Bandgap Tuning in Plasmonic Gratings

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Abstract

We investigate plasmon excitations on thin gold films coated with PMMA grating structures both, in the near field, using a scanning near field optical microscope (SNOM) and in the far field. The dependence of the size and energetic position of a bandgap on structural parameters like grating height and filling factor f is examined. With far field reflection measurements we discover a shift of the bandgap to lower energies with increasing f and we noticed a significant change in the bandgap's size ΔE which can be tuned with structural parameters.

1. Introduction

Motivated by a wide range of possible applications [1] the availability of state-of-the-art fabrication methods for implementing nanostructures, high-sensitivity optical characterization techniques and the rapid advance in computing power opened up new opportunities for the field of nanoplasmonics. Due to its ability to encode a lot of information in strongly confined waves at optical frequencies, plasmons are thought to embody the strongest points of both optical and electronic data transfer. Here we explore the possibility to tailor the frequency and the spatial mode profile of plasmons on gold films coated with PMMA gratings.

2. Sample and Measurement Setup

Our samples are prepared as follows: We evaporate a layer of chromium (10 nm) followed by a layer of gold (80 nm) on a SiO_2 glass substrate. Subsequently, we use electron beam lithography to structure 200 μm x 200 μm sized gratings with varying filling factors in PMMA electron resist. We define the filling factor $f = g/p$ as the ratio between the grating bar width g and the gratings period p, i.e. a plane gold film without grating corresponds to $f = 0$ and a gold film with a plane PMMA layer corresponds to $f = 1$. A grating period of $p = 750$ nm was chosen to excite surface plasmons in the visible [2]. Based on SEM images the filling factors for each grating is determined.

The plasmon excitation strongly depends on the external illumination configuration. We realized a setup which allows simultaneous near and far field measurements with tunable parameters. This is illustrated in Fig. 2. Adjusting the illumination direction via the angles φ and ψ changes the k vector of the incident light, which in turn determines the plasmon resonances energetic position. Different polarization settings bring along further possibilities to vary the plasmon excitation. We differentiate between two major cases. Either the electric field vector is set to oscillate parallel (Fig.2, blue arrow), or perpendicular (Fig. 2, red arrow) to the sample's surface. A camera with a software based aperture enables us to measure the intensity reflected from a selected region on the sample. To obtain the sur-

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face plasmon dispersion relation we gather reflection spectra for different angles ψ with a fixed angle φ = 45°. The near field distribution of the surface plasmon is scanned for ψ = 0°.

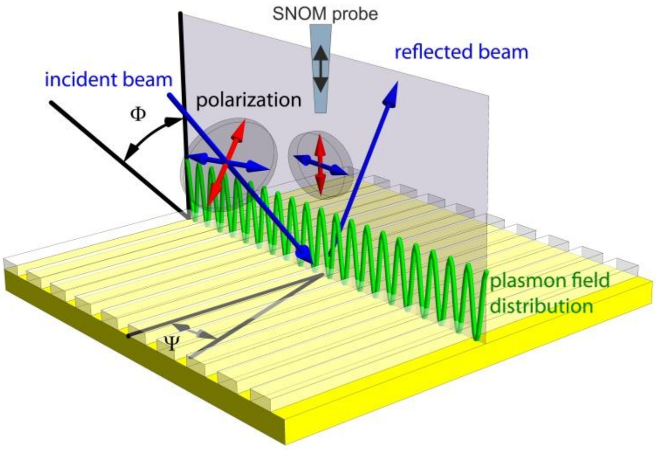

Fig. 1: Illumination settings used to excite plasmons in our setup.
The two main polarization states of the incident beam and their corresponding projections on the plane perpendicular to surface and grating bars are indicated by the red and blue arrow respectively.
The red polarization will excite the plasmon via its components perpendicular to the surface whereas the blue polarization setting will excite via components parallel to the surface.

3. Results

Our far field measurements (see Fig. 2) reveal three features regarding the occuring bandgap when varying the filling factor f. The scaled reflection intensity is plotted color coded over the excitation angle and the wavelength for each grating and polarization.

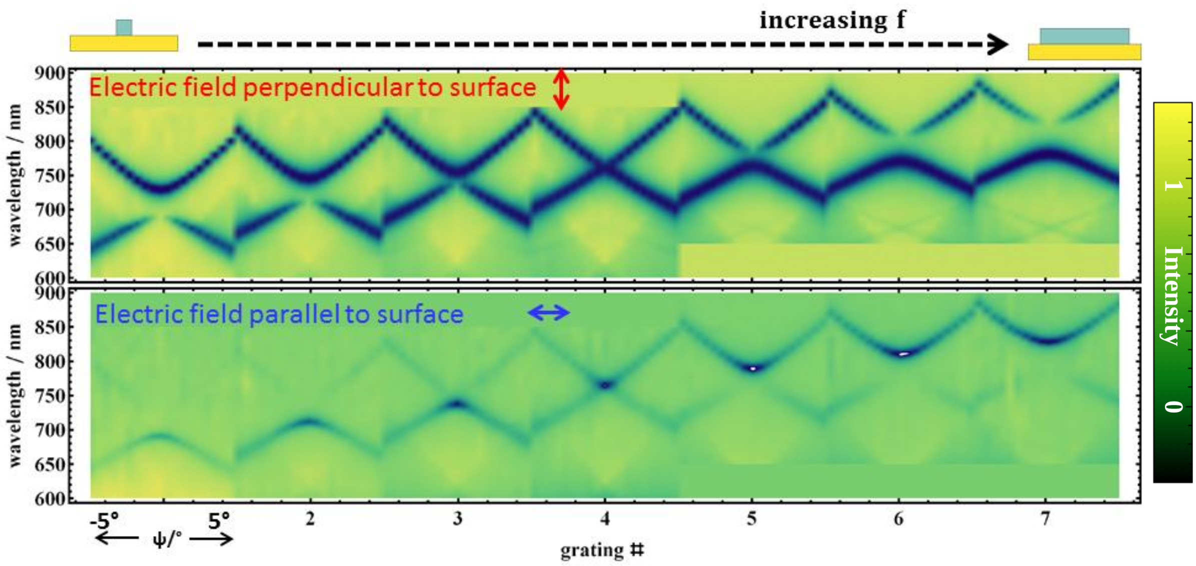

Fig. 2: Far field reflection measurements scanning the dispersion around the bandgap for gratings with varying filling factor f. The scaled reflection intensity is shown color coded. The bandgap shifts to lower energies with increasing f (I) and changes in size ΔE (II). Another gap in k-direction occurs in different branches depending on the polarization used for excitation (III).

(I) The position of the bandgap shifts to lower energies with increasing f. This can be assigned to the increasing amount of PMMA ($n \approx 1.48$) on the surface. The plasmons effective refractive index increases and the dispersion is pushed to lower energies.
(II) The bandgap size ΔE changes with f. For small f we detect an open bandgap wich shrinks to $\Delta E = 0$ for a certain value of f(Fig. 2 , grating #4) and reopens again for larger f.
(III) A polarization dependent gap in k direction appears. For perpendicular excitation (red) this gap occurs in the higher energy branch at grating #1 to #3 and in the lower energy branch for grating #5 to #7. For parallel excitation (blue) the k-gap is observed in the lower energy branch at grating #1 to #3,

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and in the higher energy branch at grating #5 to #7. At grating #4 the gap is closed. To understand feature (II) and (III) we have to investigate the near field pattern of the plasmon.
SNOM measurements at $\psi = 0$ reveal different plasmon modes for each excitation, and thus for each branch. An extract of one optical measurement is shown in Fig. 3 together with FDTD simulations. According to the simulations we detect maxima on top and in between the grating bars for perpendicular excitation (mode A), whereas parallel excitation shows maxima on the edges of each grating bar (mode B). This general mode pattern is preserved as we change f. Nevertheless, since both modes experience a different change in the plasmon mode index due to their different overlap with the PMMA grating, the bandgap size ΔE changes with f (feature II).
From FDTD simulations we can extract the electric field direction for each mode (arrows in Fig. 3). Mode A predominantly exhibits field components perpendicular to the surface. Incident light polarized parallel to the surface is therefore unable to excite this mode. Mode B in contrast mainly has components parallel to the surface, thus it cannot be excited with incident light polarized perpendicular to the surface. The k-gap (III) is based on the inability to excite both modes with one polarization. With mixed polarization we were able to close this gap.

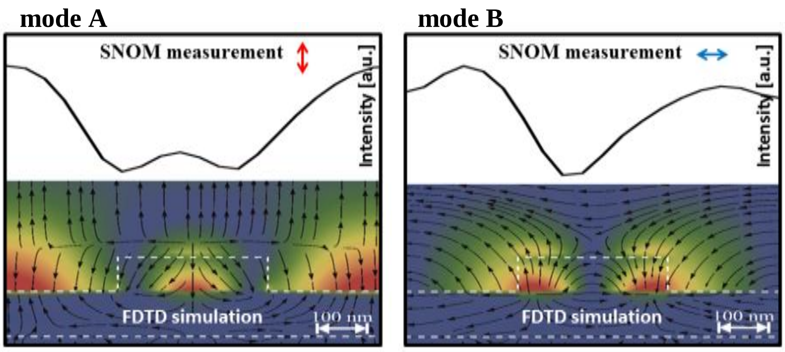

Fig. 3: Extract of our near field SNOM measurements for each polarization at $\psi = 0$. In accordance to FDTD simulations we clearly detect different mode patterns (mode A and B) for each polarization setting. Electric field directions were extracted from the simulations (black arrows).

4. Conclusion

We experimentally analyzed the plasmon dispersion of PMMA gratings on a gold film by far field reflection measurements and scanning near field microscopy. We observed polarization dependent plasmon modes with a characteristic bandgap which can be traced back to the filling factor dependent variation of the effective refractive index the corresponding plasmon mode is exposed to. We demonstrate that the grating design allows the tuning of the bandgaps energetic position and size ΔE. Experimental near field data could be well modelled using Finite Difference Time Domain (FDTD) simulations. Based on these findings it is possible to manufacture tailor-made plasmon fields at desired frequencies.

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