New effects in an ultracompact Young’s double nanoslit with plasmon hybridization

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Abstract. We present a theoretical study on the anomalous transmission of an asymmetric Young’s double metallic nanoslit with an ultrathin interval. The slit–slit interactions show exotic optical properties, particularly strong suppression of light transmission with narrow bandwidth and red/blue shifting of transmission peaks from individual slits, in contrast to currently well-developed subwavelength optical structures. Dip transmission is also observed to gradually decay with increasing interval distance. Analysis results reveal that such a phenomenon physically lies in the hybridized cross-talking of surface modes within two slits throughout the interval film in between. Depending on the plasmon hybridization type, either symmetric or antisymmetric, the newly induced optical phase retardation between the two slits can decrease and increase, respectively. This investigation suggests a potential way of nonlinearly bonding metallic waveguides and consequently aiding in the design of new plasmonic devices.

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1. Introduction

Optical transmission through a double slit is often seen as a valuable and emblematic demonstration in physics for displaying the wave characteristics of light and indicating the probabilistic nature of quantum mechanics. In the classical Young’s double-slit experiment, where the interval distance between sources is much greater than the wavelength and light propagation within the slits becomes completely independent, the interference of electromagnetic (EM) fields irradiated out of two slits is usually considered in the far field \([1]\). More recently, with the surge of interest in light scattering by nanoscale metallic objects \([2–7]\), Young’s experiment was revisited using subwavelength metal slit doublets \([8–12]\). Detailed analyses of these metal slits showed that the stationary interference patterns formed in the immediate vicinity above the slit interval brought about 10% modulation to the overall intensity of the far field. Moreover, the spatial change of such near-field interference fringes can be observed by adjusting the effective refractive index of slits \([13–15]\). In this case, given the slit separation by many optical wavelengths, their mutual field coupling is primarily mediated by the excitation of surface plasmon polaritons (SPPs) on the top and bottom facets of the structure, which is also typically featured in previous studies on the extraordinary transmission through a periodic array of subwavelength aperture \([7, 16–18]\). In other words, the energy transfer within each slit under such circumstances is solely performed by assuming a classical Fabry–Perot model; thus, the interaction between them only occurs through the SPP component diffracted from slits \([19–21]\). However, such designs are still rather large for ultracompact optical circuit applications because they are based on the output-interface phase matching of individual weakly coupled slit elements separated by a distance of the order of light wavelength.

On the other hand, as a counterpart of the subwavelength metal slit, a metallic nanoparticle has also been identified to excite localized SPP modes \([22]\). Recent studies have revealed that when these nanoparticles assemble into clusters or dimers \([23–25]\), collective plasmon modes can be created and subsequently introduce a rich array of new EM properties, such as electromagnetically induced transparency \([26]\), negative-index meta-materials for optical frequencies \([27]\), directional optical antennas and color routing \([28, 29]\). The physical concept involved is similar to that of atomic hybridization. A substantial question then arises as to what will happen if the separation distance of the two metal nanoslits is further compressed.

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considering its analogy to nanoparticle dimers. This particular question is relevant in the practical design of ultracompact optical devices.

In this paper, we investigate the transmission properties of an asymmetric width of Young’s double metallic nanoslits with a separation distance less than half of the incident wavelength, in contrast to systems that have been recently studied. Calculation results show that a prominent transmission dip with narrow bandwidth can be created because of strong cross-interval coupling between the waveguide modes confined within two neighboring nanoslits, and the transmission peak wavelength shift of individual slits can be taken as a function of separation distance. Analyses of the simulated EM field distributions microcosmically indicate that the new collective plasmon modes of the slit doublet can be generated with either symmetric or antisymmetric combination types, i.e. plasmon hybridization of individual slit modes is expected to take place.

2. Simulation method

The simulation model used is shown in figure 1. Two slits are cut through the metallic plate and separated by a thin interval thickness \(d\), with asymmetric geometrical widths of \(w_1\) and \(w_2\), respectively. The unsupported metal is embedded into an air circumstance. The calculated region is bordered by perfectly matched layers (PMLs) to reduce the influence of light reflection. A temporal Gaussian profile of a p-polarized infinite plane wave is normally impinged onto the doublet structure. The transmission power spectrum is detected on the transverse plane 250 nm away from the slit exit (the detection distance does not affect the variation tendency of our measurements) and is eventually obtained by Fourier transformation. Normalized transmission is defined as the ratio of the time-averaged Poynting vector of transmitted light to that of incidence light. To attain EM field distribution maps around the structure, monochromatic light is adopted for the incidence. All results are calculated using the two-dimensional finite difference time domain method with a uniform grid size of 2.5 nm. In our simulations, silver metal is adopted as the material, and its frequency-dependent permittivity is described by the Drude model: 

\[
\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 - i\gamma \omega}
\]

with the constants \(\varepsilon_\infty = 3.7\), \(\omega_p = 1.367 \times 10^{16} \text{ rad s}^{-1}\) and \(\gamma = 2.735 \times 10^{13} \text{ rad s}^{-1}\) [30].

Figure 1. Schematic diagram of an asymmetric double metallic nanoslit with an ultrathin interval.
3. Results and discussion

3.1. Transmission spectrum observation

To demonstrate the transmission spectrum of the asymmetric metal nanoslit doublet as a function of interval thickness, we used the following structural parameters: metal slit length $t = 350$ nm, narrow slit width $w_1 = 20$ nm and broad slit width $w_2 = 40$ nm. The simulation results are shown in figure 2, in which the transmission spectrum (dashed line) of each isolated slit is also provided for comparison. Evidently, when the metal slits have tight spacing, the available spectra present novel saddle-like profiles, i.e. two transmission peaks located in the shorter and longer wavelength regimes with one dip in between them. At the ultrathin separation of $d = 20$ nm, the two obtained peak intensities are more asymmetrical, and both peak wavelengths are slightly red-shifted with respect to the isolated individual slits. Moreover, the suppressed optical transmission begins to emerge at the wavelength of 1470 nm different from the linear combination of diffraction spectra from two isolated slits. With increasing slit distance, the intensity distribution of both peaks tends to become symmetric but with a blue shift for the shorter-wavelength peak and a red shift for the longer-wavelength one. Remarkably, at $d = 40–100$ nm, the obtained transmission peaks seem to undergo line-narrowing processes, whereas dip transmissions also display narrower and deeper appearances. Their near-null values directly demonstrate the efficient suppression of optical transmission through the doublet structure, indicating a new near-field coupling mechanism between the two slits. In this case, inter-slit coupling is actually dominated by SPP propagation along the ultrathin slit walls rather than on the entrance and exit faces of the structure. When the slit interval exceeds a thickness of $d = 400$ nm, the transmission dip intensity is gradually reduced and both peak intensities again become asymmetrically distributed. Furthermore, our simulations demonstrate that the transmission dip wavelength can be conveniently tuned by varying the length of the slits. However, at $d = 800$ nm, only one transmission peak with broad bandwidth is observed in the
available spectrum, which indicates that the coupling of scattered EM fields on the top and bottom facets begins to be predominant or that interval-wall-based plasmon coupling across the slits is greatly weakened. If the slit interval continues to increase, the optical transmission is similar to previously reported ones [8–12].

Figure 3(a) shows the wavelength shifts of two transmission peaks as a function of metal interval thickness between two nanoslits. For both peaks, the wavelength shift first rapidly decays with increasing metal separation and then remains almost constant as $d$ exceeds a certain value. Furthermore, for larger slit intervals, the blue shift of the shorter-wavelength peak seems to increase while the red shift of the longer-wavelength peak appears to decrease. Figure 3(b) shows the central wavelength and intensity contrast of the transmission dip as a function of slit interval thickness. Evidently, two distinct regimes for variation tendency of the transmission dip wavelength can be observed: first moving toward the shorter wavelengths for $d \leq 100$ nm and then shifting back to the longer wavelengths with a continuous increase in the slit interval. Moreover, from the variation profiles of the peak wavelength shift as a function of slit interval thickness, we can deduce that the slit–slit coupling in the first regime is attributed to the near-field effect, whereas the second regime corresponds to the far-field effect. On the other hand, variations in the dip intensity contrast $V = (I_{\text{peak}} - I_{\text{dip}})/(I_{\text{peak}} + I_{\text{dip}})$ demonstrate that the suppression degree of dip transmission initially increases to the maximum and then fades away at larger slit intervals, indicating weak SPP coupling across the metal slit interval.

### 3.2. Distribution of electromagnetic fields

The mechanism by which both peak wavelength shift and dip transmission occurrence are achieved for asymmetric double metallic nanoslits is an interesting area of investigation. Thus, we take $d = 100$ nm as an example to simulate EM field distribution conditions. Figure 4 shows the computed intensity plots of $H_y$ and $E_z$, as well as the phase plots of $\Phi(H_y)$ and $\Phi(E_z)$ for the asymmetric slit doublet at a shorter peak wavelength of $\lambda = 1240$ nm. The magnetic field is observed to be mostly concentrated inside the broad slit but is nearly blank for the narrow one, very different from those observed in the individual cases. Physically, such a phenomenon can be attributed to the cross-talking of SPP waves confined within the two slits throughout
Figure 4. Calculated EM field intensity (top) and phase (bottom) distributions for asymmetric double nanoslits at the transmission peak wavelength of $\lambda = 1240$ nm, when they are separated by $d = 100$ nm. Panels (a)–(d) indicate $|H_y|$, $|E_z|$, $\Phi(H_y)$ and $\Phi(E_z)$, respectively. Among them the white dotted lines mark the boundaries of the metallic films.

the between interval film, which is theoretically described in the following sections. Therefore, in this case, the broad slit plays a dominant role in peak transmission. This fact can also be evidenced in the $E_z$ field, wherein surface charges are mainly piled up on edges of the broad slit. According to Xie et al [6] that the optical transmission enhancement is basically related to the appropriate distribution of surface charges and currents on the slit walls and corners, we can understand that the obtained peak transmission through the entire doublet structure is, in fact, dominated by remitting waves from the broad slit. In addition, for this peak transmission, the population of surface charges from the electric dipoles on two edges of the slit interval has a large difference, resulting in the relatively weak field interaction strength (with an available minimum value of $|E_z| = 1.4$) along the interval surface. The $E_z$-field phase indicates that for the broad slit, charge accumulation is mainly seen in two regions (upper and lower corners), whereas for the narrow slit, charge accumulation takes place in three regions ($z = 1/3t$, upper and lower corners), indicating the existence of a high-order waveguide mode. On the metal interval top corners, the charges appear to have the same signs; however, on the bottom corners, the signs of charges are reversed. The $H_y$ field phase demonstrates that the propagation of the wall surface current is delayed by less than $0.5\pi$ between the two slits, indicating an in-phase
Figure 5. Calculated EM field intensity (top) and phase (bottom) distributions for asymmetric double nanoslits at the transmission peak wavelength of $\lambda = 1525$ nm, when they are separated by $d = 100$ nm. Panels (a)–(d) indicate $|H_y|$, $|E_z|$, $\Phi(H_y)$ and $\Phi(E_z)$, respectively.

configuration for the surface charges and the current. Furthermore, given the field penetration behavior, the surface currents along both lateral sides of the slit interval are seen to undergo composite coupling.

For the longer-wavelength peak transmission at $\lambda = 1525$ nm, the computed EM field plots are presented in figure 5. In contrast to the above observations, a waveguide mode in the narrow slit now dominates the channeling light throughout the entire structure, and the resultant large surface current on the inner slit walls and strong electric dipoles on the slit corners can be observed in the intensity plots of the $H_y$ and $E_z$ fields. For this case, surface charges from the electric dipoles on the top/bottom edges of the slit interval have a large disparity of population, so the field coupling on the interval surface appears to be relatively weak and the available minimum strength only reaches about $|E_z| = 0.4$. From the $E_z$-field phase, similar charges can be observed to appear on both the top and bottom corners of the slit interval. More interestingly, the $H_y$-field phase represents that the field propagation along the interval walls in both slits has almost the same speed, indicating an in-phase configuration of the wall surface current. Therefore, the phase difference of the $H_y$ field across the separating interval is found to be ambiguous.
Figure 6. Calculated EM field intensity (top) and phase (bottom) distributions for asymmetric double nanoslits at the transmission dip wavelength of $\lambda = 1375$ nm, when they are separated by $d = 100$ nm. Panels (a)–(d) indicate $|H_y|$, $|E_z|$, $\Phi(H_y)$, and $\Phi(E_z)$, respectively.

Figure 6 shows the computed plots of $H_y$, $E_z$, $\Phi(H_y)$ and $\Phi(E_z)$ for the asymmetric double nanoslit at the transmission dip wavelength of $\lambda = 1375$ nm. In this case, both slits can provide waveguide modes with comparable intensity distributions. In fact, for the two isolated individual slits, the sum-up optical transmission can reach about 80% of the incidence. This result means that the obtained transmission dip provides about 94% downward modulation to the linear combination of the two slits, in sharp contrast to the previously reported subwavelength structures [2, 8, 11]. As a result, a new concept on the destructive interaction between two slits should be considered. In contrast to peak transmissions, in the case of dip transmission surface charges from the electric dipoles on the top/bottom edges of the slit interval have a comparable population, making the two slit openings tightly coupled with a minimum strength of $|E_z| = 2.9$. The corresponding phase plots show that the surface charges on both the top and bottom corners of the slit interval have opposite signs, and the wall surface current in one of the slits displays a $\pi$ phase delay with respect to that of the other, indicating an out-of-phase configuration. In this case, phase variations across the separating metal interval are clearly defined.

When the slit interval thickness widens to $d = 800$ nm, the field distribution around the doublet markedly differs, which results in an evident peak transmission at the wavelength of $\lambda = 1350$ nm. As shown in figure 7, the corresponding computed plots of $|H_y|$ and $|E_z|$ display
Figure 7. Calculated EM field intensity (top) and phase (bottom) distributions for asymmetric double nanoslits at the peak wavelength of $\lambda = 1350$ nm, when they are separated by $d = 800$ nm. Panels (a)–(d) indicate $|H_y|$, $|E_z|$, $\Phi(H_y)$ and $\Phi(E_z)$, respectively.

comparable field intensities within two slits, consistent with the aforementioned observations for dip transmission but without the field overlap in the metal interval film; thus, the two slits begin to act independently during the energy transfer in the waveguide mode, and their field coupling on the output interface belongs to the far-field effect. Another interesting feature is that besides the distribution of charge dipoles near the slit edges, the surface current on the top facet of the slit interval physically links the two slits. The plots of $\Phi(H_y)$ and $\Phi(E_z)$ suggest that the phase difference between the waveguide modes of the two slits is only about 0.5$\pi$ less than that in figure 6(c), which indicates that their constructive interference is built for the peak transmission in the spectrum.

Given that the induced EM field strength in the metal slits essentially depends on the amount of surface charges/current [6, 31], we focus our attention on the microcosmic coupling processes of two close-by nanoslits. To recognize changes in surface charges/current within the metal slit by neighborhood coupling, we quantitatively compare $H_y$-field distributions on the longitudinal mid-plane of the two slits, when they are placed either individually or tightly in space. The derived results and the sketched charge distribution patterns are shown in figure 8.
Figure 8. The left column represents the magnetic field intensity profiles $|H_y|$ along the light propagation direction in two nanoslits without (dot lines) and with (solid lines) plasmon hybridization, wherein vertical short dash-dot lines mark the entrance and exit faces of the slits; the right column sketches surface charges distributed on the plasmonically coupled slit doublet. Top–bottom rows indicate transmissions at the peak wavelengths of $\lambda = 1240$ nm and $1525$ nm and at the dip wavelength of $\lambda = 1375$ nm, respectively. For the peak wavelength of $\lambda = 1240$ nm, two isolated individual slits ($w_s = 20$ and $40$ nm) are expected to give different field distributions because of their geometrical differences, i.e. high intensity for the broad slit and low intensity for the narrow one. However, when the two slits are placed close to each other ($d = 100$ nm), the low-field strength in the narrow slit is seen to further decrease in association with a dramatic change of spatial distribution patterns, whereas the high-field strength in the broad slit slightly increases. Physically, such intensity fluctuations...
can be attributed to mutual interactions between the induced SPPs on both lateral sides of the slit interval film, resulting in a field enhancement in the broad slit. According to Martin et al.\cite{32}, for a metal slit driven by an external magnetic field, the wave vector of SPPs traveling inside will be substantially affected, namely, \(k_{\text{spp}} = k_{\text{spp}}^0 \pm \Delta k_{\text{spp}}(\Delta |H_y|)\), where \(k_{\text{spp}}^0\) is the SPP wave vector of the metal slit without the external influence and \(\Delta k_{\text{spp}}\) is the modulation induced by an applied magnetic field from the neighborhood slit. Either positive or negative shift of the SPP wave vector is determined by the increase or decrease of \(\Delta |H_y|\) in the magnetic field due to plasmon hybridization, respectively. When the optical transmission is dominated by the broad metal slit, its magnetic field enhancement influenced by the narrow slit causes an increment of the SPP wave vector, which corresponds to a blue shift of the peak wavelength. On the other hand, the EM field within the narrow slit is significantly diminished, resulting in a minor contribution to the final transmission that is notably different from the common enhanced transmission by edge-scattered SPP coupling on both the entrance and exit faces of the metal structure\cite{2,5,7,18}. This kind of long-range wall SPP interaction across the slit interval film is called inter-slit plasmon hybridization, wherein the longitudinal transfer of energy within two slits becomes coherent rather than independent. Consequently, a unique set of collective plasmon modes is found.

At another peak wavelength of \(\lambda = 1525\) nm, two isolated individual slits also have highly different field distribution patterns, but a higher intensity is seen in the narrow slit and a lower intensity is observed in the broad one. When the two slits are tightly placed to satisfy the near-field coupling of the wall SPPs across the separating metal interval, their field intensities are simultaneously reduced, making the role of the broad slit negligible. As a result, this kind of plasmon hybridization depresses the magnetic field strength in the narrow slit and promotes the generation of a smaller SPP wave vector traveling inside, thereby corresponding to the red shift of the peak wavelength.

At the transmission dip wavelength of \(\lambda = 1375\) nm, a high-intensity magnetic field component can be achieved at two different slit widths. Given the out-of-phase configuration of surface charges, the interaction of SPPs confined on the two lateral sides of the interval film results in a significant increase in the narrow-slit field strength but a slight decrease in the broad slit. Such plasmon hybridization actually modifies the amount of surface charges through additional phase retardation between the two slits, leading to the suppression of optical transmission.

3.3. Theoretical analyses

Analogous to the plasmon hybridization model for nanoparticles established by Nordlander and Halas\cite{33}, we can classify the present slit–slit plasmon hybridization into symmetric and antisymmetric modes mediated by the inner-wall SPP interaction across the separating metal interval, whose configurations are depicted by the upper panels in figures 9(a) and (b), respectively. For a metal film, the excited SPP waves on two interfaces usually have different speeds and decay constants depending on the surface charge distribution and bounding dielectric environments. By taking into account the penetration of EM fields \(H_y\) and \(E_z\) inside the metal in different regions of the doublet structure as well as the coupling between the surface modes propagating along the slit walls, we can obtain the dispersion relation of plasmon hybridization.
Figure 9. (a)–(b) Excited $H_y$ profiles in the mid-transverse plane of the slit doublet structure with either symmetric or antisymmetric modes of plasmon hybridization, respectively. Here the vertical short dash-dot lines mark two lateral boundaries of the slit interval. The upper panels in the two pictures represent surface charge distribution for different hybridization modes. (c) Comparison of the wavelength dependence of phase retardation between two metal nanoslits with (solid line) and without (dash line) plasmon interactions.

modes in the metal slit doublet [34, 35]:

$$\left( \frac{1 - r}{1 + r} \right)^4 - c \left( \frac{1 - r}{1 + r} \right)^2 + e^{-2kw_1} e^{-2kw_2} = 0,$$

in which $r = (p/\varepsilon_m)/(k/\varepsilon_d)$ and $c = e^{-2kw_1} + e^{-2kw_2} + e^{-2pd}(1 - e^{-2kw_1})(1 - e^{-2kw_2})$, $k = \sqrt{\beta^2 - k_0^2\varepsilon_d}$ and $p = \sqrt{\beta^2 - k_0^2\varepsilon_m}$ are the transverse propagation constants (along the x-axis) of SPPs in dielectric ($\varepsilon_d$) and metal ($\varepsilon_m$), respectively, and $\beta$ and $k_0$ are that of SPPs in a slit (along the z-axis) and incident light in vacuum, respectively. Through simplification processes,
Figure 10. Calculated critical inter-slit distance (solid squares) for plasmon hybridization in the doublet structure as a function of wavelength, wherein the penetration length (solid line) of SPP waves in the metal is provided for comparison.

The equation (1) can be reduced to

$$\frac{1 - r}{1 + r} \pm \left[ \frac{c - (c^2 - 4 \cdot e^{-2kw_1} \cdot e^{-2kw_2})^{1/2}}{2} \right]^{1/2} = 0.$$  \hspace{1cm} (2)

In fact, the above equation explicitly describes the generation of two plasmon hybridization modes, asymmetric and symmetric, in the metal slit doublet with cross-talking interactions during the energy transfer. When the doublet structure has an asymmetric geometric width, the propagation constants within the two slits become different, and then one strongly damped antisymmetric hybridized SPP mode is easily obtained [36], which is physically attributed to the generation of a transmission dip in the output spectrum.

In the case of symmetric plasmon hybridization, the surface charges on both lateral interfaces of the slit interval are identically arranged, and the combined magnetic field \(H_y\) is not equal to zero inside the interval region, as shown in figure 9(a). This effect results in additional repulsive forces to reduce the phase retardation of SPP waves in the two slits. By contrast, in the case of antisymmetric plasmon hybridization, the surface charges distributed on the two sides of the slit interval become reversed, and the hybridized magnetic field \(H_y\) gives a zero value inside the film, as shown in figure 9(b). Thus, a relatively long-range overlapping SPP wave inside the interval region results in additional attractive forces to increase phase retardation between the two slits. Figure 9(c) compares the phase retardation \(\Delta \phi\) between the two slits as a function of incident wavelength for the asymmetric slit doublet with and without plasmon hybridization. Evidently, at the wavelength of \(\lambda = 1375\) nm, plasmon hybridization provides a new additional phase retardation to reach an approximate value of \(\pi\) such that SPP waves in both slits have a destructive interaction. At the wavelength of \(\lambda = 1525\) nm, the two plasmonically coupled metal slits can decrease phase retardation with respect to the isolated individual ones; thus, a constructive SPP interaction occurs between them. At the wavelength of \(\lambda = 1240\) nm, plasmon hybridization between the two slits becomes somewhat complex because of high-order cavity mode generation in the narrow slit, which eventually leads to a constructive SPP interaction.
Figure 11. Calculated transmission spectra of the ultrathin-spaced \((d = 100 \text{ nm})\) metal double nanoslits without evident plasmon hybridization, (a) by inserting PMLs (grid pattern) in the middle of the slit interval, wherein a right inset picture shows the magnetic field distribution around the structure at the peak wavelength of \(\lambda = 1350 \text{ nm}\); and (b) by using other geometric width ratios of metal nanoslits.

between the two metal slits owing to the phase delay of less than \(0.5\pi\) under the effect of plasmon hybridization.

3.4. Validity of the theory

Furthermore, in order to discover the dependence of plasmon hybridization on slit interval width, we define a critical inter-slit distance at which the cross-wall coupling between two metal slits begins to vanish so that interaction is fully governed by the output-interface phase matching of SPP waves, i.e. at this distance the available intensity of hybridized SPP waves disappears inside the interval film. The calculated result as a function of wavelength is shown in figure 10, wherein the geometric widths of the two slits are \(w_1 = 20\) and \(w_2 = 40\) nm, respectively. For comparison, the penetration length of surface waves in the metallic material is also provided at the corresponding incident wavelength. Evidently, the critical inter-slit distance for plasmon
hybridization is about ten times larger than the penetration length, and the difference between them seems to vary with the incident wavelength.

Given that slit–slit plasmon hybridization is, in fact, based on the reallocation of the distribution of surface charges on two lateral sides of the slit interval, this kind of coupling strength weakens with increased interval thickness. When the metal separation is sufficiently thick (e.g. $d = 800$ nm), this inner-wall SPP-based hybridization is almost completely blocked, leading to dip disappearance and coalescence of both peaks in the transmission spectrum, as shown in figure 2(b). Compared with the plasmon hybridization of nanoparticle dimers [15, 16], slit–slit plasmon hybridization mediated by the metal interval film can become more complex because of surface charge transfer and neutralization processes. Figure 11(a) shows the calculated spectrum transmitted through an asymmetric double metal slit ($w_1 = 20$ nm, $w_2 = 40$ nm and $d = 100$ nm) by inserting PMLs in the middle of the slit interval to block inter-slit coupling. Clearly, we can find only one broad peak without any dip in the transmission spectrum, in sharp contrast to the above-mentioned saddle-like observations. This result directly confirms that plasmon hybridization plays a significant role in the interaction of ultrathin-spaced metal slits.

We also discuss the influence of a propagating SPP wave vector in the slits on plasmon hybridization processes. Figure 11(b) shows a series of calculated transmission spectra for some double metal slits with different ratios of geometric width. For example, when one slit width is fixed at $w_1 = 40$ nm, the other width can be varied to values such as $w_2 = 40, 60, 80$ and $100$ nm. For the same width of the slit doublet, the obtained single-peak transmission spectrum with broad bandwidth is very similar to that of conventional edge-coupled metal slits [37, 38]. Moreover, for each configuration of other asymmetric width ratios, apart from the central broad peak transmission, only a shallow dip transmission in the spectrum is observed. Given that the effective index of the metal slit exponentially decays with increasing slit width, which corresponds to smaller SPP wave vector generation on the larger slit width, this result suggests that the plasmon hybridization effect is associated with the SPP wave vector confined on the inner walls and dependent on the wave vector discrepancy between the two slits, such that very different SPP distributions in the double slit help create new collective plasmon modes.

4. Conclusions

We theoretically demonstrate that Young’s double metallic nanoslit with asymmetrical widths can provide an evident plasmon hybridization phenomenon when spatially separated to as small as $\lambda/2$. At a certain wavelength, the optical transmission through the doublet is significantly suppressed with narrow bandwidth but corresponds to a simultaneous enhancement in EM fields within the two slits. The observed peak transmission tends to have wavelength shifts from individual slits associated with the field enhancement only in one of the slits. Such a phenomenon is found to gradually diminish with larger metal slit intervals. Analysis results suggest that the physical origin lies in the interval-based cross-talking of surface modes within volumes of the two slits rather than in the diffracted SPP coupling on the exit face of the structure. Compared with isolated individual cases, in two tight spacing metal slits EM field distributions are aptly influenced by plasmon hybridization in either symmetric or antisymmetric patterns, leading to additional phase retardation between them. By taking into account the penetration of EM fields inside the metal as well as the coupling between surface modes propagating along the slit walls, we obtain the dispersion relation of plasmon
hybridization modes in the metal slit doublet. Finally, this idea is further validated by a direct comparison of the present results with weak and blocked-off cross-interval coupling. We believe that our findings offer new fascinating possibilities such as the development of narrow-bandwidth plasmonic filters, displayers, directional color routers and nano-photocouplers. Remarkably, like the previous report [39] but using a different method, this work predicts an effective separation limit for metal nanoslits to obtain independent cavity modes, which is crucial to the design of compact nanophotonic systems.

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