Depth resolution capabilities using optical standing waves near surfaces

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ABSTRACT

We explore the optical standing wave field near surfaces at variable distances from the surface. The complex image contrast due to diffraction due to local scattering is explained by the formation of surface and lateral standing waves. By changing the distance between the image plain and the plane of the point scatterers used in the numerical reconstruction, we estimate the depth resolution to be better than 1/10 wavelengths. Increasing or decreasing the distance between image and scattering points has the effect to shift the reconstructed image in opposite lateral directions. Using a test point patters, we find that the depth resolution is asymmetric. The resolution is lower when increasing the distance as compared to when decreasing the distance of the image plane with respect to the plane of the point scatterers. We find that using numerical reconstruction of the optical standing wave field it becomes possible to image at intermediate distance from the surface with sub-wavelength lateral as well as depth resolution. The depth resolution is higher than the lateral resolution for a given distance of the image plane. Understanding in the formation of optical standing waves near surfaces opens opportunities to develop new interferometric encryption techniques.

Keywords: optical, standing waves, scanning probe microscopy, reconstruction, interferometer, holography

1 INTRODUCTION

The physics of standing waves has been explored for more than 50 years. Standing wave fields can be used to selectively enhance luminescence or enhance the Raman signal [1] or can be used as a spectroscopic sensor. [2] We explore here the optical standing wave field with optical scanning probes in collection mode at variable distances from the surface and using no feedback signal. [3, 4] The complex image contrast due to diffraction can be explained by the formation of surface and lateral standing waves. [4] While the lateral fringe spacing depends sensitively on distance between the image plane and the surface, the shape of the lateral standing waves depends on the scattering vector and the index of reflection. Scanning in the intermediate field range has the advantage that the transverse field component is larger than the longitudinal field component. This reduces probe induced effects in the recorded image. The lateral resolution is below the diffraction limit and comparable to nearfield optical techniques when scanning in the intermediate field range. We explore here the depth resolution capabilities when analysing optical standing waves near surfaces and study the influence of the finite penetration length of the light into the substrate. Understanding in the formation of optical standing waves near surfaces opens opportunities to develop new interferometric encryption techniques.

2 NUMERICAL RESULTS

Figure 1 shows the calculated standing wave field (left side) and the corresponding reconstructed image (right side) of three scattering points. The distance of the image plane with respect to the plane of the three scattering points is one wavelength. The angle of the incident beam is 45deg and the beam direction in the first two rows is rotated by 90deg. The image in the last row is the superposition of the images shown in the first two rows.

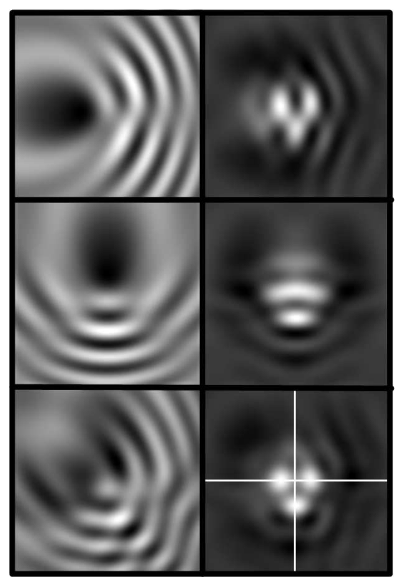

Figure 1 Calculated standing wave field (left side) and reconstructed images (right side) of three point scatterers. Distance between the point scatterers: 0.75 wavelengths; image size: 5 wavelength; angle of incidence: 45 deg.

We note that the reconstructed image has a higher contrast variations in the direction of the incident beam and combining the two beam directions at 90deg has the effects that the reconstructed image has uniform contrast variation in both normal directions. Note that when reconstructing the image with the incident beam coming from the left side the three points are resolved but not when the beam is directed from down; two of the spots are not resolved. The standing wave images have been reconstructed by de-convolution of the scattering function taking into account the angle and direction of incidence [6]. At this stage we have not included the polarization of the incident beam nor the index of refraction of the surface. The main effect of the polarization of the incident beam is the relative intensity variations in a given fringe. The point scatters are spaced at 0.75 wavelengths from each other. The numerical reconstruction images show that sub-wavelength resolution can be obtains by recording standing wave fields at a distance of one wavelength off the surface, outside the near field region, at distances comparable the wavelength of the incident beam, at intermediate distances.

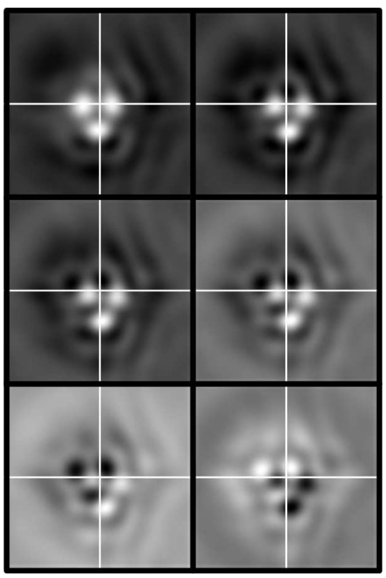

Figure 2 Reconstructed image of three point scatterers spaced at 0.75 wavelengths by increasing the distance used in the numerical reconstruction from top left to down right: 0%, 10%, 12%, 15%, 20%, 50%.

This has the advantage that the near field with both transverse and longitudinal field components, do not contribute in the image contrast and this simplifies the reconstruction process. We have previously shown that in fact the index of refraction has the effect of increasing the scattering vector and this has the consequence that the diffraction fringes are narrower spaced resulting in an even higher lateral resolution (super-resolution). [5] Lateral resolution can be furthermore improved by increasing the angle of incidence. The images shown in figure 1, assumes that the distance between image plane and surface with the point scatterers is known. This distance can be estimated in the experiment and is needed for the numerical reconstruction. We investigate the depth resolution capabilities by changing the distance used in the numerical reconstruction. Figure 2 shows the reconstructed image when combining the reconstructed images with the incident beam rotated by 90deg and increasing the distance between the image plane and the surface by 10-50%. We can see as the distance is increased, the position of the bright spots shift with respect to the lines which indicate the position of the point scatterers. The bright spots are also surrounded by dark spots. One can also observe in figure 2 that the background changes from dark to bright as one increases the distance from its correct value.

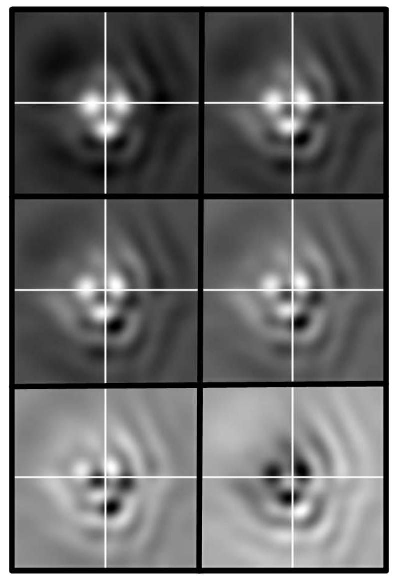

Figure 3 Reconstructed image of three point scatterers spaced at 0.75 wavelengths by decreasing the distance used in the numerical reconstruction from top left to down right: 0%, 10%, 12%, 15%, 20%, 50%.

Figure 3 shows the reconstructed images when decreasing the distance between image plane and point scatterers by 10%-50%. Again little change is observed by decreasing the distance by 10% but shifts in the spot positions are observed for larger deviation from the correct distance. Apart of the appearance of dark spots the fringes get more intense and the background brighter with decreasing distance. The error in the distance used in the reconstruction has the effect that the position of the image point shift in opposite lateral direction when increasing or decreasing the distance to the surface. In figure 2 the bright spots move down and in figure 3 the bright spots move up with changing the distance to the surface.

By changing the distance used in the numerical reconstruction we can estimate the depth resolution, or the resolution along the surface normal to 1/10 wavelengths (fig. 1, fig. 2) which represents an upper limit. The depth resolution can be improved by increasing the angle of incidence or by increasing the index of refraction of the substrate of the three point scatterers. It is also clear that the resolution depends on the scattering efficiency of the particle which in turn is given by the electronic polarizability and size of the particle.

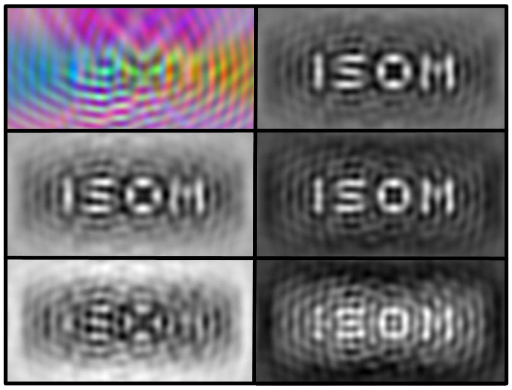

Figure 4 Reconstruction of 4 letters when changing the distance of image plane and plane of point scatterers (1 wavlength). Top left: superimposed 3 interferograms (red, green, blue). Top right: reconstructed image with correct distance. Middle row: reconstructed image when increasing/decrasing the distance by 10% (left/right). Last row: reconstructed image when increasing/decreasing the distance by 20% (left/right). Image size 6x12 wavelengths. Separation of point scatterers: 0.3 wavelengths. Letter size: 1.5x1.5 wavelengths.

Figure 4 shows the result when testing the depth resolution on a point pattern of 4 letters 'ISOM' standing for Interference Scanning Optical probe Microscopy. Each letter 1.5x1.5 wavelength in size, is defined by point scatterers spaced at 0.3 wavelengths. The top left image shows three superimposed interferograms for three different direction of incident (0, $\pi/2$, π) in three colors (red green, blue). The reconstructed image using the three interferograms and using the correct distance is shown in the top right figure. The second row shows the result of the reconstruction when the distance is increased/decreased by 10 %. The letters are still readable but the background is brighter or darker depending on whether the distance is increased or decreased. The last row shows the result when changing the distance by 20%. Interestingly one sees that the letters cannot be recognized when increasing the distance by 20% but it can still be recognized when reducing the distance by 20%. This shows that the depth resolution is asymmetric and depends on the distance of the plane of the standing wave image or interferogram and the plane of the point scatterers.

When comparing the here calculated standing wave field to experimental images we find that there are several differences which need to be resolved to make imaging of the standing wave field and numerical reconstruction a new optical imaging tool working at sub-wavelength resolution. [7] We would like to point out that the depth resolution considered here is used in the context of being able to determine the distance between the image plane and the plane of the point scatterers and not to resolve two point scatterers at different heights.

We note that the calculation of interferograms and their numerical reconstruction can be used in cryptography. Information can be defined into a point pattern. From this point pattern a interferogram can be calculated (coding) which can be transmitted to the receiver. The receiver will only be able to reconstruct the interferogram (encoding) by knowing the right parameters of the reconstruction method such as the distance between the image plane and the plane of the point scatterers.

3 CONCLUSION

We have investigated the depth resolution capabilities of the numerical reconstruction of optical standing wave field near surfaces and find that the point scatterers can be located at least within 1/10 wavelengths in a direction parallel to the surface normal. Errors in the numerical reconstruction are visible in the lateral shift of the location of the point scatteres in the plane of the surface, appearance of an inverted image and increase of the background signal. Using a point pattern defining several letters we find that the depth resolution is asymmetric. The resolution is lower when increasing the distance between the image plane and the plane of the point scatters. While the numerical reconstruction of the standing wave field cannot be applied to experimental images so far due to effects of the finite penetration of the optical wave into the substrate, we show that the technique has the potential to be applied in cryptography.

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