Optical surface diffraction and improved lateral resolution

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ABSTRACT

Optical lateral and longitudinal standing waves can be recorded using an optical scanning probe in collection mode. We describe both analytical and numerical methods to determine the image height and the location of a single point scatterer from the recorded surface diffraction image. We find that the phase of the lateral optical standing wave is minimal along the direction of the reflected beam and that the lateral standing waves are centered around the reflected beam direction. We find that the second derivative of the extracted phase peaks at the position of the point scatterer. We have estimated the image height by fitting the envelop function to the recorded intensity profile along the symmetry axis. In the intermediate distance range (several wavelengths off the surface) we can record objects of sizes smaller than the distance between the object and the image plane.

Keywords: Optical scanning probe, microscopy, surface, diffraction, interference

1 INTRODUCTION

Progress in increasing optical resolution of fluorescent labeled particles and cells, manipulation of small particles using optical tweezers and controlling light propagation in photonic crystals demonstrate the potential to extend the range of optical techniques to the sub-micrometer range [1,2]. All these techniques are based on far field optics. Improvement is obtained by the use of fluorescent labels, control of the focal point and materials processing at the scale of optical wavelengths. To overcome the diffraction limit, optical nearfield techniques aim at keeping an optical probe in the proximity of the surface thereby taking to take advantage of the enhanced optical local field [3]. The large optical wavelength compared to the probe size implies however, that the presence of the probe cannot be neglected. At intermediate distances from the surface, one can combine the advantage of reduced probe induced effects and enhanced local optical field. The overlap of incident and scattered field leads to interference, a dominant factor in the intermediate distance range [4,5]. As a result, the local optical field distribution is highly non-uniform for structured surfaces. Here we explore the local optical field in the vicinity of the surface by illuminating at an angle and scanning an optical probe. The overlap of incident and reflected waves leads first to standing waves parallel to the surface (surface standing waves, SW). These SWs can be used to orient the image plane parallel to the surface at variable distances from the surface without the use of a feedback signal. The accuracy of how parallel the image plane can be oriented depends on the size of the recorded image. A lateral structure in the surface or presence of an object influences the reflected wave which results in diffraction and the formation of lateral standing waves (LSW). The amplitude of the LSW at intermediate distances from the surface depends on the size of the local non-uniformity of the surface or its polarizability. The LSW is proportional to the incident and scattered field. The scattered field is considerably smaller than the incident field and the incident field amplifies the LSW. The incident wave can be approximated with a plane wave and the scattered wave by a dipole field. The LSW falls off only proportional to the scattering amplitude, inversely proportional to the distance due to the fact that the plane wave has constant amplitude. We note that one would expect for a single radiating dipole that the field falls off inversely proportional to the distance squared but not in the case where the scattered field overlaps with the incident plane field. Nanometer sized objects can be detected though the LSW at relative large distance from the surface [6,7]. We consider in the following only the propagating field component of a single dipole wave whose amplitude falls off at a rate inversely proportional to the distance from the object and we neglect the quasi-electrostatic longitudinal component.

2 STANDING WAVES OF A SINGLE POINT SCATTERER

When scanning close to the surface the distance between image point and object varies considerably. Figure 1a shows the lateral amplitude change at three different distances from the surface. Figure 1.b shows the normalized amplitude change. At smaller distances the field varies more than a factor of two and is less broadened than for larger distances. The lateral fringes are as a result more intense in the center and the fringes are more concentrated around the object at smaller distances. This simplifies the diffraction image in the case of several scatterers. The diffraction image from the object eventually resembles its direct image as the distances to the object is further reduced. There is a natural transition between a localized direct image and a delocalized diffraction image by changing the distance between image plane and surface. We assume here that the image plane is oriented perfectly parallel to the surface where SWs do not influence the image contrast.

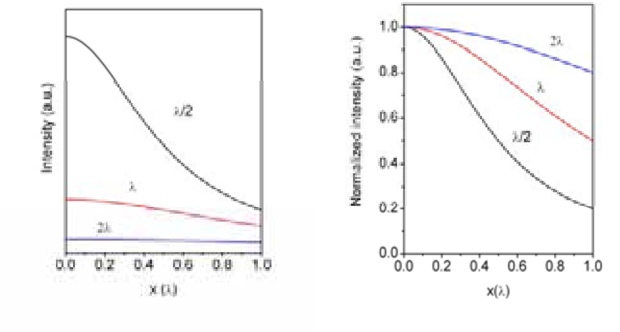

Fig. 1: Envelop function ($1/\sqrt{x^2+z^2}$) of LSW across the image at variable image height. Left: Comparison of relative intensity. Right: Comparison of normalized intensity.

In figure 2 we show the LSW of a point scatterer at three different distances from the surface. They have been calculated by taking the 1/r ($r=\sqrt{x^2+z^2}$: distance between scattering point and image point) dependence into account and neglecting the optical properties of the surface. We do not include any polarization effects at this stage due to the fact that the polarization does not influence the fringe spacing. The fringes are asymmetric due to the angle of the incident plane wave (45deg) and the intensity of the LSW at the center is significantly larger at a smaller image height. The LSW shifts to the right in the direction of the reflected beam with larger image height and differences in the intensity of the LSW are reduced. In order to determine the location of the point scatterer we have extracted the phase of the LSW along the symmetry axis as follows.

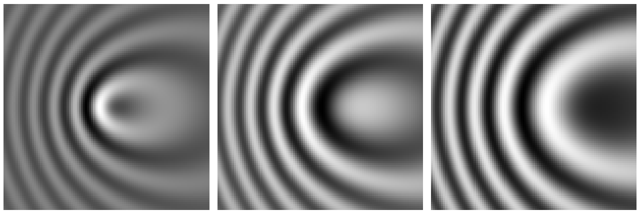

Fig. 2: Lateral standing wave of point scatterer at 0.5, 1.5 and 2.5 wavelength off the surface. Incident beam is at an angle of 45deg (left) and image size is 6 wavelengths.

First we fit the intensity profile along the symmetry axis to the envelop function or amplitude factor as shown in figure 1. We then divide the intensity profile by the fitted envelop function to obtain the corrected intensity profile from which we extract the phase. Figure 3 plots the phase of the three LSW shown in figure 2 along the symmetry axis for three different distances from the surface. We notice that the phase has a minimum which falls exactly on the reflected beam. This means that the LSW are centered around the reflected beam and as a result the shift of the LSW in direction of the reflected beam is directly related to the distance between substrate and image plane.

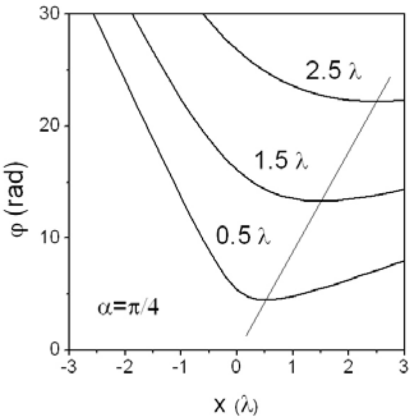

Fig. 3: Phase of the LSW as function of lateral displacement x at three different image heights; angle of incidence α=π/4. The phase is minimal along reflected beam direction (α'=−π/4).

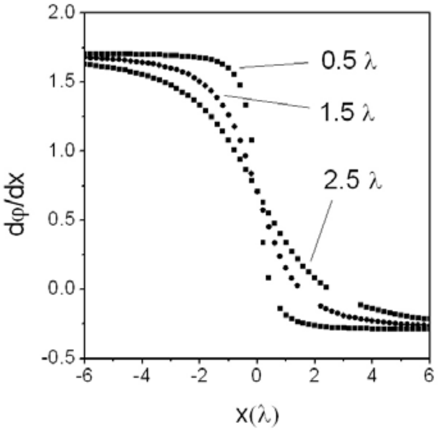

Fig. 4: First derivative of the LSW phase along the symmetry direction.

Figure 4 shows the first derivative of the phase of the LSW, a step function which intersects the x axis at the location of the minima in the phase along the symmetry axis. The sharpness of the step increases with smaller distance to the surface. Figure 5 shows that the second derivative of the LSW phase peaks at the exact location of the point scatterer. The peak is narrower for smaller distances between image plane and surface. The lateral precision to locate the point scatterer, decreases as the image height increases (FWHM=1λ, image height 0.5λ).

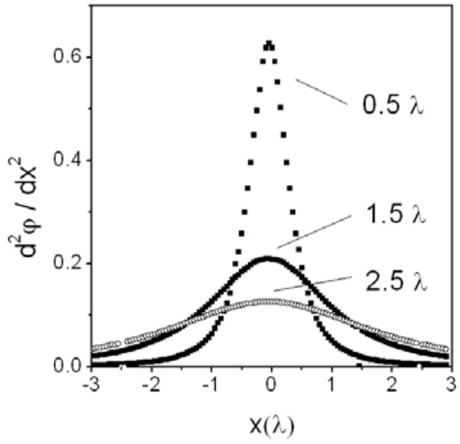

Fig.5: Second derivative of the extracted phase along the axis of symmetry, for LSW at three different image heights.

The peak of the second derivative of the phase broadens at distances (image height) larger than one wavelength. This analysis shows that we can determine the location of the point scatterer from LSW by taking the second derivative of its phase (after amplitude correction) along the line of symmetry. We note that the experimental intensity profile which first needs to be corrected by the amplitude factor shown in figure 1 depends in fact also on the location of the scatterer. The sensitivity of the amplitude factor on height is however considerably smaller than the peak in the second derivative of the extracted phase of the LSW. By taking into account two point scatterers one can in first approximation, neglect the influence of the interference between the two point scatterer. The resulting LSW can therefore be approximated by the linear superposition of two fringe patterns from a single point scatterer displaced in lateral direction. The resulting LSW has a phase which depends on the position of both point scatterers and the phase cannot be extracted in a simple way due to the increased number of degrees of parameters. The method shown here is suitable for LSWs of a single point scatterer. It allows to determine the precise location of the point scatterer and to estimate the image height. For two point scatterers one is can use numerical convolution techniques.

Here we have not included the influence of the surface which complicates the standing waves even in the case of a single point scatterer. The substrate has to be strongly reflective in order to have a large amplitude in the surface standing wave (SW). This implies that the incident beam interacts strongly with the substrate. But the light penetrates into the substrate as described by the complex optical constants and the inclusion this effect is non trivial (Thesis) within a simple dipole model. Experimentally it is found that the fringe spacing of the LSW on a silicon surface is larger than the fringe spacing used for the simplest form of the dipole model [7].

3. IMAGE DECONVOLUTION

Instead of using an analytic approach one can also apply numerical convolution methods and use the entire image to determine the position of the scattering point. Figure shows the de-convolution of the images in figure 2.

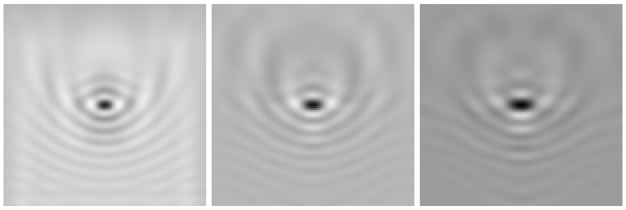

Fig.6: Result of the de-convolution of the LSW of one point scatterer using image planes at 0.5, 1.5 and 2.5 wavelengths off the surface (image size 10 wavelengths).

The spot size increases with larger distances between surface and image plane. While the broadening for the smallest distance in figure 6 is comparable to the analytical method used in figure 5, the broadening is smaller for larger distances in figure 6. For the deconvolution one needs either to know the image height or the image height is obtained by minimizing the spot size by varying the image height. Side lobes are observed around the location of the point scatterer which is characteristic of most numerical deconvolution techniques. We note that the spots which indicate the location of the point scatterer are not symmetric but narrower in the direction of the incident beam. The numerical deconvolution method has the advantage that it is not limited to a single scatterer and one can apply the same method to two or multiple scatterers.

4. CONCLUSION

We have modeled optical standing waves near surfaces in the neighborhood of a single point scatterer with an optical dipole filed and find that the location of the point scatterer is determined by the second derivative of the phase of the standing wave along the symmetry axis of the interference fringes. The LSW fringes are centered around the direction of the reflected beam. We find that the precision of the location of the point scatterer depends sensitively on the distance between image plane and substrate surface. Two neighboring point scatterer at a distance comparable to the image height can not be located using this method due to the difficulty to extract the correct phase of the optical standing wave. Numerical de-convolution using the entire image is shown to be able to determine the location of the point scatterer with greater precision for larger image heights.

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