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Dynamic cosine-Gauss plasmonic beam through phase control

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Abstract: We carry out an approach to dynamic manipulation of a nondiffracting cosine-Gauss plasmonic beam (CGPB) illuminated with an incident phase modulation within nanostructures by a spatial light modulator (SLM). By changing the hologram addressed on the SLM, dynamic control on the lobe width and the propagating direction of the CGPB is experimentally verified. Finally, we demonstrate an application example of this dynamic CGPB in routing optical signals to multichannel subwavelength wave guides through numerical simulation.

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References and links
1. Introduction

Surface plasmon polaritons (SPPs) have the ability to confine electromagnetic field at the metal-dielectric interface to deep subwavelength scale [1–3], which makes it attractive for applications in the field of integrated plasmonic circuit to significantly miniaturize the size of current optical devices [4]. Consequently, various on-chip plasmonic devices such as lenses [5–7], waveguides [8], splitters [9] and demultiplexers [10] have been proposed. Recently, to avoid attenuation caused by diffraction in SPPs propagation, nondiffracting SPPs waves, for example the plasmonic Airy beam, have been introduced [11–14]. The plasmonic Airy beam can propagate without diffraction in a finite distance [11], however, its parabolic and asymmetry trajectory severely limit the possible applications [15, 16]. To solve this problem, a new kind of nondiffracting SPPs wave, which is referred to as cosine-Gauss plasmon beam (CGPB) [16–18], was proposed based on the earlier works of non-diffracting beam in free space [19–21]. The CGPB, generated by intersecting metallic gratings [16] or nonperiodic nanohole array [15] on a metal film, can propagate in a straight line without diffraction. However, the main focus of that work is shining on the physical properties of this beam in a fixed structure and it is difficult to dynamically reconfigure the properties of CGPB based on such permanent structures.

In this Letter, we demonstrate the dynamic control of CGPB and its potential application in on-chip plasmonic devices. A simple metallic grating consisting of three grooves fabricated on a gold film is used as a plasmonic launcher (inset Fig. 1(a)) for CGPB generation. By coupling light with designed phase distribution provided by a spatial light modulator (SLM), we generate the rectilinear propagating CGPB and show its nondiffracting nature in a finite distance. By varying the hologram addressed on the SLM, we dynamically control the width of CGPB lobes and its propagating direction. We finally show a practical application example of such dynamic CGPB in routing optical signals to multichannel subwavelength waveguides. This work provides an easy-to-use method to dynamically route the energy flow of SPPs on metallic surfaces, which has great potential in reconfigurable optical interconnections.

2. Experimental setup

The experimental setup is shown in Fig. 1, and the schematic of modulation principle is shown in Fig. 2(d). An expanded He-Ne laser beam (λ = 632.8 nm) first impinges a prism splitter and reflects to an SLM to obtain the desired phase modulation. Then the modulated light impinges onto the metallic grating through an inverse arranged telescope system to excite SPPs. In order to adjust the inverse telescope system more conveniently, the first lens (L1 in Fig. 2(d)) is directly written into the hologram carried by the SLM [22] and the other lens (L2 in Fig. 2(d)) is the objective lens. The polarization of the beam is perpendicular to the
metallic grating adjusted by a half-wave plate for SPPs excitation. The grating was milled by a focused-ion beam (FIB) on an Au film evaporated onto a $24 \times 60$ mm$^2$ cover glass. The thickness of the Au film was chosen to be 220 nm in order to eliminate light transmission through it and to ensure that the SPPs generated at both interfaces do not interfere. By modifying the hologram carried by the SLM, we can dynamically modulate the properties of CGPB, such as the width of the lobes and the propagating direction of the CGPB. A near-field scanning optical microscope (NSOM) is used to detect the transverse electric intensity distribution of the SPPs on the metal film. It is also worth noting that the exciting beam in our experiment was incident from the bottom to avoid the mixture of incident beam and excited SPPs on the top of gold film.

### 3. Generation of CGPB

First, we demonstrate the generation of the CGPB through our system. For grating coupling, the magnitude of the out-of-plane electric field component $|E_z^{SP}|$ is much larger than the in-plane ones $|E_x^{SP}|, |E_y^{SP}|$ and the phase differences between all the electric field components are constant. Therefore, the $z$-component of the electric field plays a primary role in excited SPPs field, and the out-of-plane component and the in-plane components are similar in intensity distribution and the reference [23] had verified this through numerical simulations. Hence, we only consider the distribution of $E_z^{SP}$ in our analytical model presented below. The 2D Huygens-Fresnel principle is used as our theoretical model to calculate the SPPs field [24]:

$$E_z^{SP}(x, y) = \frac{i}{\sqrt{\lambda_{SP}}} \int E_z^{SP}(x_0 = 0, y_0) e^{\frac{i\pi}{\lambda_{SP}} z \cos \theta} e^{i\rho^2/\sqrt{\rho}} d\rho$$

(1)

Where, $\lambda_{SP} = 613nm$ is the wavelength of SPPs in our experiment, $E_z^{SP}(x_0 = 0, y_0)$ indicates the complex amplitude of SPPs field at point $(0, y_0)$. Term $\rho = \sqrt{x^2 + (y - y_0)^2}$ denotes the distance between point $(x, y)$ and point $(0, y_0)$, $\theta$ is the angle between $x$-axis and the vector $\rho$ pointing from source point $(0, y_0)$ to point $(x, y)$ and $\cos \theta = x / \rho$. In the theoretical model, each point of the grating along the $y$-axis acts as an SPPs point source and generates 2D spherical waves $(\cos \theta e^{i\phi}/\sqrt{\rho})$ travelling in all directions with cosine angular distribution and decreasing with the distance by $1/\sqrt{\rho}$. The complex amplitude of SPPs point sources at point $(0, y_0)$ $(E_z^{SP}(x_0 = 0, y_0))$ is proportional to that of the excitation beam, and the phase distribution is the same as that of the incident light. By summing surface waves
generated by all the SPPs point sources located at the grating, we obtain the resultant SPPs field. When the phase distribution of incident beam is modulated by a pure phase distribution 
\[ \phi(x, y) = -k_0 y \sin \alpha \] (where \( k_0 \) is the wavevector of incident beam) provided by the SLM, a CGPB is excited on the metal surface with its lobe width dynamically controlled by \( \alpha \). The parameter \( \alpha \) is simply the rotation angle of the modulated beam and it is presented more clearly in Fig. 2(d). The rotation angle of the incident beam after the objective lens (\( L_2 \)), which is denoted by \( \alpha_0 \), is magnified by the telescope system (\( L_1 \) and \( L_2 \)) with a magnification factor of \( M = f_1 / f_2 \) (\( f_1 \), \( f_2 \) denote the focal distance of lens \( L_1 \) and \( L_2 \) respectively) and thus \( \tan \alpha_0 = M \tan \alpha \). According to Eq. (1), we build an analytical model and numerically calculate the SPPs distribution as shown in Fig. 2(a). The parameters used in calculation are \( k_0 = 2\pi / 632.8 \text{nm}^{-1} \), \( \alpha_0 = 0.03^\circ \), \( M = 154 \), \( \alpha_0 = 4.61^\circ \) and \( y_m \in [-7.5, 7.5] \mu \text{m} \). To verify the validity of the analytical model, the corresponding 3D finite-difference time-domain (FDTD) simulation results are demonstrated in Fig. 2(b), and the corresponding experimental results detected by a NSOM are shown in Fig. 2(c). The three results obtained by the analytical model, the FDTD simulation and the NSOM measurement are found in a good agreement within the SPPs field distributions. It is noted that the propagation distance of the CGPB in our experiment is not as long as that in [16], because the grating length in our experiment is shorter and the crossing angle between the two interferential SPPs plane waves is smaller. Figure 2(e) and Fig. 2(h) demonstrate the normalized transverse profile of the SPPs filed at two different propagating distances (location A and B in Fig. 2 (c)). The nearly invariable transverse size between Fig. 2(e) and Fig. 2(f) indicates the nondiffraction nature of CGPB. The CGPB disappears when we rotate the half-waveplate by 90° to shift the polarization of incident light from TM to TE, verifying that what we observed is the SPPs field which is only excited at TM polarization.

Fig. 2. CGPB generated by wavefront modulation, where \( \alpha = 0.03^\circ \). The near-field intensity distributions obtained from (a) theoretical calculations (\( z \)-component), (b) FDTD simulations (in-plane component) and (c) experimental results (in-plane component) of electric field intensity measured by a NSOM. (d) Schematically show the modulation process. After modulated by the SLM, a plane wave separates into two independent ones and focused into two points on the back focal plane \( (P_1) \) of the objective lens \( (L_2) \). Then the two points recover to two plane waves after passing through the objective lens and interfere on the grating plane \( (P_2) \). (e), (f) Normalized transverse intensity distributions at locations A and B [red curve, theoretical calculations; green curve, FDTD simulations; blue curve, experimental results].
4. Dynamic modulation of CGPB

Then we experimentally demonstrate the dynamic modulation of the CGPB’s lobe width through phase control of the incident beam. As mentioned above, we can modulate the CGPB’s lobe width by varying the parameter $\alpha$, which is equal to changing the cross angle between the two plane waves generated by the SLM. So we only need to switch the hologram loaded on SLM to control the CGPB. In the experiment, we continuously change the hologram with parameter $\alpha$ increasing from 0.02 to 0.09 degree in the step of 0.01 degree, and monitor the corresponding SPPs distributions by NSOM as shown in Fig. 3(a) to 3(h), where the lobe width decreases from 3 $\mu$m to 0.682 $\mu$m and more lobes appear. Figure 3(i) shows the full width at half maximum (FWHM) of the CGPB lobes as a function of parameter $\alpha$. The solid red triangles indicate experimental results and the blue curve represents the theoretical results, presenting a good agreement.

![Fig. 3](image)

Fig. 3. Dynamic modulation of the CGPB’s lobe width. From Fig. 3(a) to Fig. 3(h), the parameter $\alpha$ increases from 0.02 to 0.09 degree in the step of 0.01 degree and the corresponding lobe width decreases from 3 $\mu$m to 0.682 $\mu$m. Figure 3(i) gives the FWHM of the CGPB’s lobes as a function of parameter $\alpha$. All other parameters are as in Fig. 2.

![Fig. 4](image)

Fig. 4. Dynamic modulation of the CGPB’s propagating direction. (a), (c) are analytical calculations with parameter $\beta = -0.06^\circ$ and $\beta = 0.06^\circ$, the CGPB propagate in the direction of $-9.16^\circ$ and $9.16^\circ$ with respect to the x axis. (b) and (d) are the corresponding experimental results imaged by NSOM. All other parameters are as in Fig. 2.

Next, we demonstrate the dynamic manipulation of the propagating direction of CGPB. By adding a blazed phase $-k_o \sin \beta \cdot y$ to the hologram, the modulating phase of SLM becomes $\phi(x, y) = -k_o \left( |y| \sin \alpha + y \sin \beta \right)$, where $\beta$ denotes the inclined angel of the whole light after the modulation of SLM and plays a key role for dynamically controlling the CGPB’s propagating direction. Then we can manipulate the flow of the CGPB by changing $\beta$, which is equal to inclining the whole wavefront of the excitation beam after the objective lens $L_2$ by an angle $\beta$, $(\tan \beta_2 = M \tan \beta)$, denotes that the inclined angle of the whole incident beam after the lens $L_2$ is magnified by the telescope system with a magnification factor $M$. Since the initial phase distribution of excited SPPs is the same as the excitation beam, the propagating direction of the SPPs is in the angle of $\beta$ with respect...
to the $x$-axis ($\beta_x > 0$ propagate below $x$ axis and $\beta_x < 0$ propagate above $x$ axis). We show the SPPs field distribution of the CGPB by the analytical model with $\beta = -0.06^\circ$ ($\beta_x = -9.16^\circ$) in Fig. 4(a) and $\beta = 0.06^\circ$ ($\beta_x = 9.16^\circ$) in Fig. 4(b), respectively. The corresponding experimental results shown in Fig. 4(c) and Fig. 4(d) agree well with the theoretical calculations.

Finally, we demonstrate an application example of this dynamic CGPB in routing optical signals to multichannel subwavelength waveguides through FDTD simulation. The dynamic CGPB’s unique properties of lobe width controlling and nondiffraction ensure higher coupling efficiency and less propagation loss than standard SPPs in dynamic routing with multichannel. The detailed arrangement is shown in the inset of Fig. 5(a). The strip waveguide array was fabricated on the gold film and assumed to be PMMA with refractive index 1.49, width 150 $nm$, thickness 250 $nm$ and centre-to-centre separation 1.5 $\mu m$. By changing the parameter $\beta$ with discrete value of $-0.15^\circ$ ($\beta_x = -21.96^\circ$) and $0.15^\circ$ ($\beta_x = 21.96^\circ$), the optical energy of the CGPB are efficiently routed between the upper three waveguide channels or the lower three ones, as shown in Fig. 5(a) and 5(b), respectively. Here we only use the simplest multichannel structures, actually the structures can be designed to optimize the coupling efficiency between CGPB and waveguides. For the flexibility to dynamically adjust the multichannel coupling using an SLM, this method has great potential in on-chip optical communications.

![Fig. 5. The dynamic coupling between CGPB and multichannel waveguides. In Fig. 5(a), with parameter $\beta = -0.15^\circ$ ($\beta_x = -21.96^\circ$), the optical energy was coupled into the above three waveguides and (b) $\beta = 0.15^\circ$ ($\beta_x = 21.96^\circ$) into the bottom three ones. The detailed arrangement was shown in the inset of Fig. 5(a). Light green color part is the waveguides and yellow part is the Au surface. The thickness and width of the stripe waveguide are 250 $nm$ and 150 $nm$, respectively. All other parameters are as in Fig. 2.](image)

## 5. Conclusions

In summary, we have theoretically and experimentally demonstrated a simple method to generate a dynamic cosine-Gauss plasmonic beam by changing holograms addressed on the SLM. In this method, we dynamically controlled the lobe width and the propagating direction of this beam, and illustrated its possible use in dynamic routing with multichannel subwavelength waveguides. More plasmonic beams could be generated and dynamically manipulated using this method, such as intensity-preserved “lossless” SPPs beam [15] and plasmonic void arrays [25, 26]. Because of the flexibility, this method could contribute to more applications in dynamic on-chip optical interconnections and nanoparticle manipulations.

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