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Long-range surface plasmon polaritons with subwavelength mode expansion in an asymmetrical system*

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Long-range surface plasmon polariton (LRSPP) modes in an asymmetrical system, in which the thin metal film is sandwiched between a semi-infinite substrate and a high permittivity polymer film with a finite thickness, are theoretically calculated and analyzed. Due to the high permittivity of the polymer film, at proper polymer film thicknesses, the index-matching condition of the dielectrics at both sides of the metal can be satisfied for supporting LRSPP modes, and the electromagnetic field above the metal can be localized well. It is found that these LRSPP modes have both long propagation lengths and subwavelength mode expansion above the metal at the optimal polymer film thicknesses. Furthermore, the requirements on the refractive index and the thickness of the polymer film to support LRSPP modes at the optimal thicknesses are found to be not critical.

Keywords: surface plasmon polaritons, field intensity confinement, long propagation length, integrated optics

PACC: 7320M, 5240D, 4282

1. Introduction

Future integrated photonic circuits for optical information will have specific requirements on the density of integration. Surface plasmon polaritons[1] (SPPs), which can break through the diffraction limit of light due to their tight field intensity confinement to the metal surface, show great promise for applications in highly integrated photonic circuits.[2,3] However, the relatively short propagation lengths ($\sim$ 100 μm)[1,4−6] of SPPs are considered to be somewhat limited in applications. By changing the metal–dielectric system to a symmetrical one with a thin metal film embedded in an infinite homogeneous background dielectric, the SPP propagation loss can be significantly decreased.[7,8] As the metal is thin and the dielectrics at both sides of the metal are in the index-matching condition, SPP modes guided by the two interfaces will couple with each other, and a special symmetrical SPP mode with a smaller fraction of the electromagnetic field inside the metal film emerges, which has a long propagation length and is usually termed the long-range surface plasmon polariton (LRSPP). Due to the long propagation length ($\sim$mm) of the LRSPP, it can be applied in many important device applications such as modulators, sensors and integrated optics.[2−4,9−16] However, the long propagation length is achieved at the expense of the field intensity confinement, for the mode size of the LRSPP in the symmetrical system is about $\sim$ 10 μm,[9−17] which is much greater than the photon wavelength and limits the density of integration. Furthermore, the metal film has to be embedded in infinite homogeneous and symmetrical background dielectrics, and thus the types of dielectric materials and the precise fabrication also become the limiting factors in applications.

In the past decade, LRSPP modes supported by thin metal films embedded in infinite asymmetrical background dielectrics have also been calculated and discussed.[18,19] In these systems, the LRSPP modes can be cut off if there is a sufficiently asymmetrical refraction index between the substrate and the top slabs surrounding the metal film, and the index-matching

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condition becomes critical as the metal film is made thin. Yang *et al*[20] reported long-range surface modes of metal-clad four-layer waveguides (dielectric-dielectric-metal-dielectric), in which the permittivities of each dielectric are nearly the same in the case of the index-matching condition. The effective mode size is about the same as that in the symmetrical system, but the propagation length is much shorter. In order to maintain long propagation lengths, the differences of the refraction index between the dielectrics surrounding the metal film have to be very small in both the systems described above, and thus these systems are very similar to the symmetrical system in applications. An asymmetrical system like a thin metal film on a one-dimensional photonic crystal surface[21] has also been studied, but the effective mode size of the LRSPP was still large and the system was complicated to fabricate. Using a high permittivity dielectric film together with the air above it to form a comparable media on the substrate for LRSPP modes[22−24] can solve the problem of materials. But up to now, the field intensity confinement and the propagation lengths of LRSPP modes in the asymmetrical system have not been discussed in detail.

In the present paper, LRSPP modes in an asymmetrical system, in which the thin metal film is sandwiched between a semi-infinite substrate and a high permittivity polymer film with finite thickness, are calculated and analyzed theoretically. Due to the high permittivity of the polymer, the electromagnetic fields above the metal will be localized much more strongly than that in the symmetrical system, and the mode expansion above the metal surface can be reduced to subwavelength scales. Meanwhile, calculations also indicate that the requirements of the refractive index and the thickness of the polymer film to support the LRSPP are not critical, which is beneficial for the choice of the polymer materials and the sample fabrication in a practical experiment.

2. LRSPP mode in the asymmetrical system

The asymmetrical system discussed in this paper is schematically shown in Fig.1. A thin metal film (Au) with a thickness of t_m is sandwiched between the semi-infinite silica substrate (permittivity ε_1) and a high permittivity polymer film (permittivity $\varepsilon_3 > \varepsilon_1$) with a finite thickness of d. The Cartesian coordinates used in the following analysis are also shown, and the SPP propagates along the x-axis with the vacuum wavelength $\lambda = 1550$ nm, vacuum wave vector $k_0 = 2\pi/\lambda$, and angular frequency ω. In the following calculations, the thickness of the metal film is set to be $t_m = 20$ nm according to previous experimental works.[11−15] The permittivities of the silica substrate, the gold metal film, and the air are set to be $\varepsilon_1 = 1.444^2$, $\varepsilon_2 = -131.19 + 12.65\mathrm{i}$, and $\varepsilon_4 = 1.0$, respectively.[10] For the polymer film, a typical high permittivity of $\varepsilon_3 = 1.6^2$ was chosen first.

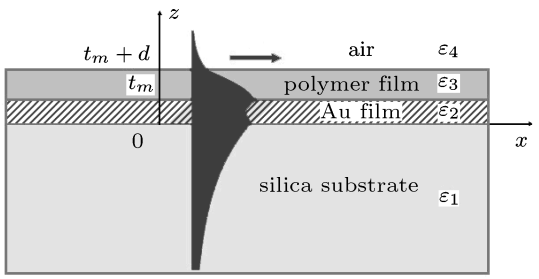


Fig.1. Schematic of a thin metal film sandwiched between the semi-infinite silica substrate and the polymer film, and SPP propagating along the x-axis.

Since we are mainly interested in the SPP modes which have a TM nature, we assume the bound solutions of the TM fields within each layer in the asymmetrical system shown in Fig.1 having the form (in terms of the H-field) of

$$H_y = \begin{cases} H_{y1}(x,z,t) = A_1 \exp(k_{z1} z) \exp(\mathrm{i}\,\beta x - \mathrm{i}\,\omega t); & z \le 0 \\ H_{y2}(x,z,t) = A_2\{\exp(-k_{z2} z) + b \exp[k_{z2}(z - t_m)] \exp(\mathrm{i}\,\beta x - \mathrm{i}\,\omega t); & 0 < z < t_m \\ H_{y3}(x,z,t) = A_3\{\exp[\mathrm{i}\,k_{z3}(z - t_m)] + a \exp[-\mathrm{i}\,k_{z3}(z - t_m)] \exp(\mathrm{i}\,\beta x - \mathrm{i}\,\omega t); & t_m \le z \le t_m + d \\ H_{y4}(x,z,t) = A_4 \exp[-k_{z4}(z - t_m - d)] \exp(\mathrm{i}\,\beta x - \mathrm{i}\,\omega t); & z > t_m + d, \end{cases} \quad (1)$$

where the subscripts 1, 2, 3 and 4 represent the silica substrate, the metal film, the polymer film, and the air, respectively; A_i ($i = 1, 2, 3, 4$), a and b are constants, but only one of them is independent and is determined by the normalization of power in the field; β is the propagation constant along the x-axis; $k_{zi} = (\beta^2 - \varepsilon_i \omega^2/c^2)^{1/2}$

($i = 1, 2, 4$) and $k_{z3} = (\varepsilon_3\omega^2/c^2 - \beta^2)^{1/2}$ are the transverse propagation constants in the silica substrate, the metal film, the air, and the polymer film, respectively. Here, the real part of β has to be greater than $k_0\ \varepsilon_1^{1/2}$ to obtain a bound solution, which means that the electromagnetic fields in the silica substrate and the air are evanescent fields, as shown in Fig.1. Based on Maxwell's equations and boundary conditions, we can obtain the eigenfunction for the propagation constant β:

$$\exp[\mathrm{i}(2k_{z3}d - 2m\pi)] = \frac{\varepsilon_2 k_{z3}[b + \exp(-k_{z2}t_m)] + \mathrm{i}\,\varepsilon_3 k_{z2}[b - \exp(-k_{z2}t_m)]}{\varepsilon_2 k_{z3}[b + \exp(-k_{z2}t_m)] - \mathrm{i}\,\varepsilon_3 k_{z2}[b - \exp(-k_{z2}t_m)]} \frac{\mathrm{i}\,\varepsilon_4 k_{z3} - \varepsilon_3 k_{z4}}{\mathrm{i}\,\varepsilon_4 k_{z3} + \varepsilon_3 k_{z4}}, \tag{2}$$

where $b = (k_{z2}\varepsilon_1 + k_{z1}\varepsilon_2)\exp(k_{z2}t_m)/(k_{z2}\varepsilon_1 - k_{z1}\varepsilon_2)$. m is an integer and represents the order of the mode. In this paper, we only discuss the symmetrical mode with $m = 0$, which is also called the LRSPP mode.[20]

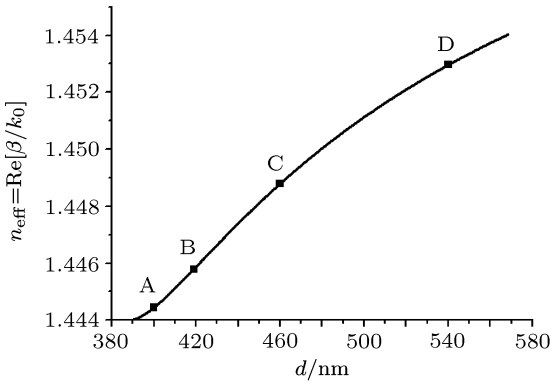


Fig.2. Relationship between $n_{\mathrm{eff}} = \mathrm{Re}[\beta/k_0]$ and the thickness d of the polymer film.

Equation (2) is solved numerically by the method of bisection. The resulting effective refractive index $n_{\mathrm{eff}} = \mathrm{Re}[\beta/k_0]$ of the bound mode in the asymmetrical system with variation of the thickness d of the polymer film is shown in Fig.2. In order to study the forms of these solutions, we need to know the relevant field distributions. Figure 3 displays the distributions of the real part of the magnetic field $\mathrm{Re}[H_y]$ along the z-axis for four typical thicknesses d (A: $d = 400$ nm, B: $d = 419$ nm, C: $d = 460$ nm and D: $d = 540$ nm), and the inset shows the details of the magnetic fields in the metal. Here, for comparison with the asymmetrical systems, we define a reference symmetrical system in which the same 20 nm gold film is embedded in the infinite silica background (permittivity $\varepsilon_1 = 1.444^2$) on both sides. The distributions of the LRSPP field in this reference system are also shown in Fig.3 (denoted by R). When the thickness of the polymer film is within the range of (389, 570) nm (solutions in Fig.2), the real part of b is positive, which means that the electromagnetic fields on both surfaces of the metal film are symmetric,[18−20] as can be seen in the inset of Fig.3. These symmetrical modes have small fractions of the electromagnetic fields inside the metal film, which is similar to the conventional LRSPP field in the symmetrical system, so the propagation losses are sharply reduced, and the propagation lengths become longer. Therefore, the symmetrical modes in the asymmetrical system can also be seen as LRSPP modes due to their long propagation lengths.

Now let us discuss quantitatively the propagation losses of the LRSPP modes in the asymmetrical system, which can be described by the imaginary parts of the propagation constants $\beta'' = \mathrm{Im}(\beta)$ and the corresponding propagation lengths L defined as $L = 1/(2\beta'')$. Their dependences on d are displayed in Fig.4 by the solid and dash lines respectively. For most of the polymer film thicknesses d, the propagation lengths L are on the magnitude of mm, which are much larger than that of a conventional SPP on the metal-silica interface ($L' = 0.11$ mm, indicated by the lower dotted line in Fig.4) and are comparable to that of the LRSPP in the symmetrical system ($L_{\mathrm{R}} = 3.58$ mm, indicated by the upper dotted line in Fig.4). It further verifies that the symmetrical modes in the asymmetrical systems are LRSPP modes. When the polymer is thin, the maximum propagation length $L = 6.06$ mm is even greater than that in the symmetrical system because the electromagnetic field in the substrate is near to the radiative mode and the energy is distributed mainly in the substrate. As the polymer film gets thicker, the propagation loss becomes greater and the corresponding propagation length decreases, since the electromagnetic field is localized better and better to the metal film, as shown in Fig.3. It should be noted that there exists a maximal point (419, 2.08) in the curve of the propagation

length. The inset of Fig.3 indicates that the corresponding field distribution in the metal film (case B) is very near to that in the reference symmetrical system (case R), so that the symmetry of the field distribution results in the long propagation length just like the symmetrical LRSPP mode in the symmetrical system. The slight deviation from absolute symmetry may come from the asymmetry of the asymmetrical system itself.

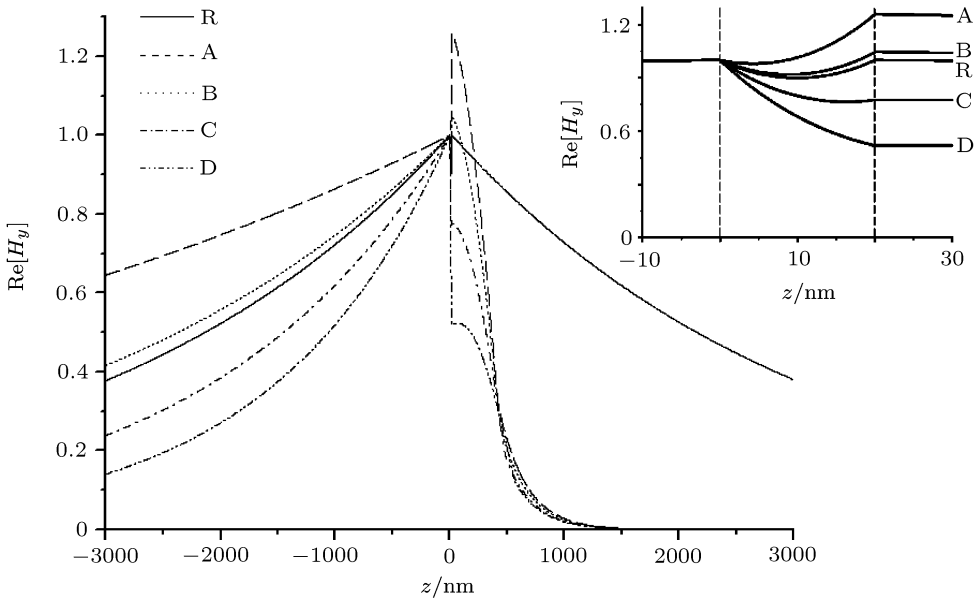


Fig.3. Distributions of the real parts of the magnetic fields Re[H_y] along the z-axis in the asymmetrical system for different thicknesses d (A: $d = 400$ nm, B: $d = 419$ nm, C: $d = 460$ nm and D: $d = 540$ nm) of the polymer film and the LRSPP field in the reference symmetrical system (R). The inset shows the details of the magnetic fields in the metal.

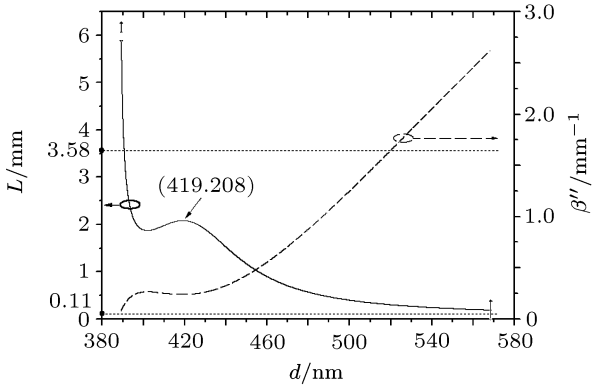


Fig.4. Imaginary parts of the propagation constants β'' (dashed line) and propagation lengths L (solid line) versus the thickness d of the polymer film. The upper and the lower dotted lines represent the propagation lengths of the LRSPP in the reference symmetrical system and the conventional SPP on the metal-silica interface, respectively.

The cut-off conditions of the LRSPP mode in the asymmetrical system were analyzed. Figure 2 shows that the LRSPP mode starts at $d = 389$ nm, and ends at $d = 570$ nm. The effective refractive index n_{eff} of the LRSPP mode increases with the polymer film thickness d. When d is less than 389 nm, n_{eff} is less than the refractive index of the substrate ($n_1 = 1.444$), and thus the electromagnetic field becomes a radiative mode in the substrate. While the polymer film thickness d is greater than 570 nm, the difference in the effective refractive indexes between the substrate and the top slabs above the metal becomes so big enough that the index-matching condition is destroyed. As a result the LRSPP mode is cut off.

3. Field intensity confinement of LRSPP in the asymmetrical system

Because of the high refractive index of the polymer film, the electromagnetic field above the metal in the asymmetrical system is localized much better compared with that in the symmetrical system, as shown in Fig.3. To obtain more straightforward information about the field intensity confinement in the asymmetrical system, the effective mode size of the LRSPP is defined by the energy flux density. Figure 5 shows

the distribution of the energy flux density S_x (z) at $d = 419$ nm as an example, where the energy flux density is given by

$$S_x(z) = \mathrm{Re}[-E_z H_y^*] = \mathrm{Re}\left[\frac{\mathrm{i}}{\varepsilon\omega}\frac{\partial H_y}{\partial x}H_y^*\right]. \quad (3)$$

The whole effective mode size D_{all} is defined as the size in the middle part of the asymmetrical system, in which the ratio of the energy flux to the total energy flux is equal to 86.5% (that is, $1 - e^2$). This can be expressed as

$$\frac{\int_{z_1}^{z_2} S_x \mathrm{d}z}{\int_{-\infty}^{\infty} S_x \mathrm{d}z} = 1 - e^2 = 86.5\%, \quad D_{\mathrm{all}} = z_2 - z_1, \quad (4)$$

where S_x $(z_1) = S_x$ (z_2), $z_1 < 0 < z_2$. Special emphasis is placed on the field intensity confinement above the metal; thus the mode expansion above the metal film D_{up} is defined as $D_{up} = z_2 - t$, as can be seen in Fig.5.

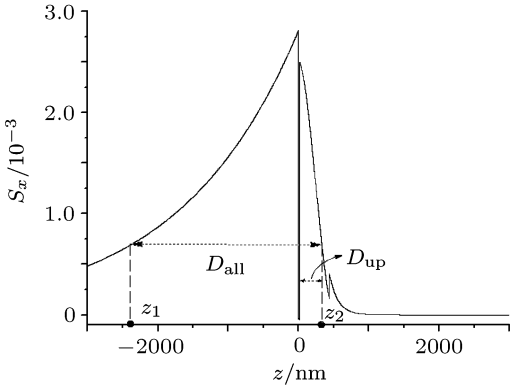


Fig.5. Distribution of the energy flux density along the z axis with $d = 419$ nm.

D_{all} and D_{up} with varying thicknesses of the dielectric film d were evaluated and displayed in Fig.6 by the solid and dashed lines, respectively. For the whole effective mode size D_{all}, it increases rapidly when the polymer film is thin because the LRSPP mode is near to a radiative mode. As the polymer film becomes thicker, the field intensity confinement of the LRSPP mode becomes better, and thus the corresponding whole effective mode size decreases with d. For the mode expansion above the metal surface D_{up}, it also decreases with the thickness of the polymer film, but does not change much. It is as small as about 300 nm, which is only about 10 percent of that in the symmetrical system ($D_{\mathrm{up}} = 3080$ nm). The reason is that the effective refractive index n_{eff} of the LRSPP mode does not change much and remains much greater than the refractive index of the air (see Fig.2) which results in tight field intensity confinement above the metal film. From the analysis above, we can conclude that the mode expansion above the metal surface can be reduced significantly by replacing the semi-infinite cover with a high refractive index polymer film of finite thickness. In practical applications, the thickness of the substrate is always much greater than the whole effective mode size D_{all} and thus we are mainly interested in the distribution of the electromagnetic field above the metal surface, so this asymmetric system may have important applications in the highly integrated optics due to the tight field intensity confinement down to subwavelength scales above the metal surface.

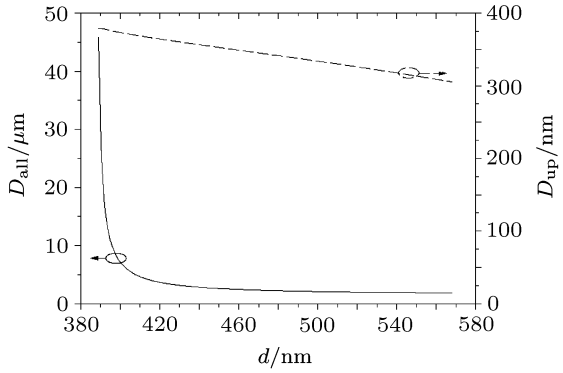


Fig.6. Variations of whole effective mode size D_{all} (solid line) and mode expansion above the metal surface D_{up} (dashed line) with the thickness of the polymer film d.

4. The optimal polymer film thickness and the requirements on the polymer refractive index

From the discussions in Sections 2 and 3, we know that there exist LRSPP modes in the asymmetrical system for a special range of polymer film thickness, and the mode expansion above the metal film can be reduced to subwavelength scales throughout this range. In applications, in order to achieve a long propagation length, the polymer film cannot be too thick; for example, it has to be less than about 433 nm to keep the propagation length more than half of that in the reference symmetrical system. On the other hand, the polymer film cannot be too thin, otherwise it approaches the radiative mode, and the large mode size may induce extra propagation loss due to the nonhomogeneity of the substrate and may decrease the

excitation efficiency of the LRSPP. A polymer film with a thickness greater than 395 nm can reduce the mode expansion in the substrate to less than 10 μm. Therefore, to satisfy these two requirements, the thickness of the polymer film should be in the range of (395, 433) nm. Within this range, the maximal point (419, 2.08) in the curve of the propagation length (see Fig.3) is the best working point, since the propagation length is as long as $L = 2.08$ mm and the mode expansion in the substrate is only about 3 μm. Furthermore, the propagation length of the LRSPP mode changes a little when the thickness of the polymer film deviates from the maximal point by about $\pm$20 nm, which means relaxed demands on the film thickness fluctuation. In fact, it is reasonable that the maximal point is the optimal working point because the LRSPP mode at this point most resembles the LRSPP mode in the symmetrical system. At this optimal thickness $d_{\rm optima}$ of the polymer film, the mode expansion of the LRSPP modes above the metal surface is reduced to about 300 nm and the field distribution in the substrate is similar to that in the symmetrical system ($\sim$ 3 μm), while the field distributions in the metal film in both asymmetrical and symmetrical systems are nearly the same. In other words, at this optimal thickness $d_{\rm optima}$, when the energy in the metal is equal to that in the symmetrical system, the total energy of LRSPP is about half of that in the symmetrical system, and thus the propagation length in the asymmetrical system ($L = 2.08$ mm) only decreases to about half of that in the symmetric system ($L_{\rm R} = 3.58$ mm) owing to the Ohmic loss in the metal.

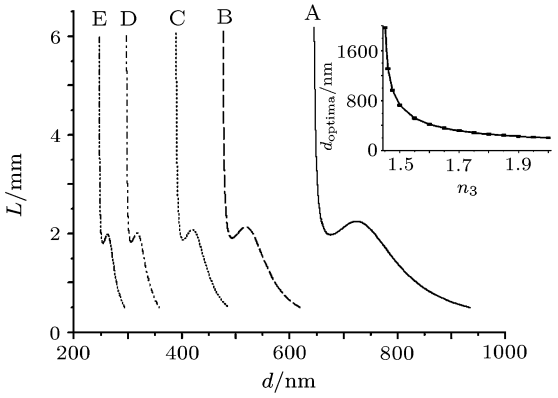


Fig.7. Propagation lengths L versus the thickness d of the polymer film for different reflective indexes n_3 of the polymer film. A: $n_3 = 1.5$; B: $n_3 = 1.55$; C: $n_3 = 1.60$; D: $n_3 = 1.70$; E: $n_3 = 1.80$; the inset shows the extracted optimal thicknesses of the polymer film $d_{\rm optima}$ for different n_3.

The discussions above are based on the refractive index of the polymer film set to be $n_3 = 1.6$. However, the conclusions are appropriate for more general refractive indexes of n_3 ranging from 1.5 to 2.0. Calculations show that in this range the shapes of the dispersion curves of the LRSPP modes resemble the $n_3 = 1.6$ case closely, and there is a maximal point in each curve of the propagation length, as shown in Fig.7. The starting and ending thicknesses of the polymer film for realizing the LRSPP decrease with the increase of n_3 in order to satisfy the index-matching condition. The optimal thicknesses of the polymer film $d_{\rm optima}$ at different n_3 values were extracted and are plotted in the inset of Fig.7. The optimal thickness also decreases with n_3 for the same reason.

The mode expansion above the metal film $D_{\rm up}$ and the propagation lengths at the optimal thickness of the polymer film $d_{\rm optima}$ in the asymmetrical system for varions refractive indexes of the polymer n_3 are shown in Fig.8. Both decrease with increasing n_3. When n_3 approaches the refractive index of the substrate, $D_{\rm up}$ becomes very large. So the proper n_3 should be greater than 1.5 to achieve subwavelength confinement. On the other hand, if n_3 is too high, the propagation length will shorten and the requirement on the optimal polymer thickness $d_{\rm optima}$ will become critical (see Fig.7). Thus polymers with the refractive indexes ranging from 1.5 to 2.0 are appropriate. In this range the propagation lengths of the LRSPP are as long as about 2 mm, while the mode expansion above the metal film $D_{\rm up}$ are less than 600 nm, which means both long propagation lengths and tight field intensity confinements are satisfied. Furthermore, calculations also indicate that a little fluctuation of the refractive index of the polymer film ($\Delta n_3 = \pm 0.01$)

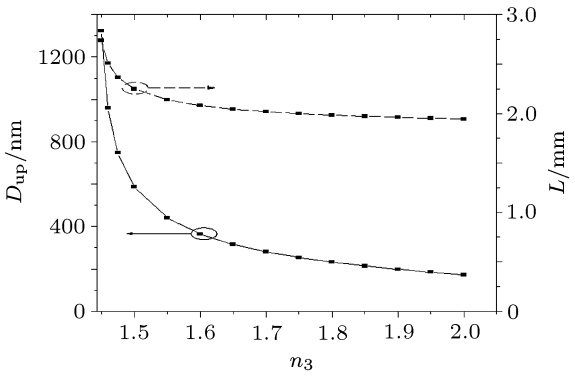


Fig.8. Mode expansion above the metal film $D_{\rm up}$ and the propagation length L at the optimal thickness with variation of the refractive index n_3 of the polymer.

will not bring large propagation loss when the polymer film is set to the optimal thickness d_{optima}, which means that the requirement on polymer material homogeneity is not critical.

5. Conclusion

LRSPP modes in an asymmetrical system, in which the thin metal film is sandwiched between a semi-infinite substrate and a high permittivity polymer film with finite thickness, have been calculated and analyzed theoretically. In this system, a high refractive index polymer film of finite thickness instead of an infinite index-matching dielectric has been used to satisfy the index-matching condition with the substrate for supporting LRSPP modes. Due to the high refractive index of the polymer film, the LRSPP field above the metal film is localized much more strongly than that in the symmetrical system. Through calculations, it has been found that there exists an optimal thickness of the polymer film to support the LRSPP mode, where the mode expansion above the metal film was reduced to the subwavelength scale, which was about 10% of that in the symmetrical system, while the propagation lengths only decreased less than 50% to about 2 mm. Calculations also indicated that the requirements on the thickness and the refractive index of the polymer film to support the LRSPP mode at the optimal thickness were not very critical. Our results demonstrated that, although the propagation length and the field confinement were incompatible factors for SPPs and usually could not be improved simultaneously, we could rather increase the field confinement in a specific direction while maintaining a long propagation length. The above investigations were made only in a one-dimensional system, but the principle should be applicable to two-dimensional systems, too. The resulting smaller mode expansion ensures smaller bend loss and higher density of integration, so the proposed asymmetrical system for LRSPPs may have wide and important applications in the field of highly integrated optics.

References

[1] Raether H 1988 *Surface Plasmons* (Berlin: Springer)
[2] Barnes W L, Dereux A and Ebbesen T W 2003 *Nature* **424** 824
[3] Pacifici D, Lezec H J and Atwater H A 2007 *Nature Photon.* **1** 402
[4] Genet C and Ebbesen T W 2007 *Nature* **445** 39
[5] Li Z, Zhang J S, Yan H F and Gong Q H 2007 *Chin. Phys. Lett.* **24** 3233
[6] Yang P F, Gu Y and Gong Q H 2008 *Chin. Phys.* B **17** 3880
[7] Sarid D 1981 *Phys. Rev. Lett.* **47** 1927
[8] Craig A E, Olson G A and Sarid D 1983 *Opt. Lett.* **8** 380
[9] Berini P 2000 *Phys. Rev.* B **61** 10484
[10] Breukelaar I G 2004 *Thesis B Sc* (Ottawa: Canada)
[11] Berini P, Charbonneau R, Lahoud N and Mattiussi G 2005 *J. Appl. Phys.* **98** 043109
[12] Charbonneau R, Lahoud N, Mattiussi G and Berini P 2005 *Opt. Express* **13** 977
[13] Chen J J, Li Z, Zhang J S and Gong Q H 2008 *Acta Phys. Sin.* **57** 5893 (in Chinese)
[14] Nikolajsen T, Leosson K and Bozhevolnyi S I 2004 *Appl. Phys. Lett.* **85** 5833
[15] Nikolajsen T, Leosson K and Bozhevolnyi S I 2005 *Opt. Commun.* **244** 455
[16] Nenninger G G, Tobiska P, Homola J and Yee S S 2001 *Sens. Actuators* B **74** 145
[17] Guo J P and Adato R 2006 *Opt. Express* **14** 12409
[18] Berini P 2001 *Phys. Rev.* B **63** 125417
[19] Wendler L and Haupt R 1986 *J. Appl. Phys.* **59** 3289
[20] Yang F Z, Cao Z Q, Ruan L Z and Fang J X 1986 *Appl. Opt.* **25** 3903
[21] Konopsky V N and Alieva E V 2006 *Phys. Rev. Lett.* **97** 253904
[22] Glasberg S, Sharon A, Rosenblatt D and Friesem A A 1997 *Appl. Phys. Lett.* **70** 1210
[23] Lyndin N M, Salakhutdinov I F, Sychugov V A, Usievich B A, Pudonin F A, and Parriaux O 1999 *Sens. Actuators* B **54** 37
[24] Pigeon F, Salakhutdinov I F and Tishchenko A V 2001 *J. Appl. Phys.* **90** 852