# Characteristics of ultra-long range surface plasmon waves at optical frequencies

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**Abstract:** It has been reported earlier that ultra-long range surface plasmon waves can be supported if dielectric layers with lower index of refraction than that of the dielectric cladding are placed on either side of the thin metal film. In this paper, we report a further investigation of the ultra-long range surface plasmon modes and the condition to support such ultra-long propagation distances at optical frequencies. We studied the effects of the index of refraction contrast between the inner layer and the cladding dielectrics, the metal film thickness, and the dispersion with wavelength. We present a condition which must be satisfied by the waveguide structure to support the bound ultra-long range surface plasmon mode.



**OCIS codes:** (240.6680) Surface Plasmons; (240.5420) Polaritons; (130.2790) Guided Waves;

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## 1. Introduction

A surface plasmon is the free electron density oscillation near the surface of a metal that is in contact with a dielectric material. The propagation of the free electron density creates a coupled physical state between the electron and photon along the boundary of the two materials, resulting in a bound surface plasmon-polariton (SPP). For a SPP to exist, the real part of the relative permittivity of the metal, $\mathrm{Re}(\varepsilon_m)$, must have the opposite sign with respect to the real part of the relative permittivity of the dielectric medium, $\mathrm{Re}(\varepsilon_d)$. Since dielectrics have positive relative permittivities, the requirement is then that the metal has $\mathrm{Re}(\varepsilon_m) < 0$ [1]. For many of the noble metals, such as Au, Ag, and Cu, this condition is satisfied over a wide range of optical frequencies.

Although a metal-dielectric interface supports SPP modes, such modes experience significantly high attenuation as they propagate, due to intrinsic electron oscillation damping loss in metals. The propagation ranges of surface plasmon-polaritons are thus on the order of several tens of microns at optical frequencies. Propagation range here, and for the entire discussion in this paper, is taken to be the distance at which the propagating electromagnetic wave’s intensity has decayed to $1/e$ of its initial value (computed as $1/(2\alpha)$, where $\alpha$ is the imaginary part of the propagation constant). It is well known that a thin metal film in a homogeneous dielectric medium supports two bound SPP modes [2, 3, 4, 5, 6, 7]. These two modes are characterized by the symmetries of their transverse electromagnetic fields. The $s_b$ mode has a symmetric field distribution with respect to the center of the metal film, while the $a_b$ mode’s fields are anti-symmetric with respect to the center of the metal film. The propagation range of the $s_b$ mode is greater than that of the SPP wave at a single surface, while the range of the $a_b$ mode is shorter. Attenuation of the $s_b$ mode decreases with film thickness, while it increases for the $a_b$ mode. As film thickness is increased, the two modes become degenerate with the solution for the single interface. Due to its relatively longer propagation distances, the $s_b$ mode is also referred as the long-range surface plasmon-polariton mode (LRSPP), and has been studied extensively in the past.

Although the propagation range of the $s_b$ mode is long relative to the other SPP modes, it is still macroscopically short and thus limits its applications. The $s_b$ mode supported by a 20 nm thick gold (Au) film in a homogeneous cladding of a refractive index of 1.45 has a propagation range of about 60 μm at the wavelength of 632.8 nm. A simple strategy for increasing the range of the $s_b$ mode is to reduce the metal film thickness. There is, however, a practical limit to deposit homogeneous metal films of less than 20 nm in thickness because metals typically form nanoscale islands in the initial deposition process [8]. Furthermore, as the thickness of a metal film approaches the nanometer scale, the quantum mechanical effect becomes dominant [9]. The quantum mechanical effect causes the properties of thin films to be completely different from those of the bulk material. Slight gains in propagation range may also be achieved by choosing a dielectric cladding with a lower index of refraction. Increasing the wavelength of the light will also increase the propagation range of the $s_b$ mode, although the wavelength of the light is usually determined by the application. Range extension of SPPs has been studied for leaky modes supported by multiple dielectric layers in asymmetric waveguide structures [10]. The structure in [10] incorporates a traditional dielectric slab waveguide in conjunction with a thin metal film. The field profile of the mode does not decay in all the dielectric layers outside the metal film.

Recently we proposed a simple scheme for reducing the loss experienced by the symmetric surface plasmon modes [11, 12]. Our technique allows for the reduction of

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propagation attenuation without changing the thickness of the metal film, the cladding refractive index, or the free space wavelength. The bound modes supported by the metal-dielectric surface plasmon waveguide structure illustrated in Fig. 1 were reported in our previous publications. It has been shown that for $\varepsilon_1 < \varepsilon_2$, the attenuation of the $s_b$ mode can be reduced significantly by increasing *d*, the thickness of the low refractive index inner dielectric layer. While a single, specific configuration of Fig. 1 was shown in the previous paper, given the significance of this new metal-dielectric surface plasmon waveguide, a detailed investigation of the properties of the structures is required.

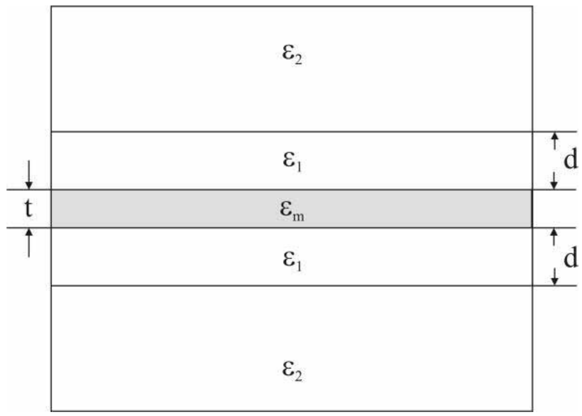


Fig. 1. The cross section of the one-dimensional ultra-long range surface plasmon waveguide consisting of a thin metal film, two low index of refraction inner dielectric layers, and the homogeneous dielectric claddings. The metal-dielectric structure is symmetric with respect to the center of the metal layer.

In the following section, it will be shown that the condition of $\varepsilon_1 < \varepsilon_2$ is not always sufficient in order to have the ultra-long range mode reported in [12]. The $s_b$ mode exhibits one of two different types of behavior as the thickness of the inner dielectric layer is increased, depending on the contrast of the index of refraction between the inner (core) dielectric layer and the cladding dielectric and also depending on the metal film thickness. The effect of varying the index of refraction contrast between the inner and cladding dielectrics is examined first. Mode indices were calculated for the structure of Fig. 1 as *d* was increased for four different cladding indices of refraction, while all other parameters were held the same. The behavior of the $s_b$ mode for differing thickness of the metal film is examined next. The wavelength dispersion effect is examined in the final section. The reflection pole method (RPM) was used to find the mode indices of the $s_b$ modes [13].

## 2. Characteristics of the ultra-long range surface plasmon mode

For the structure shown in Fig. 1, $\varepsilon_2$ and $\varepsilon_1$ are the relative permittivities of the cladding dielectric and the inner dielectric layer respectively. The dielectrics are assumed to be lossless and thus have indices of refraction that are purely real. The metal film is taken to be Au, with complex permittivity $\varepsilon_m$. The thickness of the Au film is *t* and *d* is the thickness of the inner dielectric layer. A mode will have propagation constant $\gamma = \beta - j\alpha$ and thus mode index $\gamma / \beta_0$, where $\beta_0$ is the free space propagation constant ($\beta_0 = 2\pi / \lambda$). The complex mode index is defined by a real part $\beta / \beta_0$ and imaginary part $\alpha / \beta_0$. Throughout the remainder of the discussion, $\varepsilon_1 < \varepsilon_2$ will be assumed. Clearly, no ordinary dielectric waveguide modes are supported by the structure.

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The behavior of the $s_b$ mode due to increasing thickness of the inner dielectric layer is easily viewed in terms of the two extremes, $d = 0$ and $d = \infty$. For both cases, the solution is simply that of a thin film in a single homogeneous dielectric background. When $d = \infty$, the dielectric background has an index of refraction equal to that of the inner dielectric, $n_1 = (\varepsilon_1)^{1/2}$. The mode index here will be defined as $(\gamma / \beta_0)\big|_{d=\infty}$, with the real part $(\beta / \beta_0)\big|_{d=\infty}$. Depending on the difference between the indices of refraction of the two dielectrics, the thickness of the gold metal film, and the wavelength of the light, the condition of Eq. (1) below may or may not be satisfied.

$$(\beta / \beta_0)\big|_{d=\infty} < n_2 \quad (1)$$

When Eq. (1) is true, as $d$ is increased, the mode index approaches a solution that cannot, by definition, remain bound. The $s_b$ mode therefore approaches a plane wave propagating in the cladding, with $\beta / \beta_0$ approaching $n_2$ and $\alpha / \beta_0$ approaching zero, as $d$ approaches a finite cutoff value. This results in the behavior seen in the specific case in [12]. The condition of Eq. (1) is thus the condition for the existence of the ultra-long range surface plasmon mode. The $s_b$ modes of the metal-dielectric surface plasmon waveguide, which satisfy Eq. (1) will be referred to hereafter as ultra-long range modes, $u_b$. The transverse field profile of the $u_b$ mode is symmetric with respect to the center of the metal film like that of the standard $s_b$ mode.

When the index of refraction contrast, metal thickness, or wavelength, are such that the condition for ultra-long range is not satisfied, the mode does approach a valid bound solution, therefore the limit is simply $(\gamma / \beta_0)\big|_{d=\infty}$. Attenuation is reduced slightly over the limiting case due to the tendency of the electric field to concentrate itself in regions of higher index of refraction. The low index inner dielectric layer thus acts as a buffer from the loss of the metal film until $d$ is made prohibitively large. The behavior of these modes is very similar to that of the ordinary $s_b$ mode, and they will be referred to as $l_b$ modes, indicating that they are the long-range symmetric modes. Thus the new metal-dielectric plasmon waveguide described here supports two possible variants of the ordinary $s_b$ mode. The $u_b$ mode, which has propagation range significantly farther than the $s_b$ mode, is supported when Eq. (1) is satisfied. The $l_b$ mode exists when Eq. (1) is not satisfied, and has propagation ranges similar to the $s_b$ mode. Since both modes have symmetric transverse field profiles with respect to the center of the metal film, the term symmetric will be used to refer to either of the symmetric modes supported by the guide structure of Fig. 1. The notation $s_b$ may therefore be reserved for the case of a metal film in a homogeneous dielectric background. Examples of the condition for ultra-long range and the behavior of the $u_b$ and $l_b$ modes follow.

It should be noted that, for the $u_b$ modes, since as $d$ approaches the cutoff thickness, the attenuation of the mode tends to zero, the propagation distance can be arbitrarily long if other issues are not the concern. One issue is mode confinement. A number of figures-of-merit have been proposed for long range surface plasmon waves in [14]. Regardless of the exact figure-of-merit, since the $u_b$ mode approaches a plane wave with $\beta/\beta_0$ tending towards $n_2$, the mode's confinement becomes poor as $d$ approaches the cutoff thickness. A second issue is the degree of precision required to fabricate the ultra-long range surface plasmon waveguide. This will be discussed in detail in section 2.1.

The index of refraction contrast between the inner and cladding dielectric layers, the thickness of the metal film, and the frequency of the optical waves play significant roles in determining propagation distance of the $u_b$ mode. These are examined in the following sections. Specific parameters are chosen to emphasize these effects.

### *2.1 Effects of varying the refractive index of the cladding dielectric*

The index of the symmetric mode supported by the structure in Fig. 1 was calculated as $d$ was increased. The thickness of the Au film and the index of refraction of the inner dielectric layer

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were held constant at $t = 20$ nm and $n_1 = 1.45$, respectively. The wavelength was taken to be 632.8 nm. The relative electric permittivity of gold at this wavelength used here results from an interpolation fit to Johnson and Christy's data [15] and is $\varepsilon_m = -11.65 - j1.333$. The calculations were carried out for four values of the index of refraction of the dielectric cladding, $n_2$ = 1.55, 1.50, 1.48, and 1.46, resulting in the four sets of curves shown in Figs. 2 and 3.

For the chosen parameter values ($t = 20$ nm, $n_1 = 1.45$), $(\gamma/\beta_0)\big|_{d=\infty}$ equals $1.4691 - j8.361\times10^{-4}$. Thus, $n_2 = 1.46$ does not satisfy Eq. (1). The expected behavior is evident in Fig. 3, as the $n_2$ = 1.55, 1.50, and 1.48 curves, which represent $u_b$ modes, imply significant reductions in mode attenuation as $d$ is increased. The $n_2$ = 1.46 curve shows only a shallow minimum before it asymptotes to the imaginary part of $(\gamma/\beta_0)\big|_{d=\infty}$. The condition in Eq. (1) was only violated when the contrast between the two dielectrics' refractive indices was made small since for thin films, the large majority of the energy of the symmetric mode is located in the surrounding dielectric media, and thus the mode effective index is very close to the index of refraction of the surrounding dielectric.

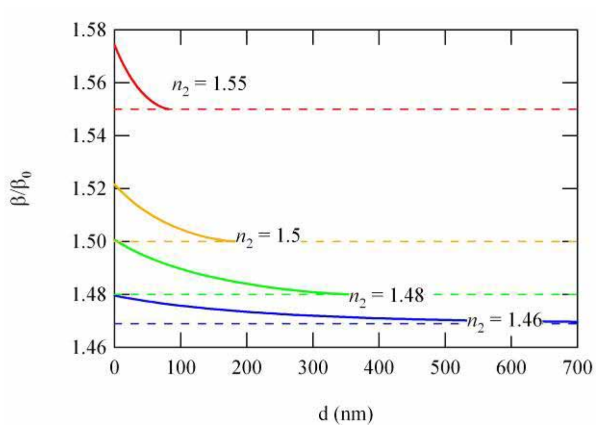


Fig. 2. Real part of the symmetric mode index for varying the index of refraction of the dielectric cladding, $n_2$. The curve for $n_2$ = 1.46 does not asymptote to the cladding index.

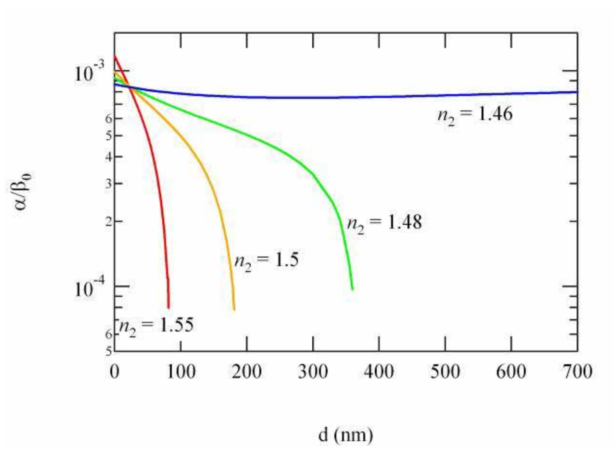


Fig. 3. Imaginary part of the symmetric mode index for varying values of $n_2$. Notice $n_2$ = 1.46 does not satisfy the condition for ultra-long range and thus is bound for all values of $d$.

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The three configurations of $n_2$ for which the attenuation is seen to decrease dramatically all have similar imaginary parts of their effective indices at $d$ = 74, 163, and 342 nm for $n_2$ = 1.55, 1.50 and 1.48 respectively. For $n_2$ = 1.55, $\gamma / \beta_0 = 1.5505 - j1.913 \times 10^{-4}$; for 1.50 $1.5005 - j1.982 \times 10^{-4}$; and for 1.48, $1.4802 - j1.880 \times 10^{-4}$. The corresponding propagation distances are approximately 263, 254, and 268 μm for $n_2$ = 1.55, 1.50 and 1.48 respectively. As stated earlier, the propagation distance of the $s_b$ mode supported by the same gold metal film in a homogeneous cladding with refractive index 1.45 is only about 60 μm.

As is evident in Fig. 3, the shape of the $\alpha/\beta_0$ versus $d$ curve is determined by the index of refraction contrast $\Delta n = n_2 - n_1$. As $\Delta n$ is reduced, the curves flatten out. The cutoff thickness of the inner dielectric layer is increased until eventually the condition for ultra-long range is no longer satisfied and the curve represents a $l_b$ mode, which has no cutoff. Finally, the curve becomes a straight line when $\Delta n$ = 0. This behavior has implications for the ease with which these structures can be fabricated. For $u_b$ modes having the longest ranges (lowest attenuation), $d$ is very close to the cutoff. Variations in the thickness of the inner dielectric layer that occur during the fabrication process will result in variations in mode index, and if they are large enough, could even cause $d$ to be over the cutoff. For a flatter curve, these variations in $d$ will have smaller effects on the mode index. Thus, structures with low values of $\Delta n$ should be easier to fabricate. A disadvantage, however, is that the higher the index of refraction contrast between the inner and cladding dielectric layers, the larger the difference between $\beta / \beta_0$ and $n_2$ will be for a given propagation distance, which implies better mode confinement.

### *2.2 Effects of increasing the metal film thickness*

Due to field coupling effects, film thickness is one of the most significant determinants of the propagation characteristics of a SPP. Increase of metal film thickness confines the symmetric mode more tightly to the metal film, and thus increase propagation losses. This effect will compete with the effects of the inner dielectric layer. Thicker metal films will have greater values of $\alpha/\beta_0$ at the initial $d$ = 0 point and much higher cutoff values of $d$. In addition, because increases in metal film thickness increase $\beta/\beta_0$, increasing $t$ while holding all else constant will eventually cause the condition for ultra-long range to be violated. This behavior is shown in Figs. 4 and 5, which plot the real and imaginary parts of the symmetric mode effective index, for different values of $t$, while holding wavelength and the indices of refraction of the dielectrics constant at 632.8 nm and $n_2$ = 1.50 and $n_1$ = 1.45 respectively.

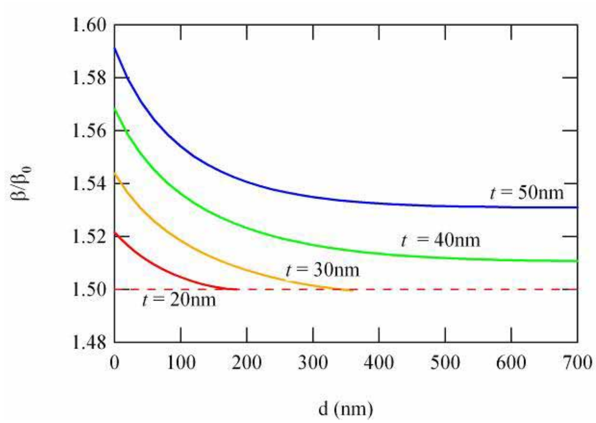


Fig. 4. Real part of the symmetric mode index for metal film thickness of $t$ = 20, 30, 40 and 50 nm. The $l_b$ modes ($t$ = 40, 50 nm) do not asymptote to $n_2$.

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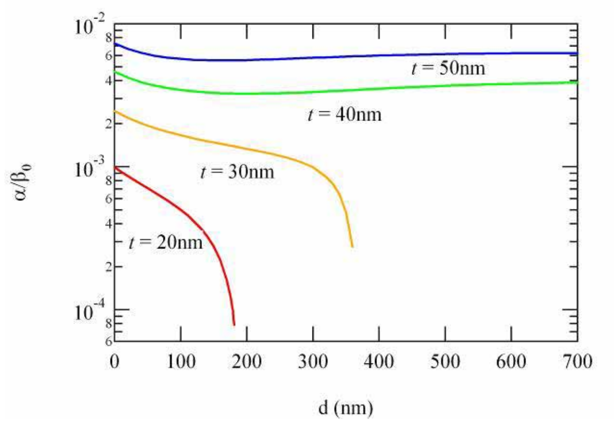


Fig. 5. Imaginary part of the symmetric mode index for metal film thickness of $t$ = 20, 30, 40 and 50 nm.

The values of $(\gamma/\beta_0)|_{d=\infty}$ for the four film thicknesses, in increasing order of $t$ are: $1.4691 - j8.361\times10^{-4}$, $1.4888 - j2.083\times10^{-3}$, $1.5104 - j3.947\times10^{-3}$ and $1.5309 - j6.270\times10^{-3}$. Film thicknesses of $t$ = 20 and 30 nm satisfy Eq. (1), while the thicker films, $t$ = 40 and 50 nm do not, as the behaviors in Figs. 4 and 5 suggest. It is clear that both the $t$ = 40 and 50 nm structures support $s_b$ modes that remain bound as they approach the $(\gamma/\beta_0)|_{d=\infty}$ values as $d$ tends to infinity.

The modes of the 20 and 30 nm thick films are ultra-long range modes and thus experience significant reductions in the imaginary parts of their mode effective indices as $d$ approaches a certain cutoff value. For the 30 nm thick film, at $d$ = 330 nm $\gamma/\beta_0 = 1.5004 - j7.363\times10^{-4}$. The corresponding propagation range is approximately 68 μm. This is farther than the propagation range of a 20 nm thick film in a homogeneous cladding and about three times greater than the case of the homogeneous cladding alone for the 30 nm thick film. These increases in propagation distance may allow for thicker films to be used in application where they previously would have been excluded because of their short ranges. Part of the intrigue of surface plasmon waveguides is that they use a conductor as the guiding material, which may also carry an electrical signal. Increasing the guide thickness increases its cross sectional area and thus decreases its resistivity. Attention should be paid to the fact that, however, $\beta/\beta_0$ for the 30 nm thick film becomes extremely close to $n_2$ for low values of $\alpha/\beta_0$ which are required for the long propagation ranges. This proximity to the cladding index of refraction implies a relatively lower mode confinement. This is not so much the case for the 20 nm thick film, which maintains a much larger distance from the light line as its attenuation is reduced. The general trend is still then, that thinner films are better suited to achieve very long travel ranges, although the new structure allows for the scale of these ranges to be increased drastically.

*2.3 Dispersion of the ultra-long range surface plasmon wave mode*

Due to the fact that the relative permittivity of most metals depends strongly on the wavelength of the incident electromagnetic wave, dispersion is a significant factor in determining the propagation characteristics of a SPP mode. The general trend is longer wavelengths experience significantly less loss than shorter ones. Due to the fact that wavelength is often determined by the application, comparisons of the behavior of the multilayer structure at three popular wavelengths are made here. Previous calculations have used a wavelength of 632.8 nm. These are compared with the effects at 850 and 1550 nm. The thickness of the film was kept constant at $t = 20$ nm as were the indices of refraction of the dielectric material, at $n_2$ = 1.50 and $n_1$ = 1.45. At 850 nm, the relative permittivity of Au [15] is $\varepsilon_m = -28.29 - j1.557$ and at 1550 nm it is $\varepsilon_m = -115.11 - j11.103$. At all wavelengths the condition for ultra-long range is satisfied. The real and imaginary parts of the $u_b$ mode indices at these three wavelengths are shown in Figs. 6 and 7.

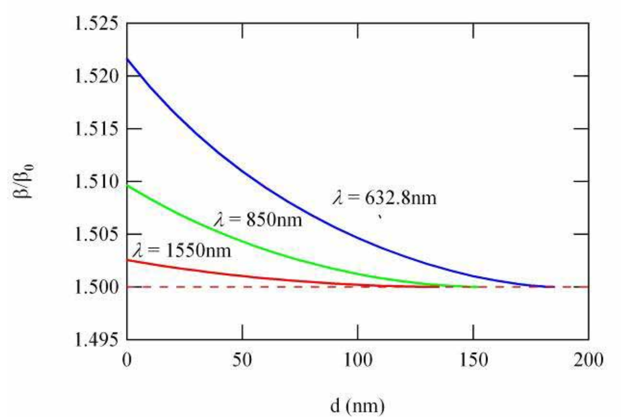


Fig. 6. Real part of the $u_b$ mode index at three different wavelengths.

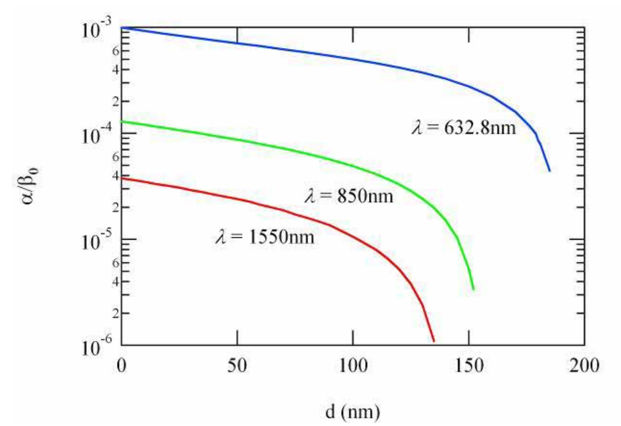


Fig. 7. Imaginary part of the $u_b$ mode index at three different wavelengths.

The trend of longer wavelengths supporting lower loss modes is clear. Longer wavelengths also have cutoffs at lower values for *d*. At all wavelengths, significant improvements in propagation distance are made as the thickness of the inner dielectric layer is increased. At 632.8 nm, a 163 nm thick inner dielectric layer results in the $u_b$ mode with index $\gamma/\beta_0 = 1.5005 - j1.982\times10^{-4}$. The corresponding propagation range is 254 μm, nearly five times that of the $s_b$ mode supported by a simple 20 nm thick film in a homogeneous dielectric background. At a wavelength of 850 nm, a 20nm thick film in a homogeneous background with a refractive index of 1.50 supports a $s_b$ mode with index $\gamma/\beta_0 = 1.5096 - j1.293\times10^{-4}$. The corresponding propagation distance for this case is 0.523 mm. For a 120 nm thick inner dielectric layer, and a film of the same thickness, however, the $u_b$ mode has $\gamma/\beta_0 = 1.5005 - j3.378\times10^{-5}$, representing a propagation distance of 2 mm. Even greater travel ranges are available as the wavelength is increased to 1550 nm. At $d = 75$ nm, $\gamma/\beta_0 = 1.5005 - j1.733\times10^{-5}$, which implies a propagation distance of 7.1 mm. These distances, 247 μm at $\lambda = 632.8$, 2.0 mm at 850 nm, and 7.1 mm at 1550 nm,

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represent significant increases over the ranges supported by at the respective structures without the low refractive index inner dielectric layers. For similar values of the real part of the mode index, propagation distance increases with wavelength. In addition, these points correspond to values of *d* that are increasingly farther from the cutoff thickness for longer wavelengths, although the confinement is reduced with increasing wavelength. The behavior of the mode propagation distances is summarized in Fig. 8.

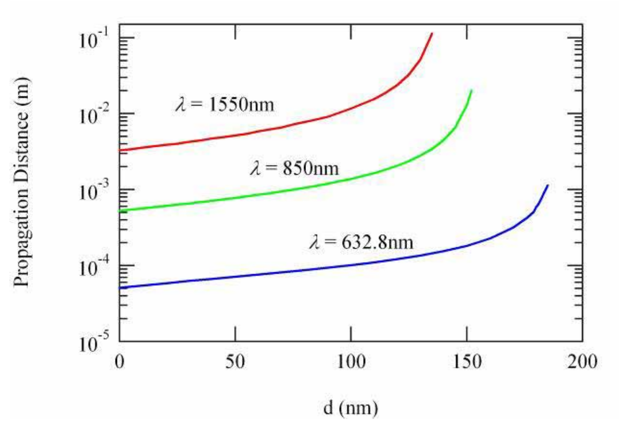


Fig. 8. Propagation distances of the $u_b$ modes at three different wavelengths.

### 3. Summary

We investigated the detailed behavior of the ultra-long range surface plasmon mode supported by the metal-dielectric surface plasmon waveguide structures. Our metal-dielectric structure only supports surface plasmon wave modes because the inner dielectric layers have smaller index of refraction than the cladding dielectric. The guiding mechanism is therefore solely the surface plasmon effect since no total internal reflection can occur from inside the inner dielectric core layer. We gave a simple condition for the ultra-long range surface plasmon mode to exist. Structures satisfying the condition will support the ultra-long range surface plasmon modes. The ultra-long range modes experience dramatic reductions in their propagation losses as the thickness of the inner dielectric layer approaches a specific critical value. Variations of the index of refraction contrast between the inner core dielectric and the cladding dielectric, the metal film thickness, and the free space wavelength change the cutoff thickness of the inner dielectric layer and the rate of the reduction of the propagation loss.

Although the surface plasmon waveguide structure studied here is a one-dimensional structure, the characteristics of the ultra-long range mode can also apply to the two-dimensional surface plasmon waveguides of finite width metal strips. Since finite width plasmonic strip guides are known to support propagation distances longer than those of infinite width films, [16, 17, 18, 19, 20, 21], the concept presented here can be extended to metal strip surface plasmon guides for even longer range plasmon modes to be realized.

It is necessary to point out that in all calculations the dielectric materials were assumed to be lossless. In the case of lossy dielectric materials, the attenuation of the ultra-long range mode will approach that of the cladding dielectric rather than zero. Intuitively, the propagation distance in the cladding dielectric is the upper bound to the travel range achievable by the ultra-long range mode. Therefore, in practice, the propagation distance of the $u_b$ mode will not be truly arbitrary limited only by considerations involving confinement and practical fabrication as previously discussed, but also fundamentally limited by the loss of the dielectric materials. The investigation of the effect of losses in the inner layer and cladding dielectric materials is relegated to future work.

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We have shown that the attenuation of a surface plasmon-polariton mode guided by a thin metal film can be significantly reduced without altering the index of refraction of the cladding, the thickness of the metal film or the wavelength of the light. This is accomplished by placing dielectric layers with an index of refraction below that of the cladding above and below the metal film. Since the surface plasmon waves are always coupled with the electromagnetic waves, the ultra-long range surface plasmon mode gives an alternative mechanism for guiding light, as opposed to the total internal reflection guiding in dielectric optical waveguides.

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