Image formation in surface plasmon polariton mirrors: applications in high-resolution optical microscopy

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\textbf{Abstract.} Image formation in focusing mirrors for surface plasmon polaritons (SPPs) is studied numerically. The transition from diffractive to geometrical optics is traced as a function of mirror size and surface polariton wavelength. The role of the mirror shape and the SPP propagation length in the image formation is also investigated. The small losses are shown to be helpful for imaging with surface waves, resulting in the increased contrast and reduced background of the images. Surface polariton focusing mirrors have recently found important applications in high-resolution optical microscopy based on short-wavelength SPP.
1. Introduction

The interaction of light with conduction electrons in metals results in numerous important effects in optics and photonics which have recently been dubbed as plasmonics [1]. These include light guiding and manipulation on the sub-wavelength scales, enhanced nonlinear effects, new optical imaging techniques, etc. Using surface plasmon polaritons (SPPs) the electromagnetic field can be manipulated on the metal surface, and mirrors, lenses, surface polaritonic crystals, resonators and even lasers can be developed for two-dimensional (2D) surface waves [1]–[4]. Very recently, curved SPP mirrors have been used to focus SPPs and create magnified images of planar objects located on a metal surface [5]–[7]. The mirrors for SPPs on a metal surface can be created using either structuring of metal surface to provide efficient SPP in SPP scattering on artificial surface objects or employing curved dielectric objects to reflect and direct SPP waves on a surface. Both magnified as well as reduced images can be obtained by appropriate positioning of the object with respect to the mirror; however the images may be significantly distorted compared to the objects.

In this paper, we have studied numerically the image formation in a curved dielectric SPP mirrors. The transition from diffractive to geometrical optics has been traced as a function of the mirror size and SPP wavelength. The role of Ohmic losses and SPP mirror shape in the image formation have been discussed. Surface polariton mirrors have recently found important applications in high-resolution optical microscopy based on short-wavelength SPPs and understanding the image formation properties is important for their applications.

2. Dielectric focusing mirrors for surface polaritons

A practical design of SPP focusing mirrors has been implemented recently in surface-polariton-assisted microscopy [5, 6]. This design uses an appropriately shaped dielectric on a metal surface for focusing SPPs excited on a metal/dielectric interface (figure 1). Such parabolic or elliptical SPP mirrors can be easily fabricated, e.g., using a small droplet of liquid dielectric placed on the metal surface or structuring polymers. The droplet boundary becomes an efficient mirror for surface waves propagating inside the droplet at almost any angle of incidence due to total internal reflection since the effective refraction index of surface polaritons \( n_{SP} = \lambda / \lambda_{SP} \) near the surface plasmon frequency \( \omega_0 \), defined by \( \varepsilon_m(\omega_0) = -\varepsilon_d(\omega_0) \), can become very large on such structures [6].

If an object placed on a metal film emits SPP waves after being illuminated with light or is illuminated by SPPs created by another structure, upon reflection from the mirror edge the SPPs...
Figure 1. Geometry of a focusing dielectric mirror for SPPs. SPPs are excited on a metal/dielectric interface by a nanostructure in a metal film and propagate inside a curved dielectric droplet forming a 2D image of the surface object which is illuminated by SPPs.

Figure 2. Diffractive optics calculation geometry: the field is calculated as a superposition of circular waves from the primary source of SPP waves and the secondary sources located at the parabolic mirror boundary.

may produce a 2D image of the object in the appropriate location on the metal surface, which may be magnified or demagnified depending on the mirror parameters and object position.

We have studied the image formation in a dielectric mirror using the diffractive optics approach described initially in [8]. Although the SPP field in this simplified approach is treated as a scalar field, the technique produced excellent agreement with the experimentally measured images of the SPP field distributions. It is assumed that a given point source of SPP wave produces a circular wave of the form $E \sim e^{i k_{SP} r} e^{-r/L} r^{1/2}$, where $k_{SP}$ is the SPP wavevector and $L$ is the SPP propagation length. When the primary circular wave reaches the mirror boundary, each point of the boundary produces secondary circular waves, similar to the Huygens–Fresnel–Kirchoff principle of conventional diffraction theory (figure 2) [9]. The field at each point inside the dielectric droplet is calculated as a superposition of all primary and secondary waves from all sources.

Firstly, we modelled the image formation from a point source of SPP waves inside a dielectric mirror. The numerical approach allowed us to trace the transition from the diffractive to the geometrical optics limit of image formation as a function of the ratio of a mirror size and SPP wavelength (figure 3). For the sake of convenience, the size of the parabolic droplet was kept constant in this simulation, while the effective refractive index $n_{SP}$ of the droplet was varied.
Lossless ($\text{Im} \varepsilon_m = 0, \ L = \infty$) approximation has been initially used. These calculations indicate that at short SPP wavelengths (large effective refractive indices) an image is formed by the droplet boundary in the locations which are consistent with the simple rules of geometrical optics. When losses are introduced, some remaining interference pattern in the background is removed, and resemblance to geometrical optics improves even further (figure 4). This has important implications for experimental realizations of the proposed imaging scheme. Although the image contrast is improved in the presence of the Ohmic losses, they lead to a finite SPP propagation length and limit the SPP mirror size and experimentally accessible distances between an object and a mirror. It appears that the quality of the image can be improved when the object-mirror-image distance is larger than the SPP propagation length (at which the SPP intensity decays by $1/e$ of its initial value). If this distance is much larger, the overall intensity of the image is significantly reduced and, although the image is still formed, it may be more difficult to observe in the experiment.

If additional primary sources are added to model, not a single point source but more complex objects emitting SPP waves, interference effects introduce some deviations from the geometrical optics picture. This can be seen in the images of an array of four point sources arranged
Figure 4. Calculated image of a point object produced by SPPs in a parabolic mirror as in figure 3(a) with the Ohmic losses included: $n_{SP} = 3 \mu \text{m}$ and $L = 5 \mu \text{m}$. The effect of the finite SPP propagation length in the presence of Ohmic losses is in the improving image quality due to suppressed background. The image size is $10 \times 10 \mu \text{m}^2$.

Figure 5. Calculated images of a square pattern object obtained using (a) diffractive ($n_{SP} = 3 \mu \text{m}, L = 5 \mu \text{m}$) and (b) geometrical SPP optics. In (b) geometrical construction is superimposed on negative of (a). The focal point of the mirror is shown with a blue point, the object is a square array formed by four red points and the resulting geometrical optics image is shown with yellow points. The image sizes are $10 \times 10 \mu \text{m}^2$.

in a square (figure 5). However, general agreement between the geometrical ray tracing and diffractive optics image calculations remains fair. For comparison, in figure 5(b) the image obtained using geometrical ray tracing is superimposed onto the negative of the image obtained with diffraction modelling in order to show good agreement between these approaches. This figure also demonstrates the image shape deformation due to imaging in the curved mirror. The degree of deformation depends on the position of the object with respect to the mirror focus, the same as in conventional 3D optics.
Figure 6. Comparison of the imaging properties of parabolic (a) and elliptical (b, c) mirrors using the diffraction optics approximation and the object and SPP parameters as in figure 5: (a) \( P = 3 \, \mu m \) and \( C = \infty \), (b) \( P = 3 \, \mu m \) and \( C = 10 \, \mu m \), and (c) \( P = 3 \, \mu m \) and \( C = 5 \, \mu m \). The image sizes are \( 10 \times 10 \, \mu m^2 \).

Finally, we have studied the effect of mirror shape on the image formation with SPP waves. The elliptical mirror with the focal distance \( P = A^2/B \) can be described as \( y = x^2/2P + y^2/2C \), where at \( C = \infty \) a parabolic mirror with the same focal distance is achieved. In order to perform a fair comparison, the images of the same square source pattern as in figure 5 were calculated using parabolic and elliptical mirror shapes, which have the same focal distance in paraxial geometrical optics approximation as the droplet in figure 5. It appears that the imaging properties of the mirrors vary drastically. The elliptical mirror in figure 6(b) appears to have lost any useful imaging properties. On the other hand, the mirror in figure 6(c) produces very clear image, which is quite similar to the shape of the original object. These theoretical data indicate that 2D SPP-based imaging is possible. On the other hand, any practical SPP imaging device would require a very good control of the dielectric mirror shape and position of the object with respect to the mirror.

3. Conclusions

We have studied the image formation in curved SPP mirrors using diffractive and geometrical optics. The geometrical optics approximation has been shown to work reasonably well in reconstructing images in parabolic and elliptical SPP mirrors. The finite SPP propagation length due to Ohmic losses in metal is important for imaging properties of SPP waves increasing the contrast and reducing background of the SPP-produced images. Although Ohmic losses (leading to a finite SPP propagation length) are a drawback limiting size of the SPP mirrors and experimentally achievable distance between an object and a mirror, they also play a positive role in improving quality of SPP-formed images.

Due to a short SPP wavelength near the frequency of surface plasmon resonance, theoretical diffraction-limited resolution of optical microscopy based on SPPs may achieve values better than \( \lambda/10 \). However, the effects of scattering, diffraction and mirror imperfections limit the performance of practical devices based on SPPs. A very good control of mirror shape would be necessary in future SPP imaging and lithographical devices.
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