Extraordinary optical diffraction from hole pair based on near-field optical thin-microcavity theory

Xu Chen¹,², Jiu Hui Wu¹,² and Pei Cao¹,²

¹ School of Mechanical Engineering, Xi’an Jiaotong University, Xi’an 710049, People’s Republic of China
² State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi’an Jiaotong University, Xi’an 710049, People’s Republic of China

E-mail: ejhwu@mail.xjtu.edu.cn

Received 22 June 2018, revised 22 August 2018
Accepted for publication 5 September 2018
Published 17 September 2018

Abstract
To realize optical coupling between various nanostructured elements and nanoscale field confinement, a fundamental model of the near-field diffraction from a subwavelength hole pair within a conducting thin film is derived theoretically. Coupling effects between these two holes are investigated in detail using the near-field optical thin microcavity theory and the coupled-mode method, and the results are then verified via finite element simulations. Some extraordinary diffraction phenomena are found and are attributed to the following two coupling mechanisms: (1) the edge effect from the thin microcavity theory that occurs at each hole edge when an incident electric field illuminates the upper surface of the thin film; and (2) the enhanced in-plane electromagnetic waves that propagate along the two film surfaces and interact with each other in the vicinity of the holes. Analysis of the effects of the structural parameters on the transmittance shows that the coupling effect can be enhanced or attenuated by the interference conditions, depending on the incident wavelength and the phase difference determined by the hole–hole distance. The extraordinary diffraction effects presented here have potential for applications in near-field optical devices.

Keywords: coupled-mode method, extraordinary transmission, hole pair, thin films

(Some figures may appear in colour only in the online journal)
The hole pair, which represents the most fundamental and simplest coupled model, has been studied both theoretically and experimentally, and this basic structure has been used to explain the physical EOT scenario. However, in these approaches it has commonly been assumed that among the relevant scattering channels, only the SPP scattering channel works [13–15]. An analytical model that described the interaction between two apertures was proposed by Nikolov in 2012 [16], and this model was used to predict both the far-field transmission and the near-field intensities of two dielectric-filled cylindrical nanowaveguides separated by a variable distance. The results obtained indicated that the oscillation amplitude decreased with increasing separation and that the oscillation period was determined by the wavelength of the SPPs at the metal–dielectric interface. An optical SPP interference model of a hole pair perforated within an opaque metal film was studied from first principles in [17]; the role played by the SPP resonances was first specified, a rigorous solution to Maxwell’s equations was derived, and the results showed that two scattering mechanisms existed, including far-field and in-plane radiated channels. The agreement with the experimental results was excellent when the hole radius \( r > \lambda_{\text{SPP}} \), where the latter is the SPP wavelength, but the results calculated using the function that was derived in [17] were underestimated when \( r < \lambda_{\text{SPP}} \) and the fundamental mode was thus assumed to occur inside the hole.

The thin microcavity theory for near-field optics was first proposed by Wu in 2011, and the field distributions inside the cavities and the resonant pattern were obtained exactly using electromagnetic theory based on the assumption that the magnetic field component was uniform along the thickness direction [18]. Using this theory, a near-field optical diffraction model for a subwavelength aperture embedded in a thin conducting film was investigated further by Wu’s group; the governing equations were solved and all electromagnetic components both inside and outside the microcavity were then obtained accurately; numerical computations were then performed to illustrate the edge effect, with an enhancement factor of 1.8 or higher under optimal conditions, and the depolarization phenomenon that occurs during near-field transmission [19, 20]. The above theory has already been applied in the field of near-field optics to subjects including super-resolution imaging [21] and the Slow light phenomenon [22] in 2016 and 2017, respectively. Using this theory, the mutual coupling mechanism is investigated here in the case where two apertures are present within a conducting thin film. The vast number of publications in the literature confirm that coupled-mode theory provides an effective mathematical method to solve the problems of interactions among several waveguides for signal processing and transmission applications in optical devices because of its mathematical simplicity and physical intuitiveness [23–27].

On that basis, the electromagnetic field components of the hole pair structure are derived accurately in this paper using a combination of the coupled-mode method and the thin microcavity theory. This paper is organized as follows: in section 2, a theoretical optical model of a hole pair within a conducting thin film is introduced; the distributions of the electromagnetic field magnitudes inside and outside these holes can be obtained accurately by combining the thin microcavity theory in near-field optics with the coupled-mode method, and the optical response of the hole pair is then derived. In section 3, a finite element (FE) simulation of this model is built; the proposed theoretical model is verified by comparing our results with those from the simulation and other results in the literature, and the factors that influence the transmittance of this model are then analyzed. Finally, the main conclusions are presented in section 4.

2. Diffraction theory of subwavelength hole pair in a thin conducting film

2.1. Thin microcavity theory for near-field optical diffraction from a subwavelength hole

To provide a full understanding of the derivation process used here, the prior knowledge of the near-field optical model of a single aperture is first briefly reviewed. The optical model that is considered in this case is a perfect electrically conducting thin film with an embedded subwavelength aperture, and the geometrical parameters of this model consist of the film thickness \( h \) and the aperture radius \( r \). A plane wave is normally incident on the structure along the \( z \)-axis, and the incident electric field is given by \( E_0 = E_0 \hat{y} = \exp(ik_0z) \) with use of the time dependence in \( \exp(-i\omega t) \). Because of the low thickness of the thin film, the magnetic field component \( H_z \) in the \( z \)-direction in the aperture can be assumed to be uniform along the thickness direction, while the other magnetic field components in the \( x \) and \( y \)-directions are \( H_x = z\partial H_y/\partial y \) and \( H_y = -z\partial H_x/\partial x \). The electric field components in the aperture can be expressed accordingly as \( E_x \), \( E_y \), and \( E_z \), based on Maxwell’s curl equations. \( H_x \) can be derived in polar coordinates based on the thin microcavity theory [19] and the power flow theorem as:

\[
H_{3r,\theta} = \sum_{n=0}^{\infty} [A_n J_{n}(kr) + C_n I_{n}(kr)] + F_n r^n \exp(i\theta),
\]

where \( J_n \) and \( I_n \) are the Bessel function of the first kind and the modified Bessel function of the first kind, respectively; the coefficients \( A_n \) and \( C_n \) can be determined using the boundary conditions \( H_{3r,\theta}|_{r=a} = 0 \) and \( \partial H_{3r,\theta}/\partial r|_{r=a} = 0 \), and \( F_n = 3k_0^2 \exp(ih_0/2)(-1)^{n+1} - 1 \pi h_0(1+1)2^{n+1}n! \), in which \( k_0^2 = (\mu_0\varepsilon^2h^2 - 12)\mu_0\varepsilon^2/h^2 \), \( \mu_0 \) is the permeability, \( \varepsilon \) is the permittivity, and \( k_0 \) is the propagation constant in the circular microcavity.

The other electromagnetic components in the aperture, which include \( E_x \), \( E_y \), \( E_z \), \( H_x \), and \( H_y \), can be obtained accurately from equation (1) and the Maxwell equations [20]. The reflected and transmitted field components in the upper and lower spaces can be expressed in polar coordinates using the
linear superposition method, respectively, as follows:

\[ \Phi^{r}(r,\theta,z) = \frac{1}{\pi} \sum_{n=\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{\Phi}^{r} (\rho) J_{n}(\rho r)e^{i\sqrt{n^{2} - \beta^{2}}(z - h/2)} \rho \, d\rho \exp(\text{in} \theta), \]

(2a)

\[ \Phi^{f}(r,\theta,z) = \frac{1}{\pi} \sum_{n=\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{\Phi}^{f} (\rho) J_{n}(\rho r)e^{-i\sqrt{n^{2} - \beta^{2}}(z + h/2)} \rho \, d\rho \exp(\text{in} \theta), \]

(2b)

where \( \tilde{\Phi}^{r} (\rho) \) is the Hankel transform of \( \Phi^{r}(r,0,h/2) \) and is defined as \( \tilde{\Phi}^{r} (\rho) = \int_{0}^{\infty} \Phi^{r}(r,0,h/2) J_{n}(\rho r) \rho \, d\rho \); \( \tilde{\Phi}^{f} (\rho) \) is the Hankel transform of \( \Phi^{f}(r,0,-h/2) \) and is defined as \( \tilde{\Phi}^{f} (\rho) = \int_{0}^{\infty} \Phi^{f}(r,0,-h/2) J_{n}(\rho r) \rho \, d\rho \). \( \Phi^{r} \) and \( \Phi^{f} \) represent \( E_{1}, E_{2}, H_{1} \), and \( H_{2} \) here, and they are used to represent the field components at the upper and lower surfaces. Equations (2a) and (2b) both satisfy the Helmholtz equation and include all evanescent reflected and transmitted waves, respectively.

Therefore, the magnitudes of the electromagnetic fields inside and outside the aperture can be obtained accurately, and numerical computations have previously been performed to illustrate the distinct edge effect and the depolarization phenomenon that occur in the near-field [18]. To study the transmission of this model, the radius of the small aperture \( r \) is selected to be 40 nm, which is less than one-tenth of the incident wavelength. After the transmission spectrum was calculated in the 500–1500 nm range at normal incidence, we found that a transmission peak exists at an incident wavelength. Because the two holes are independent, the electromagnetic fields inside each hole both obey the thin microcavity theory. Obviously, it can be seen from figure 1 that the electromagnetic components of the two holes are derived in their own respective coordinate systems, but the calculations of the total field distributions and the coupled-mode method calculations should only be carried out under the same coordinate system. Here, we use the Graf addition theorem to express the reflected and transmitted field components from aperture \( A \) in the coordinate system of aperture \( B \).

The magnetic field along the \( z \)-axis of aperture \( A \) can be written in coordinate system \( B \) as:

\[ H_{m}(r',\theta') = \sum_{m=-\infty}^{\infty} \sum_{n=0}^{\infty} [A_{m} J_{m+n}(kr) J_{m}(kr') + C_{m} I_{m+n}(kr)] \times J_{m}(kr') \exp(i(m + n)\theta') + F_{m} \exp(i\theta). \]

(3)

The magnitudes of the electric and magnetic fields inside and outside aperture \( A \) can be obtained accurately by combining equation (3) with the method described in section 2.1, and the reflected and transmitted field components in the upper and lower spaces can be labeled as \( \varphi_{A} \exp(\text{in} \rho) \) and \( \varphi_{B} \exp(\text{in} \rho) \), respectively. Accordingly, the magnitudes of the electromagnetic fields inside and outside aperture \( B \) can also be derived using equations (1) and (2), respectively, and the reflected and transmitted field components are labeled as \( \varphi_{A}^{\prime} \exp(\text{in} \rho) \) and \( \varphi_{B}^{\prime} \exp(\text{in} \rho) \), respectively.

We will focus on the energy and power that are radiated into the near-field region and the interactions between the hole pair. When the hole–hole distance decreases, the two electromagnetic field distributions are no longer independent of each other, and energy is then exchanged in the near-field within the vicinity of the two holes. The differential coupled-mode equations can be expressed as follows:

\[ \frac{d\varphi_{A} \exp(\text{in} \rho)}{d\rho} = -j\beta_{1} \varphi_{A} \exp(\text{in} \rho) + c_{12} \varphi_{B} \exp(\text{in} \rho), \]

(4a)

\[ \frac{d\varphi_{B} \exp(\text{in} \rho)}{d\rho} = -j\beta_{2} \varphi_{B} \exp(\text{in} \rho) + c_{21} \varphi_{A} \exp(\text{in} \rho), \]

(4b)

where \( \beta_{1} \) and \( \beta_{2} \) are the propagation constants of the two independent holes. According to the principle of energy conservation in a lossless system, the conjugate relationship between these coupling coefficients is given by \( c_{12} = -c_{21}^* \). In addition, a negative conjugate must be used during the derivation, so the phase factor is ignored in the subsequent discussion for simplicity. Consequently, the simplified equations are given as follows:

\[ (i\beta_{1} - \text{in} \rho) \varphi_{A} + c_{12} \varphi_{B} = 0, \]

(5a)

\[ (i\beta_{2} - \text{in} \rho) \varphi_{B} + c_{21} \varphi_{A} = 0. \]

(5b)
To obtain non-zero solutions to these equations, the determinants of the coefficients for the linear homogeneous equations must be equal to zero. For reflection region, the coupling coefficients between the two holes can be derived as follows:

\[ c_{12} = c_{21} = -\sqrt{\beta_1 n_\rho + \beta_2 n_\rho} - \beta_1 \beta_2 - n^2 \rho^2, \quad (6a) \]

where \( c_{12} \) and \( c_{21} \) are the mutual coupling coefficients in the upper surface, and \( \beta_1 \) and \( \beta_2 \) are the propagation constants of the two independent holes in the reflected region.

For transmission region, using a similar derivation to that given above, the coupling coefficients can be derived as follows:

\[ c_{12}' = c_{21}' = -\sqrt{\beta_1' n_\rho + \beta_2' n_\rho} - \beta_1' \beta_2' - n^2 \rho^2, \quad (6b) \]

where \( c_{12}' \) and \( c_{21}' \) are the mutual coupling coefficients in the lower surface, and \( \beta_1' \) and \( \beta_2' \) are the propagation constants of the two independent holes in the transmitted region.

Therefore, the field coefficients of the two holes can be derived using the coupled-mode method and near-field optical thin microcavity theory.

3. Extraordinary diffraction effects from a hole pair

Based on the theory given above, we now perform some calculations to analyze the relationships between the transmittance and some of the other parameters. The geometry that is used for this analysis of the transmittance consists of the following components: circular apertures of radius \( r = 40 \) nm, and the distance between the two holes is \( R = 110 \) nm. Additional, the metal film thickness is selected to be 20 nm in the subsequent analysis in this paper because this deduction is obtained theoretically based on the assumption that the film thickness is much smaller than the incident wavelength. When a plane wave with wavenumber \( k_0 \) (where \( k_0 = |k_0| = 2\pi/\lambda \)) is used to illuminate the nanostructure along the \( z \)-axis, the incident field can be described using an \( E \)-polarized electric field with wavelength \( \lambda \), where \( E_0 = E_0 y = \exp(ik_0z) \).

Here, the two structures are selected and their transmittance spectra are plotted in a single image for ease of observation and comparison, and this shows that different results can be produced by materials that have the same parameters. The transmittance spectrum at normal incidence from the subwavelength hole pair structure that was obtained using the FE simulation is shown in figure 2, while the film material is silver in the simulations, and the optical properties of the silver film are characterized using the Drude–Lorentz model [9], matching well with the experimental data [28]. In figure 2, we observe two phenomena: first, when the same structural parameters are used, the overall transmittance of the two-subwavelength-aperture structure is higher than that of the single aperture structure in the 550–650 nm range. The transmittances of these two structures are basically stable, as shown above, and the transmittance values are very low in the 650–1000 nm range, which is thus not shown in figure 2. This occurs because the interactions between the two holes can enhance the electromagnetic field intensity effectively at a hole–hole distance of \( R = 110 \) nm. Second, a small fluctuation occurs in the transmittance spectrum for the single aperture structure, and the wavelength that corresponds to the observed transmission peak is close to 560 nm, at which the transmittance value is approximately 0.0001. Within the same wavelength range, the transmittance spectrum for the
The two-hole structure sees a reduction from 0.002 and later shows a fluctuation in the 560–565 nm range before continuing to decrease and then becoming stable. In addition, the peak positions of these two structures are both in the 550–570 nm range, which implies that resonance occurs between the illumination and the nanostructure in the thin film. A previous publication in the literature [18] emphasized that the amplitude of this electric field enhancement was mainly localized within the near-field, and was sharpest at the position where \( z = -14 \text{ nm} \). To discuss the physical mechanism involved in this hole pair structure, we extracted the electric field distributions at the observation plane (i.e., at \( z = -14 \text{ nm} \)) at each of the transmittance peak positions shown in figure 3.

Figure 3 shows the electric field magnitude in the longitudinal section where \( y = 0 \) at the observation point under illumination at an incident wavelength \( \lambda = 550 \text{ nm} \) in the longitudinal section where \( \lambda = 550 \text{ nm} \) and the resulting distributions are shown in figures 4(a) and (b), respectively, where the field magnitude for a single aperture within the thin film is shown for reference. Two important results can be drawn from figures 4(a) and (b). First, figure 4(a) shows that the enhancement of the entire field magnitude is not noticeable, although the positions with the more obviously enhanced field magnitudes still occur at each of the hole edges, which is consistent with the edge effect. Second, figures 4(a) and (b) show that the intensity of the interference varies distinctly with wavelength. The enhancement of the transmission spectrum is indeed caused by the coupling of the electromagnetic fields between the two holes in the evanescent field at different incident wavelengths. By contrasting the results in figure 4(a) with those in figure 4(b), we can see that figure 4(a) represents the case of destructive interference in the evanescent field, where the coupling is an energy-based interaction between two-sub-wavelength scale holes located within a conducting thin film that pass through the upper surface to the lower surface, while the interaction is significantly enhanced at the peak transmittance wavelength, particularly at the outer edges.

The above analysis shows that the edge effect exists at the boundaries of the two holes and that the electromagnetic field is enhanced in the evanescent field. The electromagnetic wave that is excited by the edge effect propagates along the thin film surface to form a bound surface wave.

Suppose that the coupling coefficients of equations (6a) and (6b) are both \( jx \); we then find that a phase delay will occur near the other hole. Set \( c_1 = \sin \theta_1 \); then, when the electromagnetic wave propagates to hole \( B \), the phase shifts at the upper and lower surfaces caused by the distance can be expressed as \( \cos \theta_1 e^{-j\beta R q_{b1}^\prime} \) and \( j \sin \theta_1 e^{-j\beta R q_{b2}^\prime} \), respectively. Set \( c_2 = \sin \theta_2 \); then, the field of hole \( B \) after coupling can be rewritten using linear superposition as follows:

\[
\begin{align*}
\varphi_{B^\prime} &= \cos (\theta_1 + \theta_2) e^{-j\beta R q_{b1}^\prime}, \\
\varphi_{B^\prime} &= j \sin (\theta_1 + \theta_2) e^{-j\beta R q_{b2}^\prime}.
\end{align*}
\]

(7a) (7b)

From equation (7), we see that the coupling amplification has an effect on the hole–hole distance and the phase difference. Because \( \Delta \beta = 0 \), the mode that is excited by hole \( B \) is then coupled to the reverse mode of hole \( A \), and the electromagnetic field intensity of hole \( A \) is weakened. Higher energy at hole \( B \) leads to a weaker coupling effect, which is verified by the negative conjugate relationship of the coupling coefficient. This is the reason the coupling field between the two holes reduces the magnitude of the coupled field at certain wavelengths, as shown in figure 4(a). As for the results in figure 4(b), the constructive interference mechanism demonstrates that the field magnitudes at each edge are enhanced and propagate along the surface after the upper surface of the thin film is illuminated by the incident electric field; when the hole–hole distance is 110 nm, the creeping waves are coupled, and the electric field magnitude increases significantly at the outer edges of the two holes at certain wavelengths because of phase matching. It should also be noted that the coupling
between the two holes is dependent on phase matching in the mutual coupling coefficients. Therefore, we can determine from equation (7) that the coupling intensity may be dependent on the incident electromagnetic wavelength, the hole–hole distance and the aperture structure. To enable study of the transmission spectrum with respect to these influential factors, a detailed analysis is presented in the next section.

Through an analysis of the coupling mechanism in this model, we find that the factors that have direct effects on the transmittance are as follows: the hole radius and the separation between the two holes. In fact, when the distance between the edges of the two holes is fixed, the distance between the centers of the two holes must then increase as the radius increases. We therefore initially study the effect of the distance $R$ between the two hole centers on the transmittance. To ensure that the other structural parameters remain unchanged, we set the distance between the two hole centers to vary within the range from 90 to 1200 nm at intervals of 2 nm, and draw their transmission characteristics in figure 5(a). The results in figure 5 show that as the distance between the two hole centers increases from 90 to 200 nm, the transmittance only changes slightly and the value of this change is minimal. The reason for this is that the field magnitude enhancement process in a structure with a smaller hole–hole distance is not excited by the longer wavelengths, and the coupling is too weak to cause any major increase in transmittance. As noted in the literature [29], the most important restriction of the coupled-mode method is that the distance separating the two holes must not be too small. The accuracy of determination of both the propagation constants and the field patterns deteriorates as the separation distance decreases. Therefore, the transmittance can be ignored when the separation distance is too small. The transmittance then increases abruptly with a further increase in the hole–hole distance $R$. When $R$ increases to approximately 250 nm, the wavelength and the structure are matched; a transmittance peak then appears and its value reaches approximately 0.45, which is the maximum value obtained in the transmission spectrum. Within the range from 200 to 1000 nm, the trend across the whole transmission spectrum is similar to that of a sinusoidal curve, but with increasing separation, the transmittance peak values gradually increase and tend to become stable; this period of the transmission spectrum is consistent with the results that were derived from the coupled-mode theory earlier. Using these theoretical derivations and the simulation results, we can now predict the near-field behavior and the in-plane coupling of the two holes. The electromagnetic wave is excited by illumination at the thin film surface and then propagates along the surface within the near-field before coupling at the holes. When the hole–hole distance meets the conditions for constructive interference,
the in-plane coupling effect mainly works to promote the interference and can thus improve the transmission greatly, and vice versa. In other words, the conditions for constructive and destructive interference are both dependent on the hole–hole distance and the incident light wavelength, which meets the conditions of equation (7). As the distance between the two holes continues to increase to more than 1200 nm, the transmittance basically becomes stable and no longer rises; this means that if the separation between the two holes is sufficiently large, the hole–hole in-plane coupling has no effect on the transmittance. Figure 5(b) shows the contour plot of the hole–hole distance, and illustrates that the trend of the transmittance at every wavelength is periodic with the distance between the two hole centers increasing, while the transmittance intensity and scale of the period are different. With the wavelength increasing further, the transmission values are enhanced correspondingly. The results present here are consistent with the results that were obtained by figure 5(a) and the derivation from the coupled-mode theory earlier. Therefore, the holes can then be considered to be independent of each other, and the electromagnetic field distribution of each hole is then consistent with the single hole model, which verifies the validity of the theoretical and simulation results that are presented in this paper.

The results described above show that the hole–hole distance has a significant influence on the transmission. The use of two holes of different sizes is also found to affect the transmittance. The other parameters remain unchanged, and while the radius of one hole is fixed at 40 nm, we set the other hole radii to be 50, 60, 70 and 80 nm for the calculations. The transmission spectra of the four structures with the different hole radii in the 550–650 nm wavelength range are shown in figure 6(a). The results show that the use of different hole radii has a major effect on the transmittance properties. The transmission spectrum increases as the difference between the radii of the two holes increases, and when the two hole radii are 40 and 80 nm, the transmittance is significantly enhanced. The reason for this behavior is that the coupling imbalance is determined by the asymmetry of the model structure; the electromagnetic wave that is radiated by the illumination cannot be localized at the two apertures simultaneously, which means that the electric field magnitudes at the hole edges are not equivalent, and more strongly imbalanced coupling thus leads to higher transmittance, reaching a peak value of approximately 0.4. Each spectrum contains two obvious peaks and a valley within the 550–650 nm range, and the positions of these peaks and valleys shift to the right with increasing hole size difference. In other words, variation of the hole radius leads to a difference in the hole–hole distance, and the coupling mechanism is similar to that described above when the constructive and destructive interference conditions matched the coupled-mode theory. This also matches the theory of coherent cancellation; the coherent interaction at the wavelength of 572 nm is the most obvious, because it represents the peak position after the cancellation effect, where the strength has weakened. At the peak position, the strength is less than that at the main peak intensity, and in the wavelength range higher than 600 nm, the transmission intensity decreased and tended to become stable. The effects of the hole radius on transmittance while one hole radius has vary from 30 to 100 nm and the other hole radius is fixed at 40 nm is presented in figure 6(b), and from this figure we can obtain that at least two transmittance peaks observed in the transmission spectrum, the amplitudes of the peaks increase and the peaks positions shift to longer wavelength with the radius increasing. These results are in agreement with figure 6(a), and these parameter selection conditions may offer a certain theoretical guidance towards the design of optical devices with different transmittance properties.

In this part of the analysis, we can conclude that the influential factors can be broadly classified into two categories: one category is the parameters of the model structure, which includes the separation between the two holes, \( R \), and the hole radius, \( r \), as its main factors. Structural changes can trigger a phase difference and the magnitude of the coupling is determined by the interference conditions, which are dependent on the phase difference and the wavelength of the incident field. Beyond that, by varying the materials of the thin films and the holes, we determined that the materials have little effect on the transmittance, which gives us our second factor. Our investigations showed that another restriction of this method is that the parameters of the different media used had little effect on the actual transmission spectrum.
4. Conclusions

In conclusion, the coupling coefficient between two holes located within a conducting thin film is derived theoretically based on the near-field optical thin microcavity theory and the coupled-mode method, and the results are verified using FE simulations. The mechanism responsible for the high transmission phenomenon is also presented. The coupling process is divided into two steps: first, the edge effect occurs at the hole edges, as demonstrated using the thin microcavity theory when the incident electric field is radiated on the upper surface of the thin film; the enhanced electromagnetic wave then propagates along the film surface and interacts within the vicinity of the two holes. Finally, after comparison and analysis of the effects of the structural parameters on the transmitted behavior, we find that the phase difference is determined by the hole–hole distance, and the magnitude of the coupling is determined by the interference conditions, which are dependent on both the phase difference and the wavelength of the incident field. The conclusions drawn from this study may be useful in the development and design of near-field optical devices.

ORCID iDs

Xu Chen https://orcid.org/0000-0002-6088-3197

References

[26] Fu Q et al 2017 Weak coupling between bright and dark resonators with electrical tunability and analysis based on temporal coupled-mode theory Appl. Phys. Lett. 110 221905