PAPER

Slit width oriented polarized wavefields transition involving plasmonic and photonic modes

Xing Li, Ruirui Zhang, Yuqin Zhang, Li Ma, Changwei He, Xiaorong Ren, Chunxiang Liu and Chuanfu Cheng

College of Physics and Electronics, Shandong Normal University, Jinan 250014, People’s Republic of China

E-mail: chengchuanfu@sdu.edu.cn

Keywords: surface plasmons, polarization, interference, scattering

Abstract

Wavefield manipulation of surface plasmon polaritons (SPPs) is one of the fundamental subjects in nanophotonics. In this paper, based on the analyses of the plasmonic and photonic modes of the L-shaped slit samples with different widths, the dependence of the wavevector, amplitude and phase of the scattered wavefields on the slit width are experimentally determined. The excited plasmonic mode and photonic mode wavelets by arbitrary slit element is analyzed theoretically. Au ring-slits with different widths are also experimented as general slit structure to show the polarized patterns originated from the superimposition of the two modes, and the evolution of total and polarized intensity patterns with the ring-slit widths is studied systematically. The wavefield patterns of the polarization components are also calculated with the obtained components of wavefields and Huygens–Fresnel principle, and results of calculations and experiments are coincident. In addition, the results are validated by performing finite-difference time-domain simulations. The work may enhance the efficiency of slit engineering for SPP pattern manipulations and can be a helpful reference for the fabrication of nano-optics devices.

1. Introduction

Since the discovery of the extraordinary transmission [1], surface plasmon polaritons (SPPs) have provided a powerful tool for engineering nano-devices with various functionalities [2–5] and have given rise to interesting applications such as microscopy beyond diffraction limit [6, 7], nanoscale focusing [3, 4], compact plasmonic modulators [8] and hologram imaging [9]. In excitations and manipulations of plasmonic wavefields, metal nanoslit structures [10–16] and polarization states of the incident light [17–19] play important roles. The shape, width and orientation of slits are elements influencing the launched wavelets [17–20], and the interferences of the wavelets contribute to formations of the wavefield patterns [10–14], which can be described by the Huygens–Fresnel principle [21–23]. The polarization takes effect on the SPP wavelets in more complicated ways. Pertainning to excitations, it has been understood that incident waves of transverse magnetic (TM) and transverse electric (TE) polarizations excite wavelets of plasmonic and photonic modes, respectively [10, 13, 17, 24]. The two modes can be simultaneously excited when the polarization and slit orientations are at an angle [25–29], which has empirically been used in manipulations of wavefields such as the design of quantum eraser [28]. Instead of the usually used circularly polarized illuminations, the manipulations of SPP wavefields based on linearly polarized illuminations [30–34] have recently attracted more and more interests, such as SPP focusing [35–39]. However, in most of these applications, the slit widths of the designed structures are often smaller than the cutoff width for the photonic mode excitation [40, 41], and photonic modes together with their influences on the polarization are rarely considered.

In a previous study [29], we have proposed the methods to solve experimentally the wavefields of the two modes produced by slits with a fixed width. However, due to the fixed polarization of the reference wave used in Mach–Zehnder system therein, only the SPP wavefields component parallel to that of the incident waves have
been studied, and the general polarization properties of the excited SPP wave fields remain uninvestigated. Moreover, the SPP wave field transition with slit widths is one of the basic issues for slit engineering and wavefield manipulations, and a direct solution with experiments is of practical interest. In this work, we experimentally study the SPP wave field transitions of pure plasmonic and photonic modes by use of L-shaped nanoslits consisting of one arm with identical width and the other with varied width. In the experiment, the polarization of incident wave is adjusted to either the vertical or the horizontal directions, and the components of the wavefields are obtained from the interference fringes of the plasmonic and the photonic modes. By decomposing the incident electric vector with respect to the slit, we demonstrate that polarization of the excited wavelet deviates from that of incidence due to the unbalanced excitation of the plasmonic and the photonic modes. As general slit structure, total and polarized intensity patterns of Au ring-slits with different widths are experimentally obtained, and their evolutions with the ring-slit widths are studied systematically. The evolutions of the polarization pattern with the ring-slit widths are also calculated with the obtained components of wavefields and Huygens–Fresnel principle, and results of calculations and experiments are coincident. In addition, the results are validated by performing finite-difference time-domain simulations.

The paper is organized as follows. Section 2 introduces the experiment on L shape slits of different slit widths with the Mach–Zehnder type interferometer system. Section 3 is devoted to extract component quantities of plasmonic and photonic modes from the experimental interference fringes in section 2, including initial amplitudes, initial phases and equivalent wavevectors. Based on the wavefields of the two modes experimentally obtained in sections 2 and 3, section 4 analyzes the polarization effects of slit elements, and derives a Huygens–Fresnel type formulation of the scattered wave. Section 5 demonstrates the applicability of the formulation in section 4 by the experiment and theory on ring-slits, and shows the evolutions of the polarization pattern with the ring-slit width. Finally, section 6 concludes and summarizes.

2. Experiments and the SPP intensity patterns of the samples

Figure 1 (a) schematically shows the experimental setup. A Mach–Zehnder type interferometer is used to record the scattered wavefield launched by metal nanoslit. A He–Ne laser with a wavelength of $\lambda = 632.8$ nm is split into two arms by the beam splitter (BS1). The upper arm illuminates the sample S from substrate side and the lower arm is the reference beam. The three-dimensional translational stage is used to adjust the position of the sample. The light wave excited by the slit and scattered from the sample surface is captured by a microscopic objective, and the CCD records the interference pattern of the enlarged image and the reference beam. The CCD can also merely record the image of the scattered wavefield with the reference beam blocked. To overcome the limitation that only one component of SPPs can be detected in [29], polarizers P3 and P4 are added and can be rotated to acquire patterns of different polarized components. The schematic of the L-shaped slit sample is shown in figure 1 (b). The samples are milled in Au film with a thickness of 200 nm by focused ion beam and the substrate is fused silica. The SEM images of the fabricated samples are shown in figure 1 (c). The lengths of the
two slit arms are 10 μm. The vertical arms of the all samples have the fixed width of $W_v = 300$ nm, and the horizontal arms have the widths of $W_h = 100, 150, 200, 300, 500$ nm, respectively. We label them as samples S1 to S5. The scattered wavefield $E(x, y)$ may be reconstructed from the recorded interference patterns, and its amplitude $A(x, y)$ and phase $\Phi(x, y)$ can also be retrieved.

The experimental scattered patterns are shown in figure 2, with the corresponding samples labeled above each column of patterns. The double-headed arrows indicate the polarizations of the incident beam. By adjusting the detection polarizer $P_3$ in figure 1(a), the scattered patterns with the same polarization as the incident wave are measured firstly. In figures 2(a1)–(e1), the vertical arms of the samples play a role of TE polarization to launch waves of photonic mode, and the horizontal arms play a role of TM polarization to launch waves of plasmonic mode. Oppositely, in figures 2(a2)–(e2), the vertical and the horizontal arms launch waves of plasmonic and photonic modes, respectively. The two images figures 2(d1) and (d2) of sample S4 include the same information because of the same slit width, and their data may provide normalization for other samples. In the upper-row figures, fringes indicate that the horizontal arms of all slit samples can produce wavefield of plasmonic mode with amplitudes comparable to that of the photonic mode by the vertical arms. In the lower-row figures, nevertheless, the horizontal arms of samples S1 and S2 almost cannot produce the photonic mode wavefield, and thus no fringe is formed. When the arm width is larger than 200 nm, the amplitudes of the photonic mode gradually increase with the width. Then we may take 150 nm as the cutoff slit width for the photonic mode wavefield [42]. In the experiment, when the direction of the detection polarizer $P_3$ is adjusted perpendicular to the illumination polarization and the reference beam is blocked, no image can be observed by the CCD. This indicates that the polarizations of both the photonic and the plasmonic modes are parallel to that of the incident wave.

### 3. Wavefield constructions of plasmonic and photonic modes for the samples from the experimental data

Figure 3(a) shows the excitation of the photonic and plasmonic mode waves by a L-shaped slit with vertically polarized illumination. The electric field of the incident wave is written as $E = E_j$, with $j$ the unit vector in $y$-direction. The incidence is TE-polarized for the vertical arm of slit and is the TM polarized for the horizontal arm. Then the two arms excite waves of photonic mode (the blue line) and plasmonic mode (the green line), respectively, with their wavefronts parallel to the corresponding slit arms. The interference of the two perpendicularly propagating wavefields forms the intensity pattern.

For the patterns generated by vertical polarization incidence in figures 2(a1)–(e1), the wavefields of the photonic mode launched by the vertical arms can be expressed as $E_{\text{ph},n}^x(x) = A_{\text{ph},n} \exp(-i k_{\text{ph},n} x + i \Phi_{\text{ph},n})$. Here $k$, $A$ and $\Phi$ represent wavevector, initial amplitude and phase. The subscripts $\text{ph}$ and $n$ represent the photonic mode produced by the $n$th sample, and superscript $v$ represents vertical incident polarization. The plasmonic mode launched by the horizontal arms can be expressed as $E_{\text{pl},n}^y(y) = A_{\text{pl},n} \exp(-i k_{\text{pl},n} y + i \Phi_{\text{pl},n})$ with subscript $\text{pl}$ representing plasmonic mode. In each pattern, we choose the intensity data on a vertical line $x = 3.84 \ \mu m$, and plot the curves of $I_n^v (y)$ in figure 3(b). Obviously, $I_n^v (y)$ is the interference of $E_{\text{ph},n}^x(x)$ and
\[ E_{pl,n}^x(y), \text{ and since } E_{ph,n}^x(x) \text{ is a constant wavefront at a fixed distance for all samples, it is used to normalize the wavefields } E_{pl,n}^x(y). \]

For patterns in figures 2(a2)–(e2) of horizontal polarization incidence, the excitation of the plasmonic mode and photonic mode are reversed for the two slit arms. The vertical arm launches plasmonic mode and the horizontal arm launches photonic mode, and the corresponding expression of the two modes are \[ E_{pl,n}^h(x) = A_{pl,n} \exp(-ik_{pl,n}x + i\theta_{pl,n}) \]
and \[ E_{ph,n}^h(y) = A_{ph,n} \exp(-ik_{ph,n}y + i\theta_{ph,n}), \]
respectively. Similarly, the intensity data \[ I_{ph,n}(y) \text{ on a vertical line } x = 4.36 \text{ } \mu \text{m} \] was shown in figure 3(c). In this case, the plasmonic mode wavefield \[ E_{pl,n}^h(x) \] has similar expression to its photonic mode counterpart \[ E_{ph,n}^h(x). \]
Then \[ I_{ph,n}^x(y) \] is the interference of \[ E_{pl,n}^h(x) \] and \[ E_{ph,n}^h(y), \] with \[ E_{pl,n}^h(x) \] acting as normalization reference. Based on the these data, we can extract the equivalent wavelengths, initial amplitudes and initial phases of \[ E_{pl,n}^x(y) \] and \[ E_{ph,n}^x(y) \] from the intensity curves in figures 3(b) and (c).

From the fringe pitch of each intensity curve, the equivalent wavelengths \[ \lambda_{pl,n} = 2\pi/k_{pl,n} \] and \[ \lambda_{ph,n} = 2\pi/k_{ph,n} \] can be obtained directly. For different slit widths, the obtained \[ \lambda_{pl,n} \] and \[ \lambda_{ph,n} \] are shown in figure 3(d), respectively. For the plasmonic mode, \[ \lambda_{ph,n} \] almost increases linearly from 100 to 300 nm of slit width, while it becomes almost unvaried from 300 to 500 nm. For the photonic mode, only three data points were obtained due to the cutoff slit width. The equivalent wavelength \[ \lambda_{ph,n} \] remains to be a constant and is approximately measured to be \[ \lambda_{ph,n} \approx 781.06 \text{ nm} \] for samples from S3 to S5. This characteristic can be explained qualitatively. Waves of plasmonic mode is the hybridization of SPP and quasi-cylindrical wave (CW) [29]. When the amplitudes of SPP and quasi-CW are comparable, the main wave has a wavevector about \[ (k_0 + k_{SP})/2, \] with \[ k_0 \] and \[ k_{SP} \] the wavevectors of the incident wave and SPP wave, respectively. For smaller width of slit arm, the quasi-CW decreases, and the wavevector component \[ k_{pl,n} \] shifts to the larger scattered wavevector component of the dominant SPP, leading to the decrease of \[ \lambda_{pl,n}. \]

In contrast, the single wavevector \[ k_0 \] in photonic mode causes \[ \lambda_{ph,n} \] to be almost independent of slit width.

Obviously, \[ \lambda_{pl,n} \] and \[ \lambda_{ph,n} \] are larger than \[ \lambda_{SP} \] and \[ \lambda_0 \] respectively. The reason may be found in the scattering of the SPP from the slightly rough film surface. Based on the scattering theory under Kirchhoffs approximation [29], the scattered wavevector component \[ k_{sc,SP} \] is written as \[ k_{sc,SP} = k_{SP} - k_{sc}\zeta_{rms} \] with the root-mean-square slope \[ \zeta_{rms} \] of the slightly rough film surface [42, 43]. Similarly, the wavevector component of the quasi-CW is \[ k_{sc,CW} = k_0 - k_{sc}\zeta_{rms}, \] and this causes \[ \lambda_{pl,n} \] to vary with slit width in the range roughly from \[ (\lambda_{SP} + \lambda_0)/2 + \Delta\lambda_0 \] to \[ \lambda_{SP} + \Delta\lambda_0 \], with \[ \Delta\lambda_0 \] the equivalent wavelength shift. For photonic mode, the scattered wavefields on the same reason have the
equivalent wavelength $\lambda_0 + \Delta \lambda$. This explains the result in figure 3(d) that the largest equivalent wavelength of the plasmonic mode is roughly at the middle of the range from the smallest $\lambda_{pl,n}$ to $\lambda_{ph,n}$.

The amplitudes of $E_{ph,n}^h(y)$ and $E_{ph,4}^h(y)$ can also be obtained from the interference intensities $I_n^h(y)$ and $I_4^h(y)$, respectively. As can be seen in figures 3(b) and (c), each curve has a point of smallest minimum intensity, and at this point, the amplitudes of the two waves are considered to be equal. For the curve of the $n$th sample under vertical incident polarization in figure 3(b), the average on the data of a single complete fringe centered at this point is approximated as $2[A_{ph,n}(x = 3.84 \, \mu m)]^2$ [29]. In the practical performance, we use the smallest minimum point in the curve of sample S4 to determine the amplitude $A_{ph,n}(x = 3.84 \, \mu m)$. Then we use the obtained $A_{ph,n}(x = 3.84 \, \mu m)$ to normalize the values of amplitudes of the experimental wavefields launched by the 300 nm slit arms of $n$th samples though $A_{ph,n}(x = 3.84 \, \mu m)$ are theoretically constant. With $A_{ph,n}(x = 3.84 \, \mu m)$ obtained, we derive the amplitude value of the plasmonic mode for the $n$th sample.

Similarly, for the case of the horizontal polarization illuminations including the patterns in figures 2(a2)–(e2), the amplitude $A_{pl,n}(x = 4.36 \, \mu m)$ can be determined and normalized with the data of the curves in figure 3(c), and the amplitude value of the photonic mode for the $n$th sample is obtained. Considering that the width of the two arms for sample S4 are the same, the normalization between the two sets of obtained $A_{ph,n}$ and $A_{pl,n}$ is done by using the data of sample S4. We take amplitude values at the first maxima of the intensity curves as the initial amplitudes and they are shown in figure 3(c). It can be seen that the initial amplitude of both plasmonic mode and photonic mode increase linearly with the slit width.

After Fourier transform of the interference pattern obtained by the experimental Mach–Zehnder interferometer setup, the last component quantities, i.e., the initial phases of $E_{pl,n}^h(y)$ and $E_{ph,4}^h(y)$ can be obtained. For the vertical polarization, the obtained initial phase $\Phi_{pl,n}$ of $E_{pl,n}^h(y)$ is converted to be relative to that of $E_{pl,4}^h(y)$. Similarly, the initial phase $\Phi_{ph,n}$ of $E_{ph,4}^h(y)$ relative to that of $E_{pl,4}^h(y)$ is also achieved for the horizontal polarization case. In figure 3(f), the initial phases versus slit width for the plasmonic and the photonic modes are shown. We see that the initial phases $\Phi_{pl,n}$ of the plasmonic modes lead $\Phi_{ph,n}$ and the narrower the slits, the more they lead $\Phi_{ph,n}$. The initial phases of the photonic mode generated by wider slits lead those by narrower slits, and though only three data points are available, the linearity between the leading phase and the slit width is clearly shown.

4. Wavelets of the slit elements and the polarization effects

With the wavefields $E_{pl,n}^h(y)$ and $E_{ph,4}^h(y)$ obtained in the above, we now further consider the wavefields generated by a slit element $d$ with arbitrary orientation. As schematically shown in figure 4(a), the vertically polarized incident wave $E_0 = E_0 \hat{j}$ can be decomposed into components of $E_{0\perp} = E_0 \sin \alpha \hat{i}$ and $E_{0\parallel} = E_0 \cos \alpha \hat{j}$. Here, $\{\hat{i}, \hat{j}\}$ and $\{\hat{i}', \hat{j}'\}$ are unit vectors and $\alpha$ is the angle between the slit element and the incident polarization direction. The two components excite the plasmonic and photonic modes, respectively, and the corresponding wavefields can be expressed as $E_{pl,n} = A_{pl,n} \exp(i\Phi_{pl,n}) \sin \alpha \hat{d}' \hat{i}'$ and $E_{ph,n} = A_{ph,n} \exp(i\Phi_{ph,n}) \cos \alpha \hat{d} \hat{j}'$. Transforming the unit vectors from $\{\hat{i}', \hat{j}'\}$ to $\{\hat{i}, \hat{j}\}$, the excited wavefield at the source point $(x_0, y_0)$ can be written as:

![Figure 4](image-url)

**Figure 4.** (a) Schematic for polarization decomposition of incident wavefield. The angle between the slit and $E_0$ is $\alpha$. (b) Schematic for excitations and superposition of plasmonic and photonic modes. The red ellipse schematically shows the elliptical polarization of the superposed wavefield of the two modes.
\[
\text{d}E(x_0, y_0) = \begin{bmatrix} \text{d}E_x(x_0, y_0) \\ \text{d}E_y(x_0, y_0) \end{bmatrix} = \frac{\text{d}l}{\sqrt{\beta}} \begin{bmatrix} \cos \alpha - \sin \alpha \\ \sin \alpha \cos \alpha \end{bmatrix} \begin{bmatrix} A_{\text{pl},n}\exp(\text{i}k_{\text{pl},n}d) \sin \alpha \\ A_{\text{ph},n}\exp(\text{i}k_{\text{ph},n}d) \cos \alpha \end{bmatrix} \\
\begin{bmatrix} i \\ j \end{bmatrix}.
\]

The different values of \(A_{\text{pl},n}\) and \(A_{\text{ph},n}\) indicate that the excitations of the two modes are unbalanced. Further taking the significant phase difference \(\Phi_{\text{pl},n} - \Phi_{\text{ph},n}\) into account, we derive that the scattered wavefield \(\text{d}E(x_0, y_0)\) consisting of plasmonic mode and photonic mode in general is elliptically polarized, as depicted in figure 4(b). This means a single slit can modulate the polarization of the incident wavefields, which is of fundamental importance for manipulations of vector light waves. After simplifying the equation (1), the x and y-polarization component of the wavefield from a slit element can be represented as:

\[
dE_x(x_0, y_0) = [A_{\text{pl},n}\exp(\text{i}k_{\text{pl},n}d) - A_{\text{ph},n}\exp(\text{i}k_{\text{ph},n}d)] \sin \alpha \cos \alpha,
\]

\[
dE_y(x_0, y_0) = [A_{\text{pl},n}\exp(\text{i}k_{\text{pl},n}d) - A_{\text{ph},n}\exp(\text{i}k_{\text{ph},n}d)] \sin^2 \alpha + A_{\text{ph},n}\exp(\text{i}k_{\text{ph},n}d).
\]

The wavelets \(E_{\text{pl},n}\) and \(E_{\text{ph},n}\) can also be applied to the Huygens–Fresnel principle for calculations of the wavefields produced by slits of arbitrary shape. With the propagation factors being considered, the Huygens–Fresnel principle with the components in the directions of i and j can be derived in vector form as:

\[
E(x, y) = \begin{bmatrix} E_x(x, y) \\ E_y(x, y) \end{bmatrix} = \int \frac{\text{d}l}{\sqrt{\beta}} \begin{bmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{bmatrix} \begin{bmatrix} A_{\text{pl},n}\exp(\text{i}k_{\text{pl},n}d) \sin \alpha \\ A_{\text{ph},n}\exp(\text{i}k_{\text{ph},n}d) \cos \alpha \end{bmatrix} \begin{bmatrix} i \\ j \end{bmatrix},
\]

where \(\beta = \sqrt{(x-x_0)^2 + (y-y_0)^2}\) is the distance from the source point \((x_0, y_0)\) to field point \((x, y)\), and the first factor \(\cos \beta\) inside the integral is the inclination factor. The Huygens–Fresnel approach may be applied to the calculations of the wavefields of slit as long as there is the light wave launched from the slits. Considering the dependence of the two mode excitations on the slit width, the principle is valid when the width is larger than 100 nm for the photonic mode. And for the plasmonic mode, the slit width should be larger than dozens of nanometers.

5. The polarized and the total wavefields of ring-slits

Ring-slits in metal films are an important device for SPP wavefield manipulations. The polarizations and the evolutions of their wavefields with the slit width and ring radius are interesting and fundamental issues. Next we conduct both experiments and calculations on samples of ring-slits to check the applicability of the principle expressed in the equations (1)–(4) and to study the polarized and total SPP wavefields. We fabricate three ring-slit samples with the inner diameter 6 \(\mu m\) and slit widths 150 nm, 200 nm and 300 nm, labeled as R1, R2 and R3, respectively. The SEM images of samples are shown, respectively, in figures 5(a1)–(a3). Illuminated by vertically polarized light (the green arrows), the experimental patterns for these samples are shown in figures 5(b1)–(d3). In figures 5(b1)–(b3), the patterns are obtained without P3 and represents the total intensity \(|E_x(x, y)|^2 + |E_y(x, y)|^2\). Figures 5(c1)–(c3) and (d1)–(d3) are obtained by rotating P3 and represent the intensity of the polarization component perpendicular \(|E_x(x, y)|^2\) and parallel \(|E_y(x, y)|^2\) to the incident polarization, respectively. The evolutions of the patterns with slit widths in figures 5(b1)–(b3) are interesting. For the small slit width of 150 nm in figure 5(b1), bright fringes can be clearly observed on the top and bottom of the ring-slit while there is no fringe on the left and the right sides of the slit. With the increase of slit width, the intensity distribution become more and more homogeneous along the ring-slit as shown in figures 5(b2) and (b3). For the 300 nm slit in figure 5(b3), the bright fringes form closed circle with uniform intensity and a central bright spot in the central area of the ring-slit. The full-width at half maximum of the spot is about 260 nm, which is smaller than half wavelength of the incident light in air and can be called as super-resolution focusing [44].

This evolution can be quantitatively explained by considering the scattered wavefield by slit element, as expressed in equation (1). For a small slit width, the plasmonic mode is much stronger than the photonic mode wave with approximation of \(A_{\text{ph},n}^2/A_{\text{pl},n}^2 \approx 0\). The plasmonic mode wavelet generated by the slit is mainly derived from the perpendicular component \(E_{\text{pl},\perp} = E_0 \sin \alpha'\) of the incident light. The top and bottom of the ring-slit are perpendicular to the vertically polarized incident light (\(\alpha = \pm \pi/2\)) and can effectively excite SPPs, while the left and right of the ring-slit is parallel to the polarization of the incident light (\(\alpha = 0\)) and cannot generate SPPs. Thus, an inhomogeneous intensity distribution is shown in figure 5(b1). For a larger slit width in figure 5(b3), besides the plasmonic mode excitation, the photonic mode wave can also be excited at left and right of the ring-slit, and thus the intensity distribution of wavefield becomes uniform.
The dependence of the two orthogonal scattered components $|E_x(x, y)|^2$ and $|E_y(x, y)|^2$ on the width of the ring-slit are also studied, as shown in Figures 5(c1)–(c3) and (d1)–(d3). With the increase of the slit width, the x-polarized patterns are all composed of four fan-shaped sub-patterns with fringes, but the evolution of the y-polarized component is similar to that of the total intensity. Considering the x-polarized component expressed in equation (2), the item $A_{p/n} \exp(i\Phi_{p/n}) - A_{p/n} \exp(i\Phi_{p/n})$ is a coefficient, and the item $\sin \alpha$ $\cos \alpha$ is the same for ring-slit with different widths. Thus, the shape of the x-polarized patterns are alike for R1, R2 and R3. For the y-polarized component in equation (3), the second item $A_{p/n} \exp(i\Phi_{p/n})$ represents photonic mode which is generated by the left and right of the ring-slit. With the increase of the slit width, the photonic mode grows stronger, which results in the variation of the y-polarized component and the total intensity.

With the Huygens–Fresnel principle expressed in equation (4), we perform calculations of the scattered wavefields generated by the ring-slits which are shown in figures 6(a1)–(a3). In calculations, the values of $A_{p/n}$, $A_{p/n}$, $k_{p/n}$, $k_{p/n}$, $\Phi_{p/n}$, and $\Phi_{p/n}$ for samples of the corresponding slit widths are obtained in the previous context using the L-shaped slits. We see that all the calculated and experimental patterns of total and polarized intensities are of high consistency. This consistency may further demonstrate the accuracy and applicability of the extracted component quantities and equation (4).

To further verify the experimental results, 3D FDTD simulations of the ring-slit structures based on commercially available software FDTD Solutions (Lumerical 2016a) are also performed. In the simulation, a vertically polarized plane wave of wavelength 632.8 nm is normally incident from the bottom of the silica along the z axis. The ring-slit structures have the same structural parameters as the experimental samples. The
thickness of the gold film is 200 nm. Perfectly matched layer boundaries are used in x, y and z directions. Figures 6(b1)–(b3) show, respectively, the simulated in-plane electric field distribution at the height of 300 nm above the metal surface. We may see that the simulated intensity patterns are consistent with the experimental results. The slight differences between simulated and experimental intensity distributions may be caused by the experimental factors such as the rough surface of the metal film and the width errors in slit sample fabrication.

6. Conclusions

In summary, with scattered patterns generated by the L-shaped slits of different slit widths, we have obtained the component quantities of initial amplitudes, initial phases and equivalent wavevector components for the plasmonic and the photonic modes in the scattering detection system. Considering the unbalanced excitation of the plasmonic and the photonic modes, the excited wavelets by slit element with arbitrary angle is analyzed theoretically. The data of these quantities are used as secondary source elements to construct the Huygens–Fresnel principle of vector form. Based on the above analyses, we experimentally obtained the polarized patterns of ring-slit with different width, and studied the dependence of the patterns on the slit width. The experimental, calculated and simulated polarized patterns are of high consistence, which demonstrates the feasibility of the principle. By interpolating the obtained data of these quantities, one may use the principle to calculate the intensity patterns for structures with slit widths of wider range. We expect that the method and the results of this work would play important role in the manipulations of the scattered plasmonic wavefields. Besides, the incident angle can also influence the interference pattern of the ring-slit. Under oblique incidence, the focus spot shifts from the center, and its shape evolve to be asymmetrical. The amount of shifted distance and asymmetry depends on the incident angle [45].

Acknowledgments

This work is supported by the National Natural Science Foundation of China (NSFC) (11574185, 11604183, 11647015); Project of Shandong Province Higher Educational Science and Technology Program (J16LJ09).
References

[1] Ebbesen T W, Lezec H J, Gaeta H F F, Thio T and Woff P A 1998 Extraordinary optical transmission through sub-wavelength hole arrays Nature 391 667–9

[2] Christ A, Tikhodeev S G, Gippius N A, Kuhl J and Giessen H 2003 Waveguide–plasmon polaritons: strong coupling of photonic and electronic resonances in a metallic photonic crystal slab Phys. Rev. Lett. 91 183901

[3] Liu Z, Steele J M, Sriravanchi W, Pikus Y, Sun C and Zhang X 2005 Focusing surface plasmons with a plasmonic lens Nano Lett. 5 1726–1729

[4] Lerman G M, Yanai A and Levy U 2009 Demonstration of nanofocusing by the use of plasmonic lens illuminated with radially polarized light Nano Lett. 9 2139–43

[5] Lin J, Mueller J P, Wang Q, Yuan G, Antoniou N, Yuan X C and Capasso F 2013 Polarization-controlled tunable directional coupling of surface plasmon polaritons Science 340 331–4

[6] Rothenhausler B and Knoll W 1988 Surface plasmon microscopy Nature 332 615–7

[7] Zhang J, See C W, Songthiraj M G, Pitter M A and Liu S G 2004 Wide-field surface plasmon microscopy with solid immersion lens Appl. Phys. Lett. 85 5451

[8] Hafifin C et al 2015 All-plasmonic Mach–Zehnder modulator enabling optical high-speed communication at the microscale Nat. Photon. 9 525–8

[9] Zheng G, Muhlenbernd H, Kenney M, Li G, Zentgraf T and Zhang S 2015 Metasurface holograms reaching 80% efficiency Nat. Nanotechnol. 10 308–12

[10] Ishii S, Shalaev V M and Kildishev A V 2013 Holey-metal lenses: sieving single modes with proper phases Nano Lett. 13 159–63

[11] Dvořák P, Neuman T, Bílek M, Samofíl T, Kalousek R, Dub P, Varga P and Šikola T 2013 Control and near-field detection of surface plasmon interference patterns Nano Lett. 13 2556–65

[12] Tsai W Y, Huang S and Huang C B 2014 Selective trapping or rotation of isotropic dielectric microparticles by optical near field in a plasmonic archimedean spiral Nano Lett. 14 547–52

[13] Genevet P, Wintz D, Ambrosio A, She A, Blanchard R and Capasso F 2015 Controlled steering of Cherenkov surface plasmon wakes with a one-dimensional metamaterial Nat. Nanotechnol. 10 804–9

[14] Lerman G M and Levy U 2013 Pin cushion plasmonic device for polarization beam splitting, focusing, and beam position estimation Nano Lett. 13 1100–5

[15] Lindquist N C, Nagpal P, Meckel KM, Norris D J and Oh S-H 2012 Engineering metallic nanostructures for plasmonics and nanophotonics Rep. Prog. Phys. 75 036501

[16] Spektor G et al 2012 Revealing the subfemtosecond dynamics of orbital angular momentum in nanoplasmatic vortices Science 335 1187–91

[17] Ishii S, Kildishev A V, Shalaev V M, Chen K P and Drachev V P 2011 Metal nanoslit lenses with polarization-selective design Opt. Lett. 36 451–3

[18] Wang S, Wang X and Zhang Y 2017 Simultaneous Airy beam generation for both surface plasmon polaritons and transmitted wave based on metasurface Opt. Express 25 23389–96

[19] Wang Y, Xu Y, Feng X, Zhao P, Liu F, Cui K, Zhang W and Huang Y 2016 Optical lattice induced by angular momentum and polygonal plasmonic mode Opt. Lett. 41 1478–81

[20] Genevet P et al 2012 Ultra-thin plasmonic optical vortex plate based on phase discontinuities Appl. Phys. Lett. 100 013101

[21] Feng L, Tetz K A, Slutsky B, Lomakin V and Fainman Y 2007 Fourier plasmonics: diffractive focusing of in-plane surface plasmon polariton waves Appl. Phys. Lett. 91 081101

[22] Teperik T V, Archambault A, Marquier F and Greffet J J 2009 Huygens–Fresnel principle for surface plasmons Opt. Express 17 17483–90

[23] Archambault A, Teperik T V, Marquier F and Greffet J J 2009 Surface plasmon Fourier optics Phys. Rev. B 79 195414

[24] Goh X M, Lim I and Roberts A 2010 Planar focusing elements using spatially varying near-resonant aperture arrays Opt. Express 18 11683–8

[25] Wang J, Zhao C and Zhang J 2010 Does the leakage radiation profile mirror the intensity profile of surface plasmon polaritons? Opt. Lett. 35 194–6

[26] Drezet A and Genet C 2013 Imaging surface plasmons: from leaky waves to far-field radiation Phys. Rev. Lett. 110 213901

[27] Berthel M, Jiang Q, Chartrand C, Bellessa J, Huant S, Genet C and Drezet A 2015 Coherence and aberration effects in surface plasmon polariton imaging Phys. Rev. E 92 032302

[28] Ajimo J, Marchante M, Krishnan A, Bernussi A A and de Peralta L 2010 Plasmonic implementation of a quantum eraser for imaging applications J. Appl. Phys. 108 063141

[29] Li X, Gao Y, Jiang S, Ma L, Liu C and Cheng C 2015 Experimental solution for scattered imaging of the interference of plasmonic and photonic mode waves launched by metal nano-slits Opt. Express 23 3597–22

[30] Wang S, Wang X and Zhang Y 2018 Polarization-based dynamic manipulation of Bessel-like surface plasmon polaritons beam Opt. Express 26 5461–8

[31] Pham A, Zhao A, Jiang Q, Bellessa J, Genet C and Drezet A 2018 Interference eraser experiment demonstrated with all-plasmonic which–path marker based on reverse spin Hall effect of light ACS Photonics 5 1108–14

[32] Hu X and Wei X 2017 High efficiency broadband—90° to 90° arbitrary optical rotation realized with meta reflectarray Opt. Express 25 3641–50

[33] Ding J, Arigong B, Ren H, Zhou M, Shao J, Lin Y and Zhang H 2014 Efficient multiband and broadband cross polarization converters based on slotted L-shaped nanoantennas Opt. Express 22 29143–51

[34] Grady N, Hays J E, Chowdhury D K, Zeng Y, Reiten M T, Azad A K, Taylor A J, Dalvit D A R and Chen H T 2013 Terahertz metamaterials for linear polarization conversion and anomalous refraction Science 340 1304–7

[35] Spektor G, David A, Gjonaj B, Barta G and Orenstein M 2015 Metaflowing by a metaspherical plasmonic lens Nano Lett. 15 5739–43

[36] Spektor G, David A, Gjonaj B, Gal L, Barta G and Orenstein M 2016 Linearly dichroic plasmonic lens and hetero-chiral structures Opt. Express 24 2436–42

[37] Huft P R, Kolbow J D, Thweatt J T and Lindquist N C 2017 Holographic plasmonic nanotweezers for dynamic trapping and manipulation Nano Lett. 17 7920–5

[38] Liu J, Gao Y, Ran L, Guo K, Lu Z and Liu S 2015 Focusing surface plasmon and constructing central symmetry of focal field with linearly polarized light Appl. Phys. Lett. 106 013116
[39] Li J, Yang C, Zhao H, Lin F and Zhu X 2014 Plasmonic focusing in spiral nanostructures under linearly polarized illumination Opt. Express 22 16686–93
[40] Ding K and Ning C 2012 Metallic subwavelength-cavity semiconductor nanolasers Light: Sci. Appl. 1 e20
[41] Peltzer J J, Flammer P D, Furtak T E, Collins R T and Hollingsworth R E 2011 Ultra-high extinction ratio micropolarizers using plasmonic lenses Opt. Express 19 18072–9
[42] Polanco J, Fitzgerald R M and Maradudin A A 2013 Scattering of surface plasmon polaritons by one-dimensional surface defects Phys. Rev. B 87 155417
[43] Nayar S K, Ikeuchi K and Kanade T 1991 Surface reflection: physical and geometrical perspectives IEEE Trans. Pattern Anal. Mach. Intell. 13 611–34
[44] Fu Y Q, Zhou W, Lim L E N, Du C I and Luo X G 2007 Plasmonic microzone plate: superfocusing at visible regime Appl. Phys. Lett. 91 061124
[45] Liu Z W, Steele J M, Lee H and Zhang X 2006 Tuning the focus of a plasmonic lens by the incident angle Appl. Phys. Lett. 88 171108