Fabrication and SNOM characterization of plasmon-optical elements

S Griesing 1, A Englisch and U Hartmann

Institute of Experimental Physics, University of Saarbruecken, P.O. Box 15 11 50, D-66041 Saarbruecken, Germany.

E-mail: s.griesing@mx.uni-saarland.de

Abstract. Refractive elements like lenses and prisms for surface plasmons with predefined effective refractive index were realized by thin-film elements. We demonstrate that the straightforward approach of using topographically structured dielectric coatings like polymethylmetacrylate can be successfully applied. The preparation process can thus be greatly simplified with respect to conventional approaches. The effective refractive index for plasmons is deduced in dependence on the film thickness. The value obtained is verified by SNOM imaging of refraction on prisms. Apart from common refraction, some plasmon-specific effects were observed and explained by finite element simulations.

1. Introduction
Surface plasmons (in the following referred to as plasmons) represent a special solution of the Maxwell equations at a metal-dielectric interface. Since some years, there is a growing interest in the development of photonic circuits based on plasmons. Therefore the interaction of plasmons with structural elements has been extensivly investigated. Experimental studies on plasmons have been performed on a variety of metallic structures, e.g. nanowires [1, 2], Bragg reflectors [2], beam splitters [2], metal stripes [3] and different kinds of waveguides [4, 5]. Experiments were also performed with dielectric SiO₂ structures on top of a gold film [6].

In all experiments, electron-beam lithography (EBL) with subsequent development and lift-off process were used for structuring.

2. Approach
In the following, we present a simplified technique of producing plasmon optical devices: The use of topographically structured coatings of polymethylmetacrylate (PMMA) e-beam resist. In the context of plasmons PMMA coatings have so far only been used as matrix for fluorescent dye molecules. Thus plasmon propagation could be observed by a fluorescence microscope [2]. Structured polymer films have not yet been used for plasmonic devices. This approach represents a great simplification of the usual fabrication process in that it consists only of EBL and subsequent development as shown in Fig. 1.

![Image](image-url)

**Figure 1.** Fabrication of plasmon-optical elements by structuring of dielectric coatings.

1 Corresponding author
The plasmon wavevector can be tuned by varying the thickness of the PMMA coating. The dispersion relation can be derived from the Fresnel formula for p-polarized light [7]:

\[ 1 + r_{123} e^{2i k_i d_i} = 0. \]  

where

\[ r_{123} = \frac{r_{12} + r_{23} e^{2i k_i d_2}}{1 + r_{12} r_{23} e^{2i k_i d_2}}. \]  

Substrate and air are regarded as semi-infinite spaces with dielectric permittivities \( \varepsilon_0 \) and \( \varepsilon_3 \). Silver layer and PMMA coating are treated as thin films with thicknesses \( d_1 \) and \( d_2 \) and dielectric permittivities \( \varepsilon_1 \) and \( \varepsilon_2 \). \( r_{123} \) is the coefficient of reflectivity for the three-layer subsystem silver/PMMA/air:

\[ r_{123} = \frac{r_{12} + r_{23} e^{2i k_i d_2}}{1 + r_{12} r_{23} e^{2i k_i d_2}}, \]  

with

\[ r_{ij} = \left( \frac{k_{z,i} - k_{z,j}}{\varepsilon_i - \varepsilon_j} \right) \left( k_{z,i} + k_{z,j} \right)^{-1} \]  

and

\[ k_{z,i} = \sqrt{\varepsilon_i k_0^2 - k_x^2}. \]  

Hereby \( k_0 \) is the vacuum wavenumber of light and \( k_x \) the wavevector component parallel to the interfaces. The value of \( k_x \) depends on the dielectric permittivities and film thicknesses of metal and dielectric coating. For a given dielectric permittivity of the metal, the thickness of the metal film only slightly influences the value of \( k_x \). The latter is mainly determined by the thickness and dielectric permittivity of the coating.

The result of such a calculation, valid for an excitation wavelength of 673 nm, a silver thickness of 40 nm and a PMMA coating (\( \varepsilon_2=2.3 \)) is presented in Fig. 2. By increasing the thickness of the PMMA coating up to 230 nm, \( k_x \) can be increased to 1.50 times the wavenumber \( k_0 \) of the exciting light.

![Figure 2](image)

Figure 2. Dependence of the tangential wavevector and plasmon refractive index on the PMMA thickness.

An effective refractive index for plasmons (dotted curve in Fig. 2) can be defined as the ratio of the wavevector at the silver-PMMA interface to the wavevector at the silver-air interface:

\[ n_{eff}^{SP} = \frac{k_{Ag-PMMA}}{k_{Ag-Air}}. \]
3. Sample preparation
The individual preparation steps are shown in Fig. 1. On top of a glass substrate a 40 nm thick silver layer is sputter deposited. Subsequently, a PMMA coating is spin coated on top of the metallic film. For a given rotation rate, the thickness of the coating is dependent on the concentration of the PMMA solution. Varying the concentration between 1.2 % and 4.0 %, the thickness can be tuned between 30 nm and 240 nm. Structuring is done by using a modified field-emission scanning electron microscope and subsequent development in MIBK: IP 1:3 for 45 seconds.

4. Experimental setup
The setup used in the experiment is shown in Fig. 3(a). Plasmon excitation is realized with a modified Kretschmann-Raether configuration. A laser beam of 673 nm wavelength (laser diode) is focused through a glass prism to the silver-air interface of the sample. Plasmons are locally excited by the p-polarized light and propagate as two-dimensional beam towards the PMMA structures (Fig. 3(b)). The first structural edge is hit at normal incidence, so no refraction is expected to occur. The second edge is hit at oblique incidence, so the propagation direction is changed due to refraction effects. Plasmon monitoring is realized by scanning near-field optical microscopy (SNOM) in collection mode as shown in Fig. 3(a). The scan height is kept constant by a tuning-fork feedback system.

![Figure 3.](image)

**Figure 3.** (a) Setup for plasmon investigations. (b) Geometry used in the experiment.

5. Experimental results and discussion
Measurements were performed at prisms with different angles, two examples are displayed in Fig. 4. By measuring the deflection of the transmitted beam and by applying Snellius’ law, the effective refractive index of a 140 nm thick PMMA coating could be determined to be 1.38 ± 0.08. This result is in good agreement with the value of 1.41 expected from Eq. (3). Comparing Fig. 4 (a) and (b), two plasmon-specific effects can be realized: a beat pattern within the PMMA structures consisting of dark and bright stripes parallel to the first edge and an intensity modulation of the transmitted beam which is dependent on the prism angle.

![Figure 4.](image)

**Figure 4.** Refraction of plasmons at different PMMA-prisms. (a) prism angle 27°, (b) prism angle 40°. Plasmons propagate from top to bottom.
Fig. 5 represents a two-dimensional finite element modeling (FEM) of the intensity distribution along the propagation direction for the case of a rectangular structure.

According to Fig. 5, the plasmon mode within the PMMA structure represents an interference of symmetric and asymmetric plasmons. This interference is alternatingly localized at both sides of the silver film. If the PMMA structure ends at a position at which the intensity is zero at the silver-PMMA (silver–glass) interface, no plasmon modes at this interface are transmitted through the second edge. In the case of a prism, the second structural edge crosses the interference mode at a certain angle, and a mode mixture in the transmitted beam is expected and detectable by SNOM as intensity modulation. The detectable beat pattern within the structure results from an interference between the mixed plasmon mode and light propagating parallel to the interface. The intensity modulation at the scan height is dominated by the resulting long period.

Figure 6 demonstrates the focusing of plasmons by a spherical lens. As the diameter of the lens is larger than the diameter of the incoming plasmon beam, the lens could not be fully illuminated by the beam. Therefore, the position of the incoming plasmon beam was varied and the single scans were composed to one picture.

6. Summary
In this paper, it has been demonstrated that topographically structured polymer coatings can be successfully applied as plasmon-optical elements. Experiments demonstrate that PMMA prisms with lateral dimensions of some tens of microns influence the propagation of plasmons according to Snellius’ law. Focusing of plasmons is possible by spherical lenses. Two-dimensional FEM modeling shows that plasmon-specific effects can be interpreted as the result of a mixing of electromagnetic modes.

References
[1] H Ditlbacher, J R Krenn, N Felidj, B Lamprecht, G Schider et al 2002 Appl. Phys. Lett. 80 404.
[2] H Ditlbacher, J R Krenn, G Schider, A Leitner and F R Ausse negg 2002 Appl. Phys. Lett. 81 1762.
[3] J C Weeber, J R Krenn, A Dereux, B Lamprecht, Y Lacroute et al 2001 Phys. Rev. B 64 045411.
[4] R Charbonneau, N Lahoud, G Mattiussi and P. Berini 2005 Opt. Express 13 977-84.
[5] A Englisch, R Schoen and U Hartmann Proc. of the 12th International Conference on Scanning Tunneling Microscopy/ Spectroscopy and Related Techniques STM 03 (Eindhoven, NL, July 21-25) ed P M Koenraad and M Kemerink (AIP Conf. Proc., American Institute of Physics: Melville) pp 211-6.

[6] A Hohenau, J R Krenn, A L Stepanov, A Drezet, H Ditlbacher et al 2005 Opt. Lett. 30 893.

[7] K Choi, H Kim, Y Lim, S Kim and B Lee 2005 Opt. Express 13 8866.