

# Interference of Multiple Surface Plasmon Polaritons

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**Abstract** Benefiting from strongly electromagnetic confinement and enhancement effects, surface plasmon polaritons (SPPs) hold great promises for tailoring light on micro and nanoscale. By contrast with previous efforts which massively concentrate on localized SPP mode, we investigated the propagating SPPs in this paper. A number of symmetrical gratings on metal surface are employed to excite multiple SPPs. Interestingly, the exotic interfering phenomena have been observed. They show good agreement with free-space interferences and take advantage of precise controllability. These findings will be promising in the applications of optical tweezers and SPP lithography.

## 1. Introduction

Surface plasmon polaritons (SPPs) typically originate from the interface between noble metal and dielectric layers. Through coupling incident light onto a particle or a curved surface, a very significant near-field confinement will be brought about due to the small volume of localized surface plasmon mode. As a consequence, the confinement will lead to an extreme enhancement, i.e. electric or magnetic hot spot, which intrinsically offers a promising tool for bio-sensing and detecting, such as surface enhanced Raman scattering (SERS) and surface enhanced fluorescence (SEF). Besides them, SPP as a versatile tool has also been used in a broad range of applications, e.g. nano lithography, optical trapping and integrated optoelectronics.

Since individual SPP carrying finite energy inevitably suffers from a high attenuation, the progress of SPPs has faced challenges in expanding the propagation length in order to fill the gap between electronics and photonics interconnections. Lin et al. presented a non-diffraction plasmonic beam by means of two coupling gratings[1]. The near-field profile of the singular SPP was observed experimentally and it's bounded to a tightly narrow line up to 80  $\mu\text{m}$  distance on the Au surface. Wei et al. adopted a similar strategy but achieved dark channel SPP via the phase-shifted gratings[2]. With a lateral displacement at the adjacent endpoint of two gratings, the launched SPP was modulated to parallel distribution. Furthermore, they rationally tuned the intersecting angles of four metal nanoslits. The designed structure produced a self-imaging surface plasmon void array, which can be regarded as a 2D surface bottle beam array[3]. Although the above accomplishments are non-intuitive, the

underlying interpretation can be attributed to the multi-beam interference phenomenon. Compared with the counterpart of free-space optical elements, two-dimensional surface polariton optics is an ideal candidate for manipulating and directing SPP beams arbitrarily.

In this paper, we have systematically investigated the interference of multiple SPP beams. Through theoretical analysis and numerical simulation, it is demonstrated that the distribution of multiple SPPs interference shows good agreement with that of free space optical cases. Nevertheless, the planar interference of two-dimensional surface waves has numerous advantages: (i) miniaturization; (ii) theoretical limitation of interference period ( $\lambda/2$ ), (iii) precise control of phase shift, (iv) extraordinary interfering patterns. These promising potentials will facilitate the progress of SPPs in the applications of optical tweezers and SPP lithography.

## 2. Principle of Multiple SPP interference

A general form of  $N$  SPP-beam interference can be described as the superposition of electric field vectors of  $N$  surface waves ( $\vec{E}_1, \vec{E}_2, \vec{E}_3, \dots$  and  $\vec{E}_N$ ), as formulated below

$$\vec{E}_m = A_m \vec{P}_m \cos(\vec{k}_m \cdot \vec{r} - \omega \cdot t + \varphi_m) \quad (1)$$

In the electric field vector,  $\vec{k}_m$  and  $\vec{P}_m$  can be expressed by

$$\vec{k}_m = k(\sin\theta_m \cdot \cos\varphi_m \cdot \vec{i} + \sin\theta_m \cdot \sin\varphi_m \cdot \vec{j} - \cos\theta_m \cdot \vec{k}) \quad (2)$$

$$\vec{P}_m = \sin\phi_m \cdot \vec{i} - \cos\phi_m \cdot \vec{j} \quad (3)$$



where  $A_m$  is the amplitude,  $\vec{p}_m$  is the unit polarization vector,  $\vec{k}_m$  is the vector in the propagation direction,  $\vec{r}_m$  is the position vector,  $\omega$  is the frequency,  $\phi_m$  is the initial phase,  $k = 2\pi/\lambda$ ,  $\lambda$  is the wavelength,  $\theta_m$  is the incident angle,  $\phi_m$  is the azimuthal angle, respectively.

We utilized a series of gratings for the excitement of SPPs. The metal layer is selected to Ag and the effective wavelength of SPP is 613 nm for the incident 633 nm laser. Each nanoslit is the length of 10 micrometers and the width of 100 nanometers. A grating is composed of three nanoslits and the pitch is 613 nm for the maximum efficiency. When these gratings distribute as an axially symmetrically array, multi-beam propagating SPPs will take place and the interference occurs at the central area. We used the finite-different time-domain (FDTD) method to carry out the numerical simulations. As shown in the Fig. 1, three-beam and four-beam SPP interferences have been found. Specially, three-beam interference generates a triangle pattern and four-beam interference generates a square pattern.

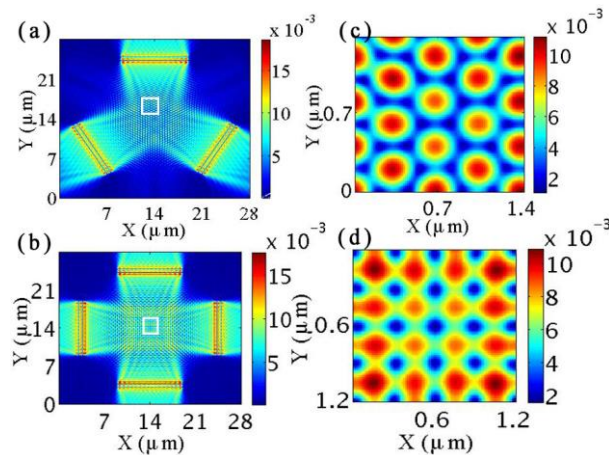


Fig. 1 Planar interference of SPP. (a) Three-beam SPP interference; (b) For-beam SPP interference; (c) and (d) represents the enlarged pattern which is highlighted by a square in (a) and (b), respectively.

Interestingly, the distribution of multiple SPPs is in accordance with those of free-space cases<sup>[4]</sup>. It's well known that the period interference is equal to  $(\lambda/2) \times \sin \theta$ , where  $\theta$  is the incident angle. It means that the theoretical limitation of laser interference lithography is a half of incident light, however, in practice, it's no way to achieve such purpose. By contrast, in the case of planar interference, the period can reach to limitation as the incident angle is inherent equal to 90 degree. Moreover, up to now there is few effort about six-beam interference in free space. Because when the number of interfering beams is over four, the interference is very complicated and hard to

control. A very slight offset of incident angle or phase will give rise to the resulting pattern significantly<sup>[5]</sup>. As shown in Fig. 2, we can control the phase shift by adjusting the grating location. The capability of phase controllability is important to obtain extraordinary interfering pattern, i.e. periodic honeycomb structures. It's also regarded as a 2D bottle beam.

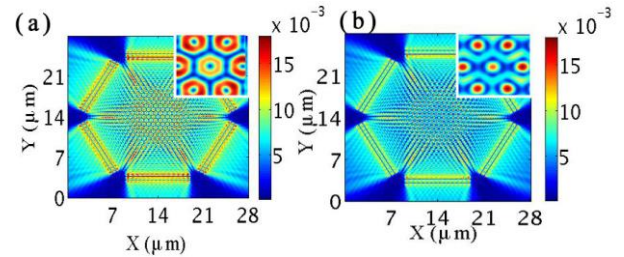


Fig. 2 The phase-shifted six-beam SPP interference. (a) no phase shift; (b)  $\pi/2$  phase shift of one of six beams

### 3. Conclusion

We systematically investigated the multiple SPP interference. By comparing with free-space interference, the planar counterpart has numerous advantages, such as minimum limitation of period, miniaturization and controllability of phase. When the number of interfering beam is up to 6, we found the exotic interfering pattern. As a consequence, the method is promising to the applications of optical tweezers and SPP lithography.

### Acknowledgment

This work is partially supported by the National Natural Science Foundation of China under Grant Nos. 61427819/61138003/61675136, the Science and Technology Innovation Commission of Shenzhen under grant No. KQTD2015071016560101.

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