Geometrical phase and surface plasmon focusing with azimuthal polarization

Weibin Chen,[1,*] Robert L. Nelson,[2] and Qiwen Zhan[1]

[1]*Electro-Optics Program, University of Dayton, 300 College Park, Dayton, Ohio 45469, USA*

[2]*Air Force Research Laboratory, Wright–Patterson Air Force Base, Dayton, Ohio 45433, USA*

**Corresponding author: wchen2@udayton.edu*

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Owing to a geometric phase effect, an isosceles triangular aperture etched into thin metal film leads to constructive or destructive interference of surface plasmons excited at the two equal sides under linearly polarized illumination. Through appropriate spatial arrangement of an array of triangles, a highly confined focal spot beyond the diffraction limit can be achieved at the geometric center under azimuthally polarized excitation with field enhancement comparable to a bull's eye plasmonic lens under radially polarized illumination. Through simply rotating the orientation of each triangle aperture by 90°, the plasmonic structure defocuses the same azimuthal polarization illumination due to destructive interference caused by a geometric π-phase difference between the two sides of the triangle and between the adjacent triangles.

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Surface plasmons are free electron oscillations due to the interactions between photons and conduction electrons confined near a metal/dielectric interface. Such interactions have provided a new approach to manipulate light at subwavelength scale and create strongly enhanced localized electromagnetic fields with a broad range of applications in physics, chemistry, and biological sciences. A surface plasmon can be excited by TM-polarized light that has electrical field in the plane of incidence. The excitation and focusing of a surface plasmon with spatially homogeneous polarization, such as linear or circular polarization, have been widely explored and exploited in various applications [1–6]. Surface plasmon excitation with spatially inhomogeneous polarization has also gained considerable research interest recently. A special class of the spatially inhomogeneous polarization that has attracted much attention is the so-called cylindrical vector (CV) beams, which include radially and azimuthally polarized beams [7]. Radial polarization has its local polarization aligned in the radial direction, which is TM polarized with respect to the typical axially symmetric plasmonic structures, such as bull's eyes [8]. Because of the symmetry matching between the axially symmetric plasmonic structures and the polarization spatial distribution, optimal plasmonic focusing has been demonstrated both theoretically and experimentally with radial polarization excitation [7–11]. Contrarily, azimuthal polarization has its local polarization aligned in the azimuthal direction, which is TE polarized with respect to these traditional plasmonic lenses. Thus azimuthal polarization has not been considered for surface plasmon excitation in general.

In this Letter, for the first time to the best of our knowledge, we report surface plasmon focusing with azimuthally polarized excitation using a plasmonic lens that consists of spatially arranged triangles. To understand its working principle, interactions between linear polarizations and an isosceles triangular aperture etched into thin metal film are explored first with three-dimensional finite element method modeling. Because of a geometric phase, an isosceles triangular aperture creates a destructive interference pattern along the axis of symmetry, with linearly polarized illumination parallel to the triangle base. On the other hand, constructive interference can be achieved with linearly polarized illumination parallel to the axis of symmetry. This interesting phenomenon enables us to design a plasmonic lens in an array format. Through careful spatial arrangement of the triangle orientations, surface plasmon focusing with a highly confined spot can be obtained under azimuthal polarization excitation. More interestingly, this plasmonic lens made of spatially arranged triangles can also produce plasmonic focusing under radial polarization illumination.

Let us first examine the triangular metallic aperture illustrated in Fig. 1(a). An isosceles triangle is etched into a 120 nm silver film deposited on glass substrate. The triangle has a base length of 400 nm and a height of 400 nm. The optical excitation wavelength is chosen to be 532 nm. As shown in Fig. 1(b), if the incident plane wave is linearly polarized along the x direction, the state

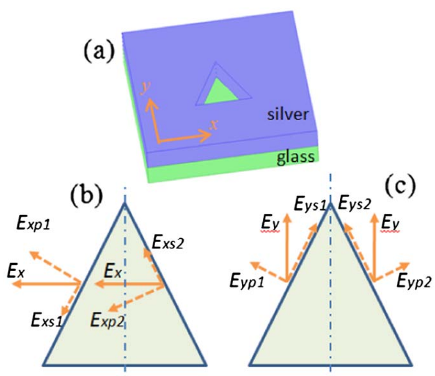

Fig. 1. (Color online) (a) Schematic diagram of an isosceles triangular slot etched into 120-nm-thick silver film. A linearly polarized beam illuminates from the glass substrate side. (b) Explanation of phase mismatch of surface plasmon excitation with x-linear polarized illumination and (c) phase match with y-linear polarized illumination.

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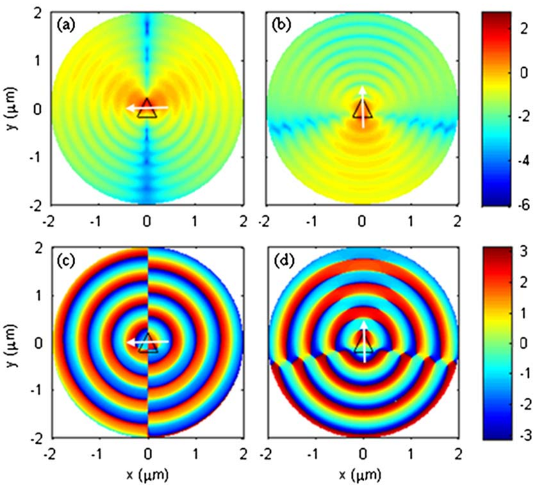

Fig. 2. (Color online) (a) Logarithmic electric energy density distribution at the air/silver interface with x- and (b) y-linearly polarized illuminations. (c) Corresponding phase distribution of longitudinal surface plasmon field with x- and (d) y-linearly polarized illuminations. The arrow line indicates the input polarization direction.

of polarization is s polarized for the base of the triangle, and is a combination of s and p polarization for the two equal sides. Only the incident beam with a p-polarized component with respect to local geometry could be coupled into surface plasmons. From Fig. 1(b), it is obvious that the p component at the left side (E_{xp1}) points from the dielectric into the metal and the p component at right side (E_{xp2}) points from the metal into the dielectric. Consequently, the surface plasmons excited on these two sides will acquire a π-phase difference that arises purely from the geometric projection. Therefore, the surface plasmons excited at these two edges interfere destructively along the axis of symmetry. On the contrary, for y-polarized illumination, the state of polarization is p polarized for the base, and is the combination of s and p polarizations for the two equal sides. Surface plasmons are excited from all three edges. Moreover, the p components at the left and right sides are in phase [Fig. 1(c)]. Therefore, the surface plasmons excited at these two edges interfere constructively along the axis of symmetry.

To verify this simple geometric analysis, a three-dimensional finite element method (COMSOL) model was developed to numerically study the surface plasmon excitation with an isosceles triangular aperture under linearly polarized illumination. The computed logarithmic energy density and phase distributions under x-polarized excitation are illustrated in Figs. 2(a) and (c). Since the triangle base is parallel to the incident field, there is no surface plasmon excitation at this side. As shown in Fig. 2(c), surface plasmons at the two equal sides have a π-phase difference, resulting in destructive interference of the surface plasmon field along the symmetry axis of the triangle. On the contrary, for y-polarized illumination, surface plasmons are excited from all three edges of the triangle. Furthermore, surface plasmons at the two equal sides are in phase [Fig. 2(d)], leading to constructive interference of plasmonic field along the axis of the triangle [Fig. 2(b)].

If these triangles are spatially arranged along a circle and illuminated by azimuthal polarization, the local polarization will be linearly polarized with respect to each individual triangle. Thus, coupling into surface plasmons occurs and each of the triangular apertures acts like a secondary wavelet source. In principle, plasmonic focusing under azimuthal polarization excitation can be achieved. However, the geometric phase effect of the isosceles triangle under linearly polarized illumination discussed above needs to be taken into consideration very carefully. To illustrate this point, eight isosceles triangles are arranged along a circle with their axes of symmetry aligned to the center of the circle (Fig. 3). Each triangle has a base length of 1.2 μm and a height of 400 nm. The distance from the base to the center is 2.2 μm. The incident beam is azimuthally polarized with a doughnut-shaped field distribution of $E_o \bullet r \bullet \exp(-r^2/w^2)$, where w is the beam waist and is assumed to be 3 μm in the following calculation. The maximum energy density of the input beam is normalized to 1. For each individual triangle, the local polarization of the illumination is polarized parallel to the base. Surface plasmons excited at the two sides of each triangle have a π-phase difference. Moreover, surface plasmons from adjacent triangles also have a π-phase difference. This phase difference leads to destructive interference of surface plasmons, resulting in a doughnut-shaped field distribution with a dark center.

A highly confined spot with size beyond the diffraction limit can be achieved with azimuthally polarized excitation through eliminating the geometric π-phase difference by appropriate spatial arrangement of the triangle orientations. As shown in Fig. 4(a), the plasmonic lens structure has 32 isosceles triangles arranged along a circle with a radius of 2.4 μm. The axis of symmetry of each triangle is aligned to the azimuthal direction. The triangle has a base length of 440 nm and a height of 440 nm. Under an azimuthal polarization illumination, at each individual triangle, the local polarization of the illumination is polarized along the axis of symmetry [similar to Fig. 1(c)]. Therefore, the surface plasmons excited at the two equal sides of a single triangle are in phase. Because of the axial symmetry of both the metallic structure and the optical

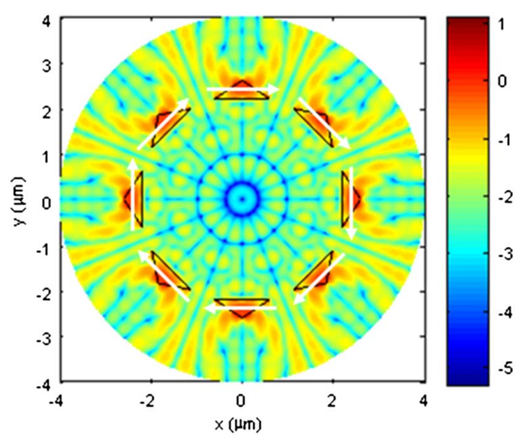

Fig. 3. (Color online) Logarithmic electric energy density distribution at the air/silver interface with eight isosceles triangles arranged in symmetric mode under azimuthally polarized illumination (illustrated by the arrows). Doughnut spot is obtained due to destructive interference of surface plasmons.

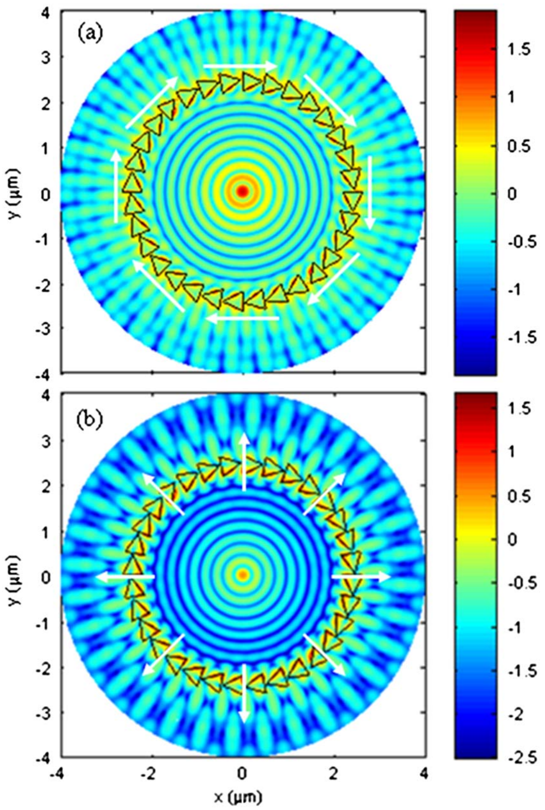

Fig. 4. (Color online) (a) Logarithmic electric energy density distribution at the air/silver interface with 32 isosceles triangles arranged in antisymmetric mode under azimuthally polarized illumination. A highly confined focal spot is obtained at the center. (b) Logarithmic electric energy density distribution of the same structure under radially polarized illumination. A solid spot with lower field enhancement is observed.

excitation geometry, surface plasmons excited by the triangles at all azimuthal directions interfere constructively to produce a bright spot at the center of the spatially arranged triangles. The field enhancement is found to be 5.90, which is comparable to the previously reported enhancement factor of a single annular metallic ring under radially polarized excitation [8]. The value of the enhancement is calculated by the ratio of the field strength at the focus to the maximum of the input field. The FWHM of the focal spot is about 186.4 nm ($\sim 0.35\lambda$). The plasmonic lens structure is optimized for the above illumination with field distribution $E_o \bullet r \bullet \exp(-r^2/w^2)$ and $w = 3$ μm. The field enhancement factor of the designed plasmonic lens varies if the illumination condition is changed. There are two components contributing to the total plasmonic field, including a longitudinal component and a transverse component. The longitudinal field component is 5.43 times the transverse component and dominates the total field distribution. The electric field near the vicinity of the focus is purely polarized along the longitudinal direction that is normal to the structure surface, generating a kind of optical "needle" field [8]. More interestingly, the same structure can also be applied to focus a radially polarized beam. As shown in Fig. 4(b), a solid spot with the same spot size and a field enhancement of 1.81 is obtained. If each triangle is rotated by 90°, the resulted plasmonic structure will defocus the azimuthally polarized illumination due to destructive interference caused by the geometric π-phase difference between the two sides of a triangle and between the adjacent triangles (Fig. 5).

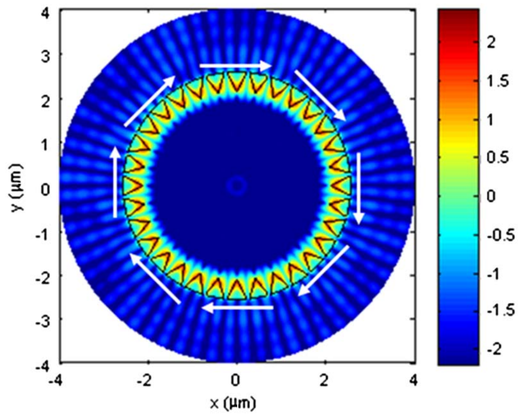

Fig. 5. (Color online) Logarithmic electric energy density distribution with 32 isosceles triangles arranged in symmetric mode under azimuthally polarized illumination.

In conclusion, a tightly focused plasmonic field can be obtained by matching azimuthally polarized illumination to spatially arranged triangular apertures. A focal spot beyond diffraction limit is obtained through constructive interference of the surface plasmon waves excited at triangular apertures at different azimuthal directions. The focusing property of this plasmonic lens exhibits strong dependence on the orientation of the triangular apertures due to a geometric phase effect. Strategies for optimizing the field enhancement factor of bull's eye plasmonic lens under radially polarized illumination can also be utilized for this novel plasmonic lens structure made of triangular subapertures, such as designing more annularly arranged triangular apertures along the radial direction, with their distances satisfying the circular Bragg condition [8]. The highly confined focal spot may find applications in optical imaging, sensing, material characterization, and biological applications.

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