Interference of Airy surface plasmons

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Abstract

We study theoretically and experimentally the interference of two Airy surface plasmons. We investigate the variation of the focal spot for different separation distance between the beams. We find that the focal maxima is very sensitive to the phase difference between the interfering waves. We also show that the position of the focal spot can be controlled by the tilt of the incident beam. We observe that even a slight change of the angle of incidence leads to a significant shift of the spot. Unique properties of Airy surface plasmons can find an application in plasmonic circuitry and optical surface tweezers.

1. Introduction

Non-diffracting Airy waves were theoretically predicted in 1979 by Berry and Balazs [1] and were recently extended to surface polariton waves propagating on a smooth metal surface [2, 3, 4, 5]. In addition to the unique properties of the non-spreading beams in free space, Airy surface plasmons tightly confine radiation energy near metal-air interface. Similar to their 3D counterparts Airy plasmons do not diffract inside their diffraction free zone, they propagate along a parabolic trajectory, and recover their shape after passing through obstacles. These properties make Airy waves attractive for plasmonic circuitry applications and surface manipulation of nano-objects.

One of the most remarkable properties of the Airy waves is their interference. Efremidis and Christodoulides [6] have shown that in free space a radially symmetric Airy packet exhibits abrupt focusing, where the intensity in the focal region dramatically increases by up to 3 orders of magnitude. However, to date the interference of Airy waves have not been considered for Airy plasmons. Even though we cannot expect such a strong field enhancement in the focus of two Airy plasmons due to the metal losses, the study of the interference of non-diffracting surface waves represents an important step on the way to practical applications. In this work we investigate experimentally and numerically the interaction of two Airy plasmons generated by a specially designed diffraction gratings and describe the main properties of their interference pattern.

2. Fabrication and experimental setup

We fabricate the diffraction gratings to excite Airy plasmons in a 150 nm thick gold film deposited on a glass substrate [Fig. 1(a)]. The pattern is milled using a Focused Ion Beam (FIB) nano-fabrication

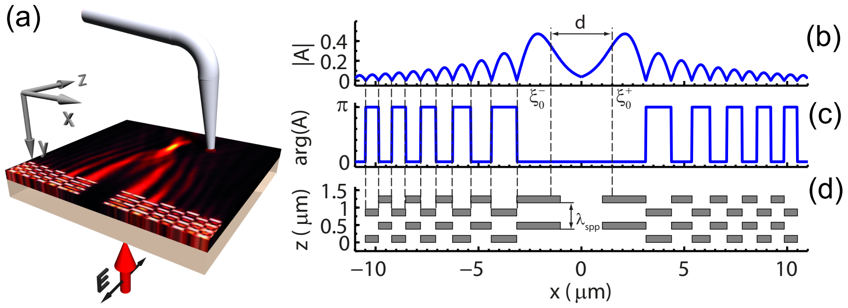

Fig. 1: Generation of Airy plasmons: (a) Schematic of the experimental setup with the engineered grating. Each grating is composed of 11 periods of 200 nm thick slits (in z-direction) and varying width in x-direction. The grating is excited from the glass substrate side with a broad Gaussian beam at 784 nm and polarization perpendicular to the slits. (b, c) Absolute value and phase of the amplitude function of the Airy plasmon. The main lobe half width is $x_0 = 700\,\text{nm}$. ξ_0^- and ξ_0^+ indicate local argument (x-coordinate) zeros of the left and right Airy functions. (d) Grating geometry for generation of Airy plasmons. $\lambda_{\text{SPP}} = 764\,\text{nm}$ denotes the SPP wavelengths.

technique. The design of the grating is discussed in detail in our previous work [3]. The pattern couples radiation from free space to surface-plasmon polariton (SPP) modes applying simultaneously the required phase and amplitude modulation. Plasmonic excitation is achieved by the repetition of the pattern with a period equal to SPP wavelength $\lambda_{\text{SPP}} = 764\,\text{nm}$ [Fig. 1(d)]. At the same time phase modulation of π is applied by the shift of neighbour columns by the half of SPP wavelength [Fig. 1(c-d)].

We prepare a number of patterns with different separation distance d [Fig. 1(b)] between the gratings. The samples were illuminated then from the bottom by a linearly polarized laser beam at $\lambda_0 = 784\,\text{nm}$, wide enough to ensure homogeneous illumination of the patterned areas. The angle of incidence can be varied in the setup. We measure near-field distribution at the metal-air interface by a Scanning Near-Field Microscope (SNOM) Nanonics MultiView 4000. Experimental results are compared with FDTD simulations done with a commercial software package RSoft.

3. Results and discussion

When the diffraction pattern is illuminated, a bright narrow focal spot appears at the intersection of two main lobes of Airy plasmons. The position of the spot depends on the separation distance between the gratings d. In Fig. 2 we present the results of the near-field measurements and the corresponding numerical simulations for Airy plasmons with separation distances of $d = 1.5, 3.0$, and $5.0\,\mu\text{m}$, respectively. The numerical (a-c) and experimental (d-f) field maps demonstrate a good agreement. In the experiment the main lobes of the generated plasmons are slightly wider than in the numerics, which leads to a little expansion and lower contrast of the focal region. Our studies show that the width of the focal region rapidly decreases until separation distance of $3.0\,\mu\text{m}$ and after that asymptotically tends to a certain limit. The intensity maxima decreases monotonically with a separation distance for a paraxial solution obtained following Ref. [2] [[Fig. 2(g)]. Non-paraxial solution, as it is in our experiments, demonstrates more complicated behavior. The intensity firstly decreases but then reaches a local maxima at around $d = 2.0\,\mu\text{m}$ and after that goes down monotonically.

The position of the maxima in the interference pattern is very sensitive to the angle of incidence of the excitation beam. Thus, according to FDTD simulations for a grating with separation distance of $d = 2.5\,\mu\text{m}$ the variation of the illumination angle by 5° causes a focal spot shift by $1.3\,\mu\text{m}$ along x-direction and for the angle of 10° the spot moves by $2.3\,\mu\text{m}$. The dynamics was also observed experimentally. The dependence of the focal spots position on the incident angle of the excitation beam can be utilized for the control of the location of the intensity maxima opening new possibilities for on chip particle

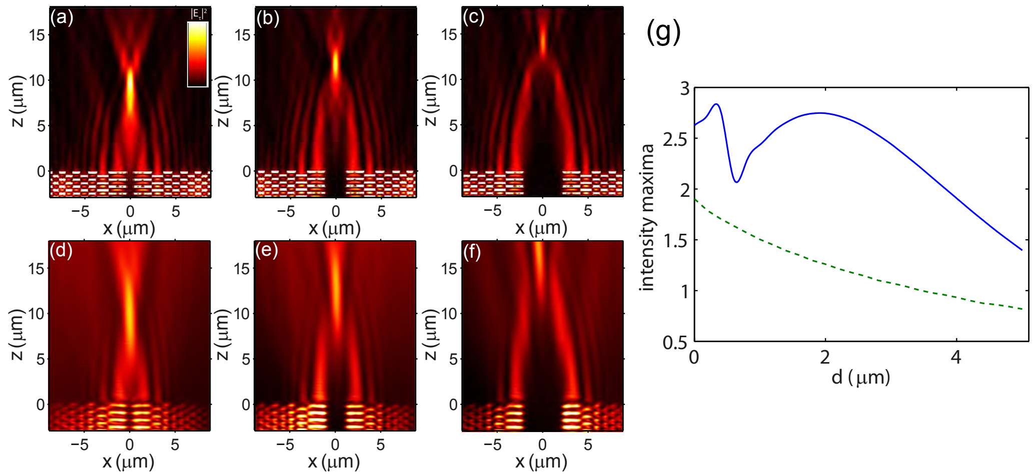

Fig. 2: Tangential component of electric field calculated by FDTD (a-c) and measured by SNOM (d-f), for $d = 1.5\,\mu$m (a,d), $d = 3.0\,\mu$m (b,e), and $d = 5.0\,\mu$m (c,f). (g) Simulated normalised intensity maximum versus separation distance d for non-paraxial ($x_0 = 0.7\,\mu$m, solid curve) and paraxial ($x_0 = 1.0\,\mu$m, dashed curve) solutions.

manipulation.

Our study also shows that the interference pattern is highly dependant on the relative phase shift between the interfering Airy plasmons. The phase shift can be introduced via the dislocation of one of the diffraction patterns along z-direction. In this case the focal spot does not deviate from the centre but rather looses its intensity and when the phase shift reaches π becomes inseparable from the background. When the phase offset is equal to 2π the focus appears again demonstrating brightness and shape very similar to the initial picture despite the launch position of one of the Airy plasmons is shifted by one SPP wavelength. Field maps demonstrating this dependence were simulated by FDTD as well as observed experimentally.

3. Conclusion

In conclusion, we have studied experimentally and numerically the interference pattern of Airy plasmons. We have observed a strong focal spot at the intersection of two main lobes and we have investigated the dynamics of the focal region for different separation distance between the grating. We have shown that the tilt of the incident beam causes the shift of the intensity maxima in x-direction. In contrast to that a phase offset of one of the Airy plasmons affects the intensity maxima. The described interference properties can be useful for plasmonic circuitry applications and for the design of surface optical tweezers.

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