Multifunctional and multi-output plasmonic meta-elements for integrated optical circuits

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Abstract: Based on a novel phase-sieve method by in-plane interference processes, a well-designed nonperiodic nanogroove array on gold surface is proposed as a multifunctional and multi-output plasmonic meta-element (MPM) for surface plasmon polariton waves. An MPM functions as a plasmonic lens (PL) as well as a plasmonic array illuminator (PAI), and another MPM acts as two PLs with an intersection angle of $\pi/4$ are fabricated and validated by leakage radiation microscopy measurements. Our proposed scheme with implemented functionalities could promote potential applications in high density integrated optical circuits.

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References and links

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1. Introduction

The aggressive pursuit of ever-increasing high levels of integration on optical circuits has been a hallmark of the industry and the academy. Unfortunately, the minimum lateral size of dielectric photonic components is limited to about half a wavelength of light by the fundamental laws of diffraction [1]. New opportunities for confining light to rather small dimensions are provided by utilizing surface plasmon polaritons (SPPs), which are hybrid modes of photons and electronic charge-density oscillations at a metal/dielectric interface [2–4]. Various planar plasmonic devices have been successfully fabricated to control the propagation of plasmonic fields because of their unique two-dimensional (2D) confinement of electromagnetic field at the metal surface. These devices include plasmonic lenses [5–7], waveguides [8–10], reflectors [10–12], interferometers [13,14], metasurfaces [15] and so on. To date, most of these devices are single-functional elements; thus, a new class of multifunctional plasmonic devices, which could be a key ingredient in achieving compact and high-speed optical system, must be developed. More recently, spatially-defined phase modulation methods for manipulating SPP propagations from a nonperiodic array were carried out and have achieved great success [16–19]. However, these approaches all have a common severe limitation, in which the SPP wavefront emerging in a specific direction is a nonperiodic array to mold SPP wavefront in multiple directions for multifunction/multi-output purpose. If this case is possible, what kind of wavefront could be constructed?

In this study, we propose a multifunctional and multi-output plasmonic meta-element (MPM) on gold films, which can control SPP wavefronts in two or four predefined directions with different functions. The MPMS were composed of uniform subwavelength grooves on the metal surface, the positions of which were determined via a novel phase-sieve method. Two MPMS were fabricated and validated. One functioned as a vertically oriented plasmonic lens (PL) as well as a horizontally oriented plasmonic array illuminator (PAI) and the other functioned as two PLs with an intersection angle of π/4. As such, multichannel and multifunction manipulations of SPPs can be directly achieved in a single component by using these devices.

2. Principle

The schematic of an MPM is shown in Fig. 1(a). A typical MPM is a set of subwavelength grooves on a gold film with a substrate, of which positions and sizes are carefully designed via a newly developed phase-sieve method that will be presented later. When the MPM is illuminated from the air side, the excited SPPs at the grooves are launched in the ±x and ±y directions, respectively. As such, multichannel and multifunction manipulations of SPPs can be directly achieved in a single component by using these devices.
lattice period, \( m \) and \( n \) are the column and row indexes, respectively. A portion of the cells is selected and fabricated into the same-sized grooves by using a focus ion beam milling system. When the MPM is normally illuminated with a plane wave, every point on the grooves functions as a point dipole source of SPPs (with an infinitesimal area of \( dS \) and a location of \( \mathbf{r}_s \)) that radiates with the same initial phase. According to the Huygens-Fresnel principle, the resulting electric field of the SPPs can be obtained by adding up the contributions from all the point sources within the grooves. The electric field at point \( \mathbf{r} \) that originates from groove \((m, n)\) is expressed in the complex phasor form when \(|\mathbf{r} - \mathbf{r}_{mn}|\) is larger than several SPP wavelengths [20]:

\[
E_{m,n}(\mathbf{r}, \mathbf{r}_{mn}) = \int_{\text{groove\ area}} A(\mathbf{r}_s) \left( \hat{z} - i \frac{k}{k_{SPP}} \frac{\mathbf{r} - \mathbf{r}_s}{|\mathbf{r} - \mathbf{r}_s|} \right) \cos(\phi_s) \exp\left( i k_{SPP} |\mathbf{r} - \mathbf{r}_s| \right) dS, \tag{1}
\]

where \( A(\mathbf{r}_s) \) is the field amplitude of the SPP point source, \( k_{SPP} \) is the propagation constant of the SPPs at the air/gold interface, \( k_z \) is the wave vector along the \( z \) direction, and \( \phi_s \) is the azimuthal angle between the polarization direction of the incident beam and the vector \( \mathbf{r} - \mathbf{r}_s \) as defined in Fig. 1(b). The integration is over the whole groove area. Since the physical process of coupling free-space light to SPPs is not included in the model of dipole source of SPPs, therefore the limitation of Eq. (1) is that it is inapplicable to deal with any problems related to the coupling efficiency and phase. As a result, it would be mandatory to resort to full-wave simulations when the coupling effect should be considered. The total electric field at \( \mathbf{r} \) is the sum of the contributions of all individual grooves:

\[
E_{\text{Total}} = \sum_{\text{groove\ \{m,n\} in \ MPM}} T_{m,n} E_{m,n}, \tag{2}
\]

where \( T_{m,n} \) is the transmission coefficient accounting for the scattering loss that the SPPs experience by crossing over other grooves. For simplicity, we assume \( T_{m,n} = t^{p_{m,n}} \), where \( t \) is the transmission over a single groove and \( p_{m,n} \) is the number of the grooves to cross. Note that the resultant SPP intensity distribution given in Eqs. (1) and (2) depends on the polarization of the incident light as well as the positions of the grooves. Hence, the question of manipulating SPP wavefronts in multiple directions becomes that of identifying the groove positions to simultaneously satisfy the prescribed field patterns in different directions. For an MPM of \( M \times N \) rectangles, \( 2^M \times 2^N \) groove position combinations are possible. In principle, a numerical method, e.g., simulated annealing algorithm, would be valid for such a global optimization problem. In this paper, a simple and feasible design algorithm named phase-sieve method, which is free of intricate numerical calculations, is used and developed as follows: i) A collection of grooves is chosen to generate the designed wavefront propagating in the fixed direction according to the designed function. The position indexes of the grooves is composed of a set \( \{(m, n)\}_1 \). ii) The second set of grooves \( \{(m, n)\}_2 \) is chosen to implement the second function in another direction. iii) The groove set \( \{(m, n)\}_2 \) of the MPM is then derived by the intersection \( \{(m, n)\}_1 \cap \{(m, n)\}_2 \). The “intersection” operation is defined to generate a groove set which is formed of elements that belong to both \( \{(m, n)\}_1 \) and \( \{(m, n)\}_2 \).
3. MPM functions as a PL and a PAI

To demonstrate this method, we initially implemented an MPM that functions as a PAI along the x-direction and a PL along the y-direction in the working wavelengths $\lambda_0 = 830$ and 873 nm (SPP wavelength $\lambda_{SPP} = 814$ and 858 nm), respectively. In general, $a_1$ and $a_2$ should be $0.5\lambda_{SPP}$ to obtain a high coupling efficiency [21]. The designed MPM has a rectangle grid ($M \times N = 61 \times 61$) with $a_1 = 410$ and $a_2 = 429$ nm, thereby making the total pattern size to be $25 \mu m \times 26 \mu m$. The reason that $a_1$ is not equal to $0.5\lambda_{SPP}$ will be discussed later.

3.1. Design method

To determine the groove set $\{(m, n)\}_1$ of the PL, the grooves in the $n$th row ($n = 0, \pm 1, \pm 2, \ldots, \pm (N-1)/2$) are arranged to contribute to a focal spot at $R_n = (0, f_n)$, where $f_n$ should be larger than $(N-1)a_2/2$ to keep the focus outside the MPM area. When illuminated by a $y$-polarized beam the selected $\{(m, n)\}_1$ should satisfy Eq. (3) to ensure the launched SPPs from the $n$th row could constructively interfere at $R_n$,

$$2(l + \varepsilon) \pi \leq k_{SPP} \left[ |R_n - (r_{m,n} \pm 0.5a_1, a_1)| - d_n \right] \leq (2l + 1 + \varepsilon) \pi,$$

where $l = 0, 1, 2, \ldots$, and $\varepsilon = 0$ or 1 for $n$ that is odd or even, respectively, $r_{m,n} \pm 0.5a_1, a_1$ are the midpoints of the lateral sides of the groove $(m, n)$ and $d_n = f_n - na_2$ is the distance from $R_n$ to the $n$th row. Equation (3) indicates that the grooves in each row form a Fresnel zone plate-like structure with a focal length $d_n$. Besides $(0, f_0)$, another focus exists at $(0, 2na_2-f_0)$ for each row because of symmetry. In general, we define two types of PLs depending on $f_n$: monofocal PLs and bifocal PLs. In the former case, $f_n$ is maintained constant, i.e., $f_n = f$. Since the period of the grid along the $y$ axis is $a_2 = 0.5\lambda_{SPP}$, the SPPs launched from all the $N$ rows constructively interfere to give rise to a focus at $(0, f)$. In the latter case, $f_n = f + na_2$, which results in $2N$ foci for the $N$-row grooves ($N$ foci on the positive $y$-axis and $N$ on the negative $y$-axis). As a consequence of coherent superposition, two focal spots with a large focal depth appeared on the two sides of the PL, which are symmetrical with respect to the $x$-axis. For the given parameters of $M$, $N$, $a_1$, $a_2$, and $k_{SPP}$, the focal positions can be estimated by $(0, \pm f) = (0, \pm (0.89f + 14.3) \mu m)$, which was obtained by linear fitting the numerical values as shown in Fig. 2. Here, we adopted a bifocal PL design with $f = 40 \mu m$, which resulted in two foci at $(0, \pm 50 \mu m)$. The resultant pattern of $\{(m, n)\}_1$ is shown in Fig. 3(a).
Fig. 2. Simulated focal length $f'$ is plotted with respect to the design parameter $f$, which is varied from 15.0 to 60.0 $\mu$m with an increment of 5.0 $\mu$m. $f'$ is determined from numerical calculation using Eqs. (1) and (2) with $t = 1.0$.

A PAI is capable of transforming a uniform plane light wave into regular arrays of plasmon spots, which is designed according to the plasmon Talbot effect [22]. Figure 3(b) shows the designed pattern of the groove set $\{(m, n)\}_2$ of the PAI, of which the unit cell consists of three $a_1 \times a_2$ grooves. The groove set $\{(m, n)\}_2$ has a period of $2a_1$ in the $x$-direction and $3a_2$ in the $y$-direction. For an $x$-polarized incident beam, any two adjacent columns of the PAI will launch a regular array of focal spots with a spacing of $3a_2$ in the $y$-direction and a repeating length of $\lambda_{SPP}/\{1-[1-(p\lambda_{SPP}/3a_2)^2]^{1/2}\}$ in the $x$-direction, where $p$ is the diffraction order of SPPs at the grooves. The MPM has $M/2$ periods along the $x$-direction and the launched SPPs at all periods should constructively interfere. Therefore, $a_1$ should be carefully chosen. Through numerical calculations, $a_1 = 410$ nm is found to be applicable. However, the designed MPM has a doubled period of $6a_2$ in the $y$-direction because the designed MPM is the intersection pattern of the groove sets of PL and PAI. As a result, the multiple spots of PAI have a period of $6a_2 = 2.6$ $\mu$m in the $y$-direction. Here, the extra phase shift and the scattering loss of SPPs crossing over a single groove are ignored.

Fig. 3. (a) Pattern of the groove set of the designed bifocal PL. The even and odd rows are drawn in red and black, respectively, for clarity. (b) Pattern of the groove set of the designed PAI. The inset is the magnified image of a part of the pattern containing four unit cells, in which one unit cell is indicated in red to guide the eyes.
3.3. Experiment

A scanning electron microscopy (SEM) image of the fabricated PAI (x-direction)/PL (y-direction) is shown in Fig. 4(a). The sample was fabricated using a focused ion beam milling system on a 50 nm-thick gold film that was sputtered onto a microscope slide glass substrate. A linear polarized laser beam from a wavelength-tunable CW Ti-Sapphire laser was normally incident upon the sample from the air side. The polarization of the light was tuned using a half-wave plate. The SPP intensity distribution was detected using a leakage radiation microscope (LRM) equipped with a high NA oil-immersion objective (100 ×, NA = 1.4), three auxiliary lenses with a focal length of 120 mm, and a charge coupled device. A spatial filter was introduced to filter out the directly transmitted light through the gold film [23].

For a \( y \)-polarized \((\theta = 90^\circ)\) incident beam with \( \lambda_0 = 873 \) nm, the LRM image of the SPP intensity distribution is shown in Fig. 4(b). The SPPs are symmetrically emanating in the vertical direction and they are focused into two focal spots at \((0, \pm 49 \mu m)\). The transverse \((x)\) and longitudinal \((y)\) intensity profiles of the upper focus are shown in Fig. 4(c), which show that the transverse and longitudinal full widths at half-maxima (FWHMs) are 1.3 and 17 \( \mu m \), respectively, by fitting them to a Gaussian profile. The PL may hold potentials for exotic applications in optical trapping and energy delivering because of its fairly large depth of focus \((\sim 20 \lambda_{SPP})\) and the high aspect ratio \((\sim 13)\) of the focus shape. To compare with the experimental results, numerical calculation was performed using Eqs. (1) and (2) with \( t = 1.0 \). Figure 4(d) shows the simulated SPP intensity distributions corresponding to Fig. 4(b). The simulated focal positions are \((0, \pm 49 \mu m)\), which are the same as the experimental results. The simulated transverse and longitudinal FWHMs of the focal spot are 2.0 and 27 \( \mu m \), respectively, which are slightly larger than the experimental results. The deviations from the experimental results are caused by neglecting the SPP-groove scattering in our model. However, the features in the experimental images are accurately reproduced in the calculated result, which means that the calculation method using the Huygens-Fresnel principle and SPP dipole sources can describe the behavior of MPMs very well and demonstrate the design principle.
When the incident laser was switched to \( x \)-polarization (\( \theta = 0^\circ \)) at \( \lambda_0 = 830 \) nm, PAI is activated. The experimental and simulated intensity distributions are shown in Figs. 5(a) and 5(b), respectively. In the \( x \)-direction, the plasmon Talbot carpets with multiple focal spots are unfolded with a high contrast. The dashed lines in Fig. 5(a) indicate the positions of three focus arrays at \( x = -32, -24, \) and \(-17 \) \( \mu \)m. The intensity profiles along these dashed lines are extracted and shown in Fig. 5(c), which reveals an averaged spot spacing and transverse FWHM of 2.6 and 1.0 \( \mu \)m, respectively. The profile at \( x = -24 \) \( \mu \)m undergoes a lateral shift by half a Talbot distance along the \( y \)-direction with respect to those at \( x = -32 \) and \(-17 \) \( \mu \)m. This result is a typical half-period revival phenomenon in the Talbot image. Therefore, the repeating length in the experiment is 15 \( \mu \)m, which is exactly the same as the simulation result.
Fig. 5. Performance of the PAI (x-direction) operated at $\lambda_0 = 830$ nm and polarization angle $\theta = 0^\circ$. (a) LRM image of PAI. The dashed lines 1, 2, and 3 indicate the positions of $x = -32$, $-24$, and $-17$ $\mu$m, respectively. (b) Simulated SPP intensity distribution. The white box marks the MPM boundary. (c) Intensity profiles along the dashed lines in (a). The curves were offset for clarity.

Fig. 6. LRM images of the MPM at $\lambda_0 = 800$ (a), 809 (b), 820 (c), 830 (d), 840 (e), 850 (f), 860 (g), 873 (h), and 880 nm (i) for polarization angle $\theta = 45^\circ$. 
The MPM also functions as a demultiplexing element because the two functions are designed for different wavelengths. To investigate its demultiplexing properties, the experimental results corresponding to the incident light wavelength $\lambda_0$ from 800 to 880 nm with a fixed polarization $\theta = 45^\circ$ are shown in Fig. 6. At $\lambda_0 = 830$ nm, which is the design wavelength of PAI, only the function of PAI is available. The launched SPPs propagating along the $\pm y$-direction are fairly weak and have no focal spot at all. When the incident wavelength was tuned to 873 nm, which is the design wavelength of PL, two strong focal spots are obtained on the $y$ axis, and the launches of SPPs along the $\pm x$-direction are restricted. Therefore, such a device implements different functions for different incident wavelengths. In addition, the two functions can be also being designed for the same working wavelength by tuning the grid size.

4. MPM with non-orthogonal outputs

Thus far, we demonstrated an MPM with mutually perpendicular outputs. Essentially, directions of the outputs can be tuned using non-orthogonal grids. To this end, a rhombic grid is employed to implement an MPM with two monofocal PLs operating along the directions of $\pm y$ axis and $[\pm 1, \pm 1]$. The design wavelengths are 809 and 873 nm ($\lambda_{SPP} = 793$ and 858 nm), respectively. The primitive lattice vector basis $a_1$ is along $+x$ axis and $a_2$ along $[-1, +1]$ with $a_1 = 607$ nm and $a_2 = 561$ nm as shown in Fig. 7(a). The groove set $\{(m, n)\}_1$ of the PL along the $y$-direction is determined by applying Eq. (3) with $f_s = 52 \mu m$, which corresponds to a focus at $(0, 52 \mu m)$. With a designed focus at $R = (37 \mu m, 37 \mu m)$, the groove set $\{(m, n)\}_2$ of the second PL could be generated using Eq. (4),

$$
(2l+\epsilon)\pi \leq k_{SPP} \left[ |R - (r_{m,n} \pm 0.5a_i a_j)| - d_m \right] \leq (2l+1+\epsilon)\pi, \quad (4)
$$

where $l = 0, 1, 2, \ldots$, and $\epsilon = 0$ or 1 for $m$ that is odd or even, respectively, $r_{m,n} \pm 0.5a_i a_j$ are the positions of the midpoints of the upper and lower sides of the groove $(m, n)$, and $d_m$ is the distance between the focus and the $m$th column, which is located on the line $y = x + ma_1$.

Figure 7(b) is the SEM image of the MPM with an $M \times N = 61 \times 61$ rhombus grid. The entire footprint is $24 \mu m \times 37 \mu m$. Figures 7(c) and 7(d) are the LRM images recorded at $\lambda_0 = 809$ and 873 nm, respectively, with a fixed polarization angle $\theta = 77.5^\circ$. The SPPs are efficiently launched in the $[0, +1]$ and $[+1, +1]$ directions and converged into foci at $(0 \mu m, 51 \mu m)$ and $(38 \mu m, 38 \mu m)$, respectively. For the incident wavelength of $\lambda_0 = 840$ nm, which is between the two design wavelengths, no focal spot can be found, as shown in Fig. 7(e). In this work, rectangular and rhombic grids were used and the current designs essentially show different functionalities for two directions. In principle, it is possible to expand our designs to three or even more directions by using a triangular, hexagonal or octagonal grids. The challenge is that, in such cases, the resultant groove set $\{(m, n)\}$ is derived by intersection of more than two groove sets $\{(m, n)\}_1 \cap \{(m, n)\}_2 \cap \{(m, n)\}_3 \ldots$. Therefore, a small number of grooves are retained in $\{(m, n)\}$, which inevitably degrades the performance. One possible solution is to expand the device footprint (larger $M$ and $N$), so that more grooves would be included. As a result, a tradeoff has to be made between the functionality and the compactness of the device. Recently, polarization-dependent SPP unidirectional excitation using circular polarization are realized where the direction of SPP excitation can be well controlled by changing the helicity of the incident light [24,25]. To respond to circular polarization, more complicated building-blocks for the MPMs are desired and the design method should be improved correspondingly.
5. Conclusions

In conclusion, we proposed and demonstrated a multifunctional and multi-output meta-element for controlling SPPs by using well-designed nonperiodic subwavelength groove arrays. We integrated a PL and a PAI in an MPM with perpendicular output directions. We also show that the directions of the outputs are tunable by simply altering the grid geometry. The agreement between the experimental and simulation results shows the feasibility of the proposed phase-sieve method. The method offers a new way of achieving a high density of functionality and effectively scales down the size of integrated optical circuits.

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