Local diffuse light scattering and surface inspection

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ABSTRACT

The use of local diffuse light scattering has the potential to extend the application range of non-contact inspection. Area averaging is reduced and the sensitivity is significantly increased using optical interference near surfaces. We use the discrete dipole model to show how the optical properties of the surface and the scattering particle influence the shape of the diffraction fringes. Scaling of the lateral shift and size of the first diffraction fringe can be used to estimate the distance of the image plan from the surface and the position of the surface non-uniformity.

Keywords: diffuse light scattering, optical scanning probe, surface inspection

1 INTRODUCTION

Overlap of the incident and scattered field near surfaces from local non-uniformities forms lateral standing waves which can be mapped using a scanning optical probe in collection mode. The amplitude of the lateral standing wave is proportional to incident beam and the scattering field amplitude. Although the scattering amplitude of a scatterer may be small due to its size, interference gives rise to lateral standing waves or interference fringes which are amplified by the incident field. The observation of Wiener fringes near surfaces with an optical scanning probe in collection mode has been demonstrated [1] and experimental studies on single scatterers and micro-gratings showed the lateral standing waves can be detected using a local optical probe in the proximity of the surface [2]. The use of interference substrates is particularly attractive to enhance the local optical field and to increase the sensitivity for the detection of nanoparticles on surfaces [3]. Particularly important in making use of this experimental approach are quantitative models with which it would be possible to determine local optical properties of surfaces.

Optical surface inspection uses conventional lens based systems which necessarily average over the size of the spot which is limited by optical diffraction. Optical scanning probe miscroscopy in collection mode, operated at intermediate distances from the surface, has the advantage that the lateral resolution is not limited by optical diffraction but by the definition of the optical probe tip. Operating the optical probe tip at intermediate distances has the advantage that the optical probe is less exposed to collisions with the surface. The probe surface distance can be controlled at intermediate distances using optical surface standing waves [1].

2 RESULTS AND DISCUSSION

We consider in the following model simulations of a single point scatterer on a surface and investigate the influence of the substrate on the lateral standing waves. The local optical field can be detected by scanning a probe in collection mode in the proximity of the surface. Figure 1 shows the geometry considered here: incident and reflected beam, optical probe, substrate and image plane.

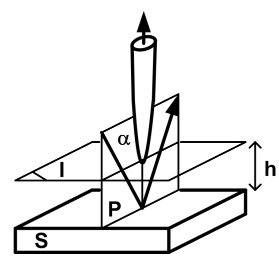

Fig. 1: Geometry of plane of incidence (P), incident and reflected beam direction, optical probe, substrate (S), image plane (I) and distance between image plane and surface (h).

The scattered field form a point scatterer can be described by the oscillating dipole induced by the incident field. The oscillating dipole field has three contributions proportional to $1/r^3$, k/r^2 and k^2/r. Where r is the distance between the dipole and the image point and k is the wave vector. The field contribution proportional to k^2/r is purely transversal and can propagate to the far field (the field vector is oriented in a plane perpendicular to r). This contribution is smaller for short distances such as in the nearfield [4, 5] but becomes comparable at distances of $\lambda/2\pi$ and is larger in the middle and far field. We consider in the following only distances larger than $\lambda/2\pi$. This has the advantage that the probe coupling to the surface is considerably smaller and the amplitude of the lateral standing waves is larger.

The intensity variation of the local optical field due to the interference of a plane wave and oscillating dipole wave of the point scatterer can essentially be described by interference terms of the form:

$$\Delta I(r) \propto \cos((k - k_d)\cdot r) \quad (1)$$

k is the incident or reflected wave vector, $\mathbf{k}_d$ is the scattering wave vector and $\mathbf{e}_r$ is the unit vector along **r**:

$$k_d = k \cdot e_r \quad (2)$$

Figure 2.a) shows the intensity of the local field by taking into account the incident and reflected wave (TE polarisation) and their interference with the point scatterer described essentially by terms of the form (1). The incident beam considered here, is inclined by 45 deg to the left as shown in Figure 1. The induced dipole of the point scatterer used here corresponds to an induced charge $q = 0.7\ 10^{-31}$ C for an electric field amplitude of 1V/m. The distance between surface and image plane is 1λ. The optical properties of the substrate are not included in figure 2.a). On the microscopic scale, the refractive index can be explained entirely by elastic scattering. Elastic scattering has the overall effect of slowing down the propagation of the electromagnetic wave in the medium. The proximity of the medium influences as a consequence the scattering vector of the point scatterer. We approximate the influence of the neighbouring substrate by scaling the scattering wave vector k_d with the average index of refractive at the surface ((1+n)/2).

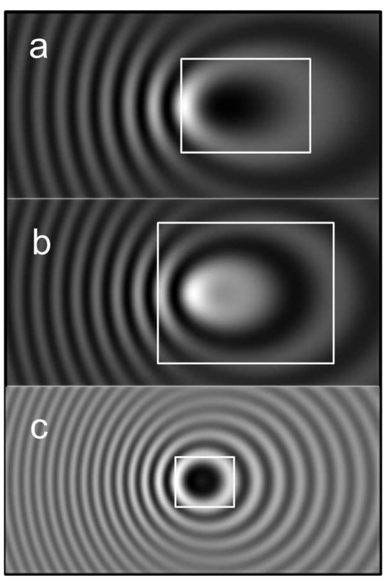

Fig. 2: Diffraction fringes of single point scatterer; image size 5x10 λ, image height 1 λ: a) taking no substrate into account, b) on SiO2, c) on Si.

Figure 1.b) shows the calculated time averaged intensity of the local optical field by taking into account the incident, reflected wave and the induced dipole of the point scatterer and including the effect of the refractive index of the substrate of SiO_2 (1.43) in 2.b) and in 2.c) Si (4.38). Comparing the fringes in the three images of figure 2 we notice that the fringes in the centre, in the form of an ellipsoid, is less elongated along the direction of incidence as the index of refraction of the substrate gets larger (2.a,b,c). This shows that the increased diffraction wave vector is directly related to the shape of the lateral standing waves. Apart of the more circular shaped fringes, the number of fringes is increased with increasing index of refraction of the substrate. The high sensitivity of the shape of the diffraction fringes and fringe spacing on the refractive index of the neighbouring medium opens the possibility to locally determine the relative refractive index by simply observing the diffraction fringes of a point scatterer. The size of the induced dipole moment influences the fringe contrast but does not influence the fringe shape and fringe spacing. We notice that the fringe centre in the three images in figure 2 is shifted to the left and is not located at the same place in 2.a), 2.b) and 2.c). The actual position of the point scatterer is in the centre of the image in figure 2. Figure 3 shows the calculated local field intensity in the plane of incidence in the case of a point scatterer on SiO_2.

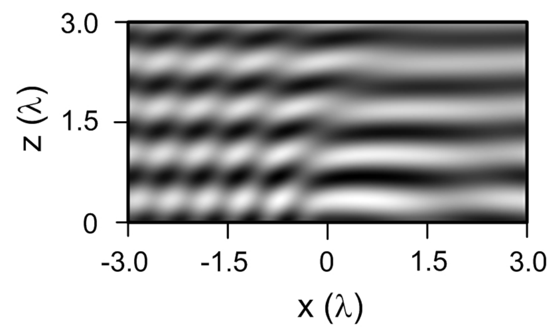

Fig. 2: Local optical field intensity in plane of incidence. Incident beam TE polarized. Horizontal fringes are due to the surface standing wave, vertical and tilted fringes are due to the lateral standing wave.

The horizontal fringes are the surface standing waves formed by the incident and reflected beam. Fringes in vertical direction which intercept the surface standing wave are the lateral standing wave of the point scatterer. The fringes are spaced narrow on the side of the incident beam (left) and are spaced much wider on the side of the reflected beam (right) in accordance with figure 2. From figure 3 we can also see that the fringes from the lateral fringes are tilted to the right. Images of the lateral standing waves recorded at larger distances from the surface and parallel to the surface shift as a result in the direction of the reflected beam. The fringes are displaced from the centre of the image to the right, the side of the reflected beam. Interestingly this shift depends on the substrate.

Figure 4 shows the lateral standing waves in a plane parallel to the surface at different image heights for a point scatterer on SiO_2. The lateral standing wave shifts consistently to the side of the reflected beam with increasing distance from the substrate; at the same time the fringe spacing increases due to the larger distance to the point scatterer and the fringe contrast gets smaller. It can be shown that this shift is linear with increasing distance. It has been earlier shown that the location of the point scatterer can be determined from the lateral standing wave by taking the second derivative of the phase of the local intensity in direction of the incident beam [4].

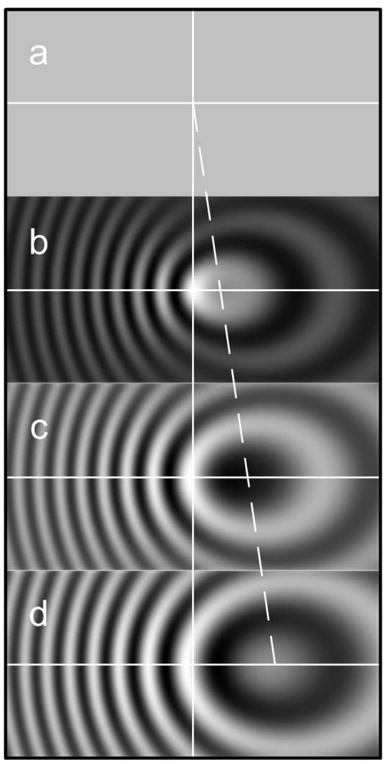

Fig. 4: Lateral standing wave of point scatterer at 1 λ (b), 2 λ (c), 3 λ(d) from the surface (image size 5x10 λ, TE polarization).

We suggest here a different method easier to implement from actual measurements of lateral standing waves. By recording two images at different heights, knowing the distance between the two image planes, we can predict the location of the centre of the fringes for a different distance to the surface due to the fact that the lateral shift is linear in variation of the distance to the substrate. This is demonstrated in image 4.a). Connecting the centres of the three diffraction images (4.a, 4.b, 4.c) recorded at distances in regular intervals, we can extrapolate the location of the point scatterer at the centre of the rectangle 4.a). This shows that the shift of the centre of the diffraction by changing the distance to the surface can be used to determine the distance between image plane and surface. While it is possible to predict the centre of the diffraction for a different distance from the surface, one has to use in a general situation, an additional criterion to decide the very proximity of the surface such as the disappearance of the first diffraction fringe. In that sense the size of the ellipsoid gives information about the distance between the image plane and the surface when the index of refraction of the substrate is known.

3 CONCLUSION

We have considered lateral standing waves of a single point scatterer on a substrate which can be recorded using a optical fibre probe operated at intermediate distance from the surface. We find that the lateral standing wave is influenced by the substrate index of refraction through the modified scattering wave vector. The scattering wave vector can be scaled to the average refractive index of the media on both sides of the interface. The ellipsoids of the lateral standing waves around the scatterer are more circular when increasing the average index of refraction. The shape of the ellipsoid is directly related to the index of refraction of the substrate. The lateral shift of the lateral standing wave depends, for images corresponding to different distances to the surface, on the average index of refraction. We have shown how the lateral shift between two images recorded at different distances from the surface can be used to determine the centre of the lateral standing wave at a different distance. The distance between image plane and surface can be estimated provided the index of refraction of the substrate is known. The analysis shown here is semi-quantitative and more detailed simulation and comparison with experimental images on test substrates will be needed to make local diffuse light scattering a viable tool for surface inspection of surfaces.

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