P 2000 *Phys. Rev.* B **61** 10484
[24] Herminghaus S, Klopfleisch M and Schmidt H J 1994 *Opt. Lett.* **19** 293
[25] Whitney A V *et al* 2005 *J. Phys. Chem.* B **109** 20522
[26] Weber W H and Ford G W 1981 *Opt. Lett.* **6** 122
[27] Okamoto K *et al* 2004 *Nat. Mater.* **3** 601
[28] Smith L, Wasey J A E and Barnes W L 2004 *Appl. Phys. Lett.* **84** 2986
[29] Stratton J A 1941 *Electromagnetic Theory* (New York and London: McGraw-Hill)
[30] Wedge S *et al* 2004 *Phys. Rev.* B **69** 245418
[31] Bonod N *et al* 2003 *Opt. Express* **11** 482
[32] Pendry J B 2000 *Phys. Rev. Lett.* **85** 3966
[33] Fang N *et al* 2005 *Science* **308** 534
[34] Hibbins A P *et al* 2004 *Phys. Rev. Lett.* **92** 143904
[35] García-Vidal F J and Pendry J B 1996 *Phys. Rev. Lett.* **77** 1163
[36] Kim W *et al* 1999 *Phys. Rev. Lett.* **82** 4811
[37] Pockrand I, Brillante A and Möbius D 1980 *Chem. Phys. Lett.* **69** 499
[38] Lenac Z and Tomas M S 1989 *Surf. Sci.* **215** 299
[39] Andrew P and Barnes W L 2004 *Science* **306** 1002
[40] Neogi A *et al* 2002 *Phys. Rev.* B **66** 153305