Novel metal-dielectric structures for guiding ultra-long range surface plasmon-polaritons at optical frequencies

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ABSTRACT

It is well known that propagation ranges of surface plasmon-polaritons supported by thin metal films are significantly limited by losses due to the concentration of a portion of the mode's energy within the metal. Propagation distances may be increased by using lower frequency light or thinner metal films. Implementation of these techniques is limited, however, and may not always be desirable. A layered structure, which allows for propagation ranges to be increased while holding the wavelength of the light and film thickness constant has been proposed. The surface plasmon-polariton guide consists of a metal film surrounded above and below by a thin, low index of refraction dielectric layer. When set in a dielectric cladding of higher index of refraction, the thickness of the inner dielectric layer may be increased up to a cutoff to achieve dramatic extension in propagation range. The effects of adjustment to parameters of the guide, such as the dielectric cladding index of refraction, metal film thickness and wavelength are discussed. Due to the fact that propagation distance and mode confinement are closely related, these two properties are investigated together, and the merits of the guide are discussed.

Keywords: Surface plasmon-polariton, guided waves, optics of metals

1. INTRODUCTION

A surface plasmon-polariton (SPP) is a TM electromagnetic wave coupled to the collective longitudinal oscillations of the free electron density existing near the surface of a metal. The requirement for the existence of a SPP is that the metal in contact with the dielectric must have a relative permittivity whose real part is negative at the frequency of the light which will be used to excite the SPP. Many metals, such as gold (Au), silver (Ag), copper (Cu) and aluminum (Al) satisfy this condition over a wide range of optical frequencies.[1]

SPP modes propagating along a single, isolated surface experience significant attenuation along the direction of propagation. The intensity of their electromagnetic waves typically decays to 1/*e* of the initial value within several tens of microns. A thin metal film in a homogeneous dielectric medium however, may support longer ranging SPP modes. Two bound modes, characterized by the symmetry of their transverse electromagnetic fields, are present in this case[1-7]. The two modes are denoted s_b and a_b according to the difference in the symmetries of their fields. The transverse field components of the s_b mode are symmetric about the center of the metal film while those of the a_b are anti-symmetric. The propagation range of the s_b mode is greater than that of the single surface mode, and increases with decreasing film thickness, while the opposite behavior is true for the a_b mode. Due to the relatively long propagation distances it supports, and the fact that these may be increased by decreasing film thickness, the s_b mode has generated much interest and been studied extensively in the past[1-7].

Although the propagation range of the s_b mode is long relative to other SPP modes, it is still macroscopically short and thus limits applications, especially at higher frequencies, such as those in the visible range. For example, the s_b mode supported by a 20 nm thick Au film in a homogeneous cladding of refractive index 1.45 has a propagation range of approximately 60 μm at the wavelength of 632.8 nm. The simplest 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 the metal film approaches the nanometer scale, quantum mechanical effects become dominant, causing the properties of the thin film to differ significantly from those of the bulk material[9]. Slight additional gains may also be achieved by choosing a dielectric cladding with a lower index of refraction. Increasing the wavelength of the light will

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also increase the propagation range of the s_b mode, although the wavelength to be used is often determined by the application.

Range extension of SPPs by other methods has been studied by Wendler and Haupt[10] and Kou and Tamir[11]. It was found that varying the asymmetry of the cladding index of refraction, above and below a thin metal film, could result in sharp gains in propagation distances immediately preceding a cutoff value[10]. It was also found that a traditional dielectric slab waveguide, placed above a thin film surface plasmon guide, could act as a sink for the mode's field and energy density. This reduction in the proportion of the energy propagating in the metal film resulted in increases in propagation distance[11].

Recently we proposed a simple scheme for reducing the loss experienced by the symmetric SPP modes[12-14]. Our technique allows for increases in propagation distance to be achieved without changing the thickness of the metal film, the cladding refractive index, or exitation wavelength. The bound modes supported by the metal-dielectric surface plasmon waveguide structure illustrated in Fig. 1 and variations in their propagation constants have been discussed[12-14]. Work by Zia et al.[15] has discussed the fact that reductions in mode attenuation generally result from increased proportions of the propagating mode's energy being carried in outside of the lossy metal film. Therefore, increases in propagation distance are typically achieved at the expense of mode confinement. The trade off, however, is not strictly proportional, and varies significantly with different geometries, materials (both dielectrics and metals) and wavelengths[15]. The figure of merit, relating attenuation to mode confinement, thus varies greatly from guiding structure to guiding structure[16]. The aim of this work is to investigate the trade off between mode propagation range and confinement for the structure of Fig. 1. The merits of the guide are evaluated through investigation of the propagation range and confinement characteristics supported by various configurations of the guides shown in Fig. 1.

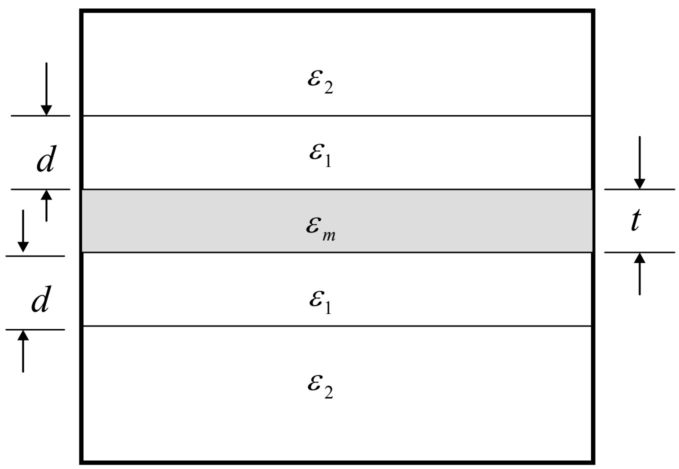

Fig. 1. The one dimensional layered metal-dielectric SPP guide. In all cases, $\varepsilon_1 < \varepsilon_2$ is assumed.

2. PROPERITES OF ULTRA-LONG RANGE SURFACE PLASMONS

For the structure shown in Fig. 1, ε_1 and ε_2 are the relative permittivities of the inner and cladding dielectrics respectively. The complex relative permittivity of the metal film is $\varepsilon_m = \varepsilon_m' + j\varepsilon_m''$. The thickness of the metal film is t and d is the thickness of the inner dielectric layer. A mode will propagate with propagation constant $\gamma = \beta - j\alpha$ and therefore effective index γ / β_0, where β_0 is the free space wavenumber ($\beta_0 = 2\pi / \lambda$). Propagation distance or range, throughout this discussion is defined as

$$L_{SPP} = \frac{1}{2\alpha}. \quad (1)$$

It has been shown that the guiding structure may support different behaviors of surface plasmon modes. As $d \to \infty$, the propagation constant of the surface plasmon mode approaches that of the s_b mode supported by a thin metal film of the same thickness in a homogeneous cladding of refractive index $n_1 = \sqrt{\varepsilon_1}$. While the real part of the solution, β / β_0, to this limiting case will by larger than n_1, it may or may not be larger than n_2. If it is, then the behavior of the mode is similar to that of the usual s_b mode, transitioning between the solution to the thin film in cladding index n_2 and that with n_1 as d is increased. If it is not, however, then as d is increased, the solution approaches one that cannot, by definition, remain bound. It will be shown that, in the latter case, the structure of Fig. 1 may support modes that experience significant reductions in their attenuation with increasing inner dielectric layer thickness, up to a cutoff point. These modes will be referred to as ultra-long range modes. Equation (2),

$$\left(\beta / \beta_0\right)\Big|_{d\to\infty} < n_2, \tag{2}$$

gives a necessary, but not adequate condition for the existence of an ultra-long range mode. It was found that for longer wavelengths and thinner metal films, ultra-long range modes are supported even if the cladding index is very close to the value of $\left(\beta / \beta_0\right)\Big|_{d\to\infty}$. The value of n_2 for which an ultra-long range mode will be supported increases above $\left(\beta / \beta_0\right)\Big|_{d\to\infty}$ with decreasing wavelength or increasing film thickness. Modes exhibiting dramatic reductions in attenuation with increasing d are denoted u_b and those which do not are labeled l_b, for long-range mode.

The dispersion relation for a symmetric mode supported by the structure shown in Fig. 1 may be derived in the usual manner, through writing the TM associated magnetic and electric fields in each layer and matching boundary conditions at each interface. The relation takes the form

$$\frac{\varepsilon_1 \kappa_m}{\varepsilon_m \kappa_1} \tanh\left(\frac{\kappa_m t}{2}\right) + \frac{\varepsilon_1 \kappa_2 \cosh(\kappa_1 d) + \varepsilon_2 \kappa_1 \sinh(\kappa_1 d)}{\varepsilon_2 \kappa_1 \cosh(\kappa_1 d) + \varepsilon_1 \kappa_2 \sinh(\kappa_1 d)} = 0, \tag{3}$$

where

$$\kappa_1 = \sqrt{\gamma^2 - \beta_0^2 \varepsilon_1},\ \kappa_2 = \sqrt{\gamma^2 - \beta_0^2 \varepsilon_2}, \text{ and } \kappa_m = \sqrt{\gamma^2 - \beta_0^2 \varepsilon_m}.$$

Equation (3) may be verified to reduce to the appropriate s_b mode dispersion relation,

$$d \to 0: \quad \varepsilon_2 \kappa_m \tanh\left(\frac{\kappa_m t}{2}\right) + \varepsilon_m \kappa_2 = 0 \tag{4}$$

and

$$d \to \infty: \quad \varepsilon_1 \kappa_m \tanh\left(\frac{\kappa_m t}{2}\right) + \varepsilon_m \kappa_1 = 0, \tag{5}$$

in the limits $d \to 0$ and $d \to \infty$, as indicated. The propagation constant of a mode can be found by minimizing the absolute value of (3) through the same procedure used in Ref. 7 to find the modes of a simple metal film set in a homogeneous dielectric cladding. Mode indices calculated in this manner were checked against previous results which used another method[12, 14] and found to be in good agreement.

In addition to the capability to transport signals with low attenuation, the other important aspect of a guide is its ability to localize electromagnetic radiation, termed confinement. A number of measures of confinement have been proposed.[15,16] In these calculations we focus on the spatial extent of the mode's transverse magnetic field. Given that the fields of the mode will decay exponentially in the normal direction away from the metal-dielectric interface, the usual measure is the width in between the two points where the field has decayed to $1/e$ of its value at the interface, as illustrated in Fig. 2. For the guide of Fig. 1, the field of a u_b mode will decay increasingly slowly in the cladding. The spatial extent of the mode increases significantly up to the cutoff point.

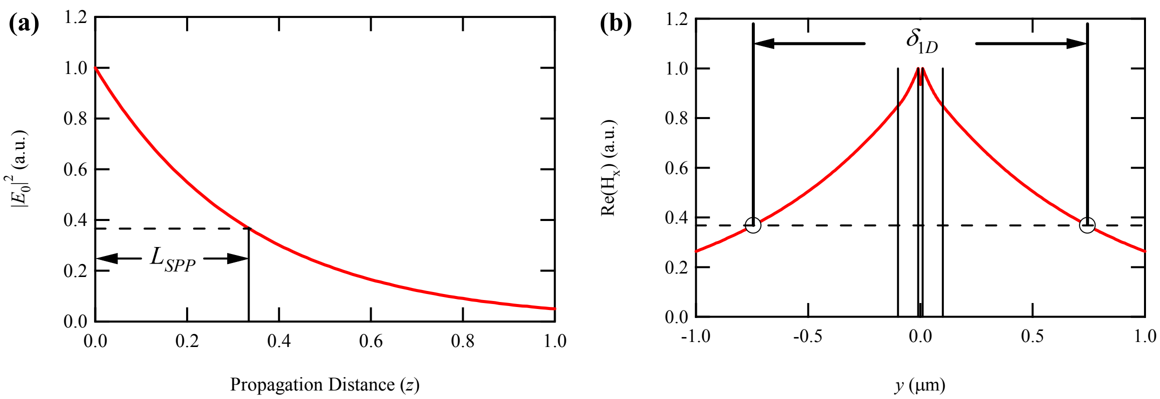

Fig. 2. The definitions of mode propagation range (a) and spatial extent (b). The measure of propagation range follows convention, and that of mode spatial extent is the same as in Ref. 15. Here, for illustrative purposes, $|E_0|^2$ in (a) and H_x in (b) are normalized separately such that their amplitudes are 1 at the initial point and the surface of the metal respectively. The dashed line is at $1/e$. The extents of the metal film and inner dielectric layer are also shown as the black vertical lines. The figure in (b) happens to correspond to a 20 nm thick film with d = 100 nm.

2.1 Effects of varying dielectric cladding's refractive index

The reflection pole method[17] was used to determine mode indices for four different cladding indices as d varied from zero to near the cutoff. Minimization of the absolute value of (3) will also yield the mode index, as was mentioned. The metal was taken to be Au, with relative permittivity $\varepsilon_m = -11.65 - j1.333$ at $\lambda = 632.8$ nm, obtained from an interpolation fit to the data of Johnson and Christy[18]. The thickness of the film was chosen to be t = 20 nm, and the refractive index of the inner dielectric layer was held constant at n_1 = 1.45. The four cladding indices investigated were n_2 = 1.55, 1.50, 1.48, and 1.46. For the parameter values chosen, $\left(\gamma / \beta_0\right)\big|_{d\to\infty}$ as defined in the previous section equals $1.4691 - j8.361\times10^{-4}$. The case of n_2 = 1.46 therefore does not satisfy (2), and the significantly different behavior is evident in Fig. 3.

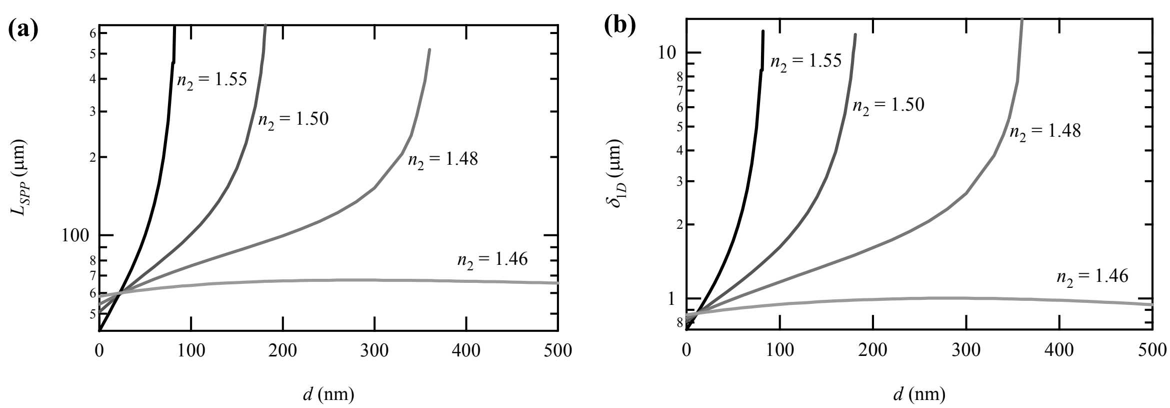

Fig. 3. Propagation distance (a) and confinement (b), both in microns, for differing values of the cladding refractive index. The refractive index to which each curve corresponds to is indicated on the graphs. Clearly the case of n_2 = 1.46 corresponds to a l_b mode, while all others are u_b modes.

The graphs of the propagation distances and confinement factors in Fig. 3 clearly illustrate the expected behavior of the u_b and l_b modes. The u_b modes experience significant increases in propagation range as d is increased. At the same time the spatial extent of the mode increases as well. For example, when $n_2 = 1.48$ and $d = 340$ nm, the u_b mode is characterized by a spatial extent of 4.6 μm, and a propagation range of 242 μm. These represent an approximately 5 and 4.5 fold increases respectively over the values corresponding to the associated s_b mode present when d = 0. Adjusting parameter values to $n_2 = 1.50$ and $d = 160$ nm, one finds $\delta_{1D} = 4$ μm and $L_{SPP} = 227$ μm, which correspond to increases of slightly less than 5 and approximately 4.5 for the values of δ_{1D} and L_{SPP} associated with the s_b mode of a film of equal thickness in a homogeneous cladding of index n_2. When n_2 is increased to 1.55, a much thinner inner dielectric layer has increased effects on the mode propagation characteristics. Here, for $d = 75$ nm, the mode is confined within 4.9 μm, and has a propagation range of 275 μm. These both represent increases of about 6.5 fold over the simple thin film case values. The implication is then that the figure of merit of the mode, if taken to be the ratio of propagation distance to spatial extent, L_{SPP}/δ_{1D}, as in Ref. 16, remains very stable as the thickness of the inner dielectric is increased.

Additionally, as is evident in Fig. 3, the shapes of the two curves are determined by the magnitude of the index of refraction contrast between the cladding and inner dielectric layers. The curves flatten out as the contrast is reduced. The cutoff thickness of the inner dielectric layer, d_c, is increased until eventually the mode is characterized as a l_b mode. This behavior has implications for the ease with which these structures may be fabricated. For a flatter curve, the mode's propagation characteristics will be less sensitive to uncontrolled variations in d that might occur during the deposition of the thin film. The implication is then that a lower contrast between the cladding and inner dielectric layers, which still supports a u_b mode, is most desirable for ease of fabrication.

Finally, since for a fixed inner dielectric layer thickness and refractive index, the mode propagation constant can be varied greatly with changes in the cladding index, it may be possible to use the configuration to modulate a SPP signal. Examination of Fig. 3 shows that relatively small refractive index variations in the cladding dielectric may vary the attenuation of the mode significantly. Comparison of the $n_2 = 1.50$ and 1.48 or the $n_2 = 1.48$ with the 1.46 curve shows that propagation range could be more than doubled or tripled due to refractive index variations of only 0.02. Electro-optic effects might achieve refractive index variations large enough in magnitude, or thermo-optic effects could be used[19]. These might be used to modulate attenuation or extinguish a mode by driving it over cutoff. In addition to active signal modulation, the fact that large variations in the propagation constants of the u_b modes occur for relatively small changes in cladding index might be used for sensing applications.

2.2 Effects of varying metal film thickness

Due to the coupling of SPP fields at the two metal-dielectric interfaces, film thickness is one of the most significant determinants of the SPP's propagation characteristics. Mode indices were determined for film thicknesses of $t = 20$, 30, 40, and 50 nm, while n_1 and n_2 were held constant at 1.45 and 1.50 respectively, with the wavelength still at 632.8 nm as in the previous section.

Because increasing strip thickness increases $\left(\beta/\beta_0\right)\big|_{d\to\infty}$, only the cases $t = 20$ and 30 nm satisfy (2). This behavior can be seen in Fig. 4, which plots the propagation range and spatial extent of the u_b and l_b modes over a range of values for d. Only the cases where $t = 20$ and 30 nm show increases in L_{SPP} and δ_{1D}, while the guides with metal films 40 and 50 nm thick support modes that simply approach the solution of a s_b mode in a cladding with refractive index equal to that of the inner dielectric.

While the s_b mode may only propagate a distance of approximately 20 μm along a 30 nm thick film, when d is increased to 330 nm, the u_b mode may travel nearly 67 μm, a greater than three fold increase in range. This distance is also comparable to the range of a s_b mode traveling along a 20 nm thick film in a cladding of similar refractive index. The spatial extent of the mode at this point is about 2 μm, also about a three fold increase from the corresponding s_b mode value. As before, the figure of merit of the guide remains stable. The increases in propagation distance may allow for thicker films to be used in applications where they previously would have been excluded because of the very short propagation ranges they support. The increases in propagation distance however, need to be balanced against the increase in confinement. In addition, it should be noted that the 2 μm mode size is about twice as large as the size of a mode supported by a 20 nm thick film.

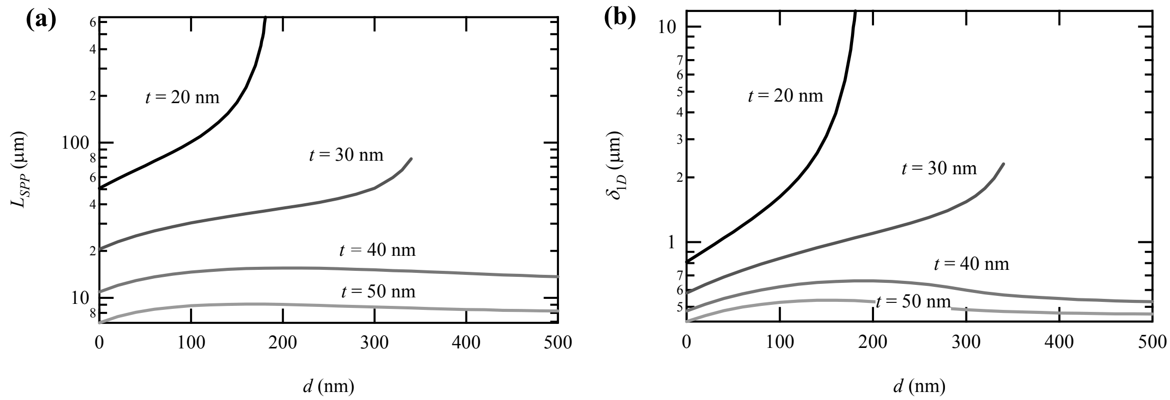

Fig. 4. Propagation distance (a) and confinement (b) for 20, 30, 40 and 50 nm thick films, as are indicated. The 20 and 30 nm thick films support u_b modes, while l_b modes are supported by the 40 and 50 nm thick films. The dramatic increases in propagation range and spatial extent seen for the thinner film guides are not evident in the l_b modes.

Attention should also be paid to the fact that the longest ranges for the thicker film will occur extremely close to the cutoff thickness of the inner dielectric layer and thus may be very difficult to achieve in practice. This is not as much the case for the 20 nm thick film, which supports propagation ranges that increase with d at a faster rate well below d_c, but more gradually very close to the cutoff. The general trend is still that thinner films are better suited to achieve long travel ranges, although the new structure allows for the scale of these ranges to be increased dramatically.

2.3 Dispersion effects

The relative permittivity of most metals is strongly dispersive, and therefore the characteristics of SPP modes will differ significantly across various wavelengths. While the attenuation coefficient of the complex index of refraction is known to increase with increasing distance below the plasma frequency, the magnitude of ε_m' is greatly increased at the same time, with the effect that the significantly reduced proportions of the mode's fields lie within the metal film. The overall effect is therefore that with increasing wavelength, a thin metal film will support less confined modes that experience less attenuation as they propagate. To analyze the effects of dispersion, mode indices were calculated at $\lambda = 632.8$, 850, and 1550 nm, holding all other parameters constant at n_1 = 1.45, n_2 = 1.50, and t = 20 nm, as d was increased. The relative permittivity values at 850 and 1550 nm are $\varepsilon_m = -28.29 - j1.557$ and $-115.11 - j11.103$ respectively. The results are summarized in Fig. 5.

The trend of longer wavelengths supporting lower loss modes is clearly visible. At longer wavelengths, the cutoff value of the inner dielectric layer is reduced. It has already been mentioned, that for a cladding with a refractive index of 1.50, at $\lambda = 632.8$ nm, a mode with size 4 μm and a propagation range of 227 μm is supported when the thickness of the inner dielectric layer is increased to 160 nm. Calculations show that propagation ranges of 2 mm and 6 mm are supported at wavelengths of 850 and 1550 nm when $d = 120$ and 60 nm respectively. The spatial extent of the modes is $\delta_{1D} = 6.5$ and 10 μm, approximately. These values are about four times as large as the s_b mode present when d = 0 for the $\lambda = 850$ nm case and about double for 1550 nm wavelength. The ratio of the mode's propagation distance to its size again remains very stable.

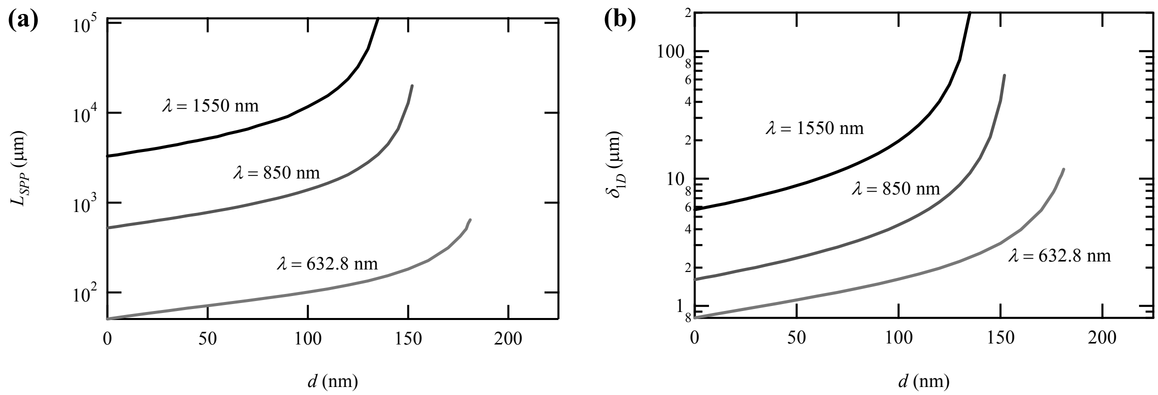

Fig. 5. Propagation distance (a) and confinement (b) for three different wavelengths; 632.8, 850 and 1550 nm. The wavelength to which each curve corresponds is indicated on the graphs. The condition of equation (2) is satisfied at all three of the wavelengths.

3. SUMMARY

The propagation and confinement characteristics of the ultra-long range mode have been examined. The SPP guide of Fig. 1 has been shown to exhibit a cutoff condition, which must be satisfied in order for a u_b mode to be supported. For an ultra-long range mode, the propagation distance of the SPP mode increases significantly with d. An expression for a necessary, but not adequate cutoff condition for the existence of a u_b mode was given. Over the range of wavelengths and film thicknesses investigated, the cutoff condition of (2) appears to be useful as an approximate guide to whether or not a u_b mode will be supported. Calculations of mode propagation ranges and sizes show both to increase at approximately the same rate with the thickness of the inner dielectric layer, and thus the figure of merit based on the ratio of the two remains stable.

The effects on the behavior of the u_b mode of variations in cladding index of refraction, film thickness, and wavelength were investigated. It was found that all will play a role in determining whether a mode satisfies the condition for the ultra-long range mode, and also significantly effect the behavior of its propagation characteristics with respect to inner dielectric layer thickness. The relation of cladding index to whether the mode satisfies (2) is immediately obvious. In addition, higher cladding refractive indices will correspond to reduced cutoff thicknesses of the inner dielectric layer, and larger increases in propagation range. Since raising the thickness of the metal film will increase the magnitude of the real part of the s_b mode's propagation constant, as well as increase confinement, thicker films will require increasingly larger contrasts between the inner and cladding dielectrics in order support u_b modes. It is possible to guide u_b modes along 30 nm thick metal films which attenuate at lower rates than s_b modes along films that are only 20 nm thick. Thicker metal films may therefore be used if they are desirable for easier or more reliable fabrication, or integration with other components. Where figure of merit is the primary concern however, thinner metal films are advantageous since a u_b mode may be guided along a 20 nm thick film with the same propagation distance but with better confinement. Wavelength was also found to be an important determinant of the propagation characteristics of the u_b mode. Longer wavelengths will support ultra-long range modes over a wider range of the other parameters. In addition cutoff thickness of the inner dielectric layer is reduced for increasing wavelength, while propagation range and mode size are increased.

Although the figure of merit of the guide configuration varies little, the structure offer the possibility in delivering signals across chip scale distances at a wider range of wavelengths than a conventional thin metal film guide. The effectiveness of the structure at shorter wavelengths may be increased by applying the principle to a thin strip configuration, which is known to reduce mode attenuation in itself[20-25]. The ability to deliver a range of wavelengths allows for greater freedom in the selection of sources and detectors. In addition, sensing devices tend to operate best at a specific range of wavelengths. It has been mentioned that for SPR sensors used to detect the formation of a thin adlayer, sensitivity will, above a certain wavelength, decrease with increasing wavelength as the probe depth is made increasingly large[26]. Finally, since the propagation characteristics may be affected greatly by changes in the refractive index contrast between the cladding and inner dielectric layers, the possibility of using the configuration to modulate a signal, or as a sensor configuration has been discussed.

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