Optical 3D Measurement of Micro Structures

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Introduction

Proving the performance of high precision micro components requires special knowledge and techniques in their design and manufacture. With dimensions ranging from less than 0.1 mm to several mm, such components are often delicate and fragile and require non contact measurement techniques. This calls for the use of optical inspection techniques. Optics offers many advantages such as very fast, non contact inspection, no influence on the measured object, 3D measurement capability, full field inspection and many more.

Especially during the last few decades there has been a growing interest in optical inspection applications. Modern optical techniques are driven by computer techniques, software and video techniques and show an enormous degree of innovation every year. In this paper, we present and compare two optical techniques for 3D measurement, both of which offer full field 3D information and are specially suited for micro structures: white light interferometry and digital holography.

Microscope set-up

In a classical microscope the observed object is viewed through a microscope objective, fig. 1. The image is further magnified by a tube lens and an ocular lens. The magnified image is projected onto a CCD camera and can be observed on a monitor or analyzed by computer software. The information gained by this technique is a plane image of the object including the intensity of each object point. Lateral dimensions can be obtained from the image if the camera has been calibrated relative to the dimension of the object.

It should be noted that lateral resolution is limited by the numerical aperture of the system due to light diffraction effects /1/. The lateral resolution is normally described by the radius of an Airy disk:

$$y_{min} = 0.61 \frac{\lambda_0}{N.A.} \qquad (1)$$

λ_0 = vacuum wavelength of the used light
$N.A. = sin(u_{max})$ = numerical aperture of the objective

In air the numerical aperture cannot be larger than 1. Consequently, the lateral resolution of the microscope is typically limited to a fraction of the light wavelength, or 0.2 to 0.5 micrometers. If the third dimension of the object is required, additional information has to be generated. Two possible methods will be described in the following sections.

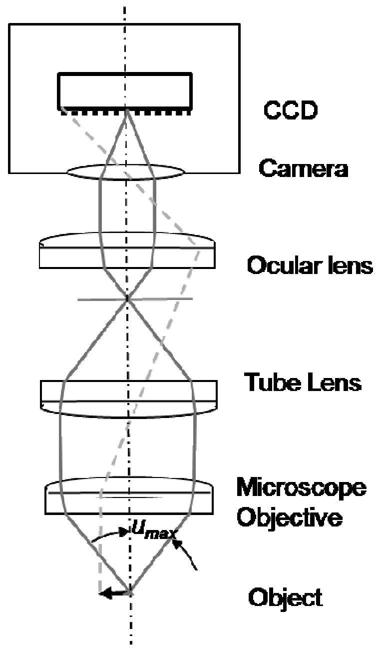


Fig. 1: Principle of microscope

White Light Interferometry

The use of the interferometry principle allows generation of the third dimension. In an interferometer the superposition of a reference and an object wave leads to interference effects as long as the path distance between the two interferometer arms is smaller than the coherence length /2/. With a white light source that typically has a coherence length of a few micrometers, an interference signal can only be observed if the two interferometer arms are nearly identical.

A white light interferometer uses such a short-coherence light source. Moving the reference or the object arm of the interferometer causes an interference signal to appear if the optical path length of the object arm approaches the optical path length of the reference arm ($a = b$), fig. 2. If the detector is replaced by a CCD camera, it is possible to analyze such burst signals at each camera pixel at the same time. In this way, the surface topography of the object can be analyzed if the object is moved and the amplitude of the movement is recorded, fig. 3. The vertical accuracy of this technique is in the range of 0.1 micrometer; lateral resolution is limited by the same effects as in microscopy.

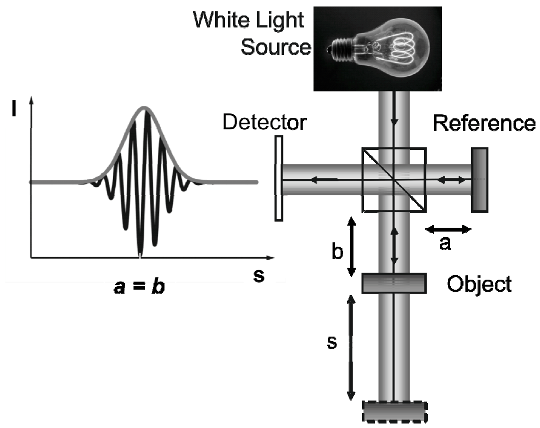


Fig. 2: White light interferometry principle

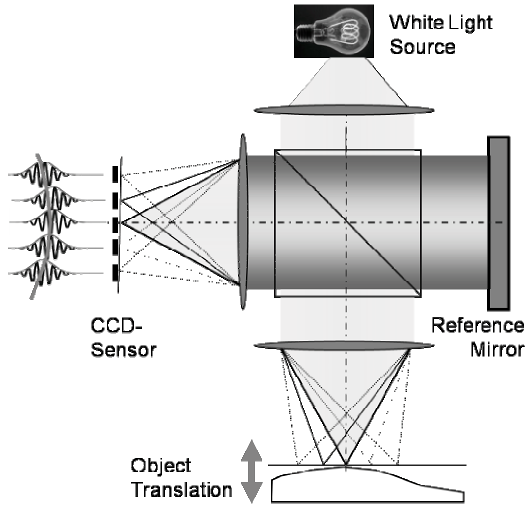


Fig. 3: Simultaneous measurement of multiple points using a CCD camera

Digital Holography

A relatively new technology to record 3D surface information is digital holography, fig. 4, /3, 4/. The object is illuminated by a coherent laser wave *O* (fig. 4) and recorded by a CCD camera. In principle, a formerly plane illumination wave front O will be take the shape of the surface of the object when it is reflected towards the CCD camera. The phase of this deformed wave front is registered by superposition with a reference wave *R* forming an intereference pattern (fig. 4). The reconstruction of this interference pattern will reveal the object phase. Due to 2π ambiguity in interferometry the phase has to be demodulated. The result is the surface topography of the object with a vertical resolution of typically 1 nanometer.

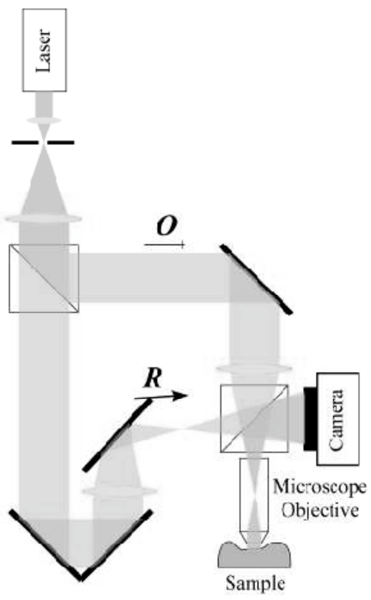


Fig. 4: Optical set-up for digital holography

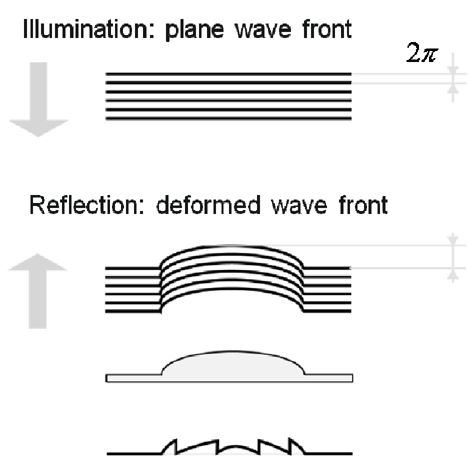


Fig. 5: Comparison of object and reference

wave front

The advantage of this technique is that the object phase (=amplitude) is recorded with one single image. No scanning is required and even moving objects can be analyzed. On the other hand, step heights greater than half the laser wavelength cannot be quantified due to the 2 ambiguity already mentioned. Therefore, this technique is generally limited to relatively smooth surfaces. However, it should be mentioned that new developments using dual wavelength techniques allow this limitation to be overcome. The lateral resolution of the technique is again limited by diffraction as in classical microscopy.

Application Examples

Roughness measurement

White light interferometry is commonly used for roughness measurements. Full field image recording and the vertical scanning technique are give to give information even in the case of steps or rough surfaces with steep gradients. The example shows the profile of a drilled steel surface. The sample was measured with a 50X objective, fig. 6. The measured R_a value (1.41um) corresponds excellently with the value measured using a tactile measuring system (1.42um). Additionally, the full field information allows a complete 3D surface profile plot, fig. 7.

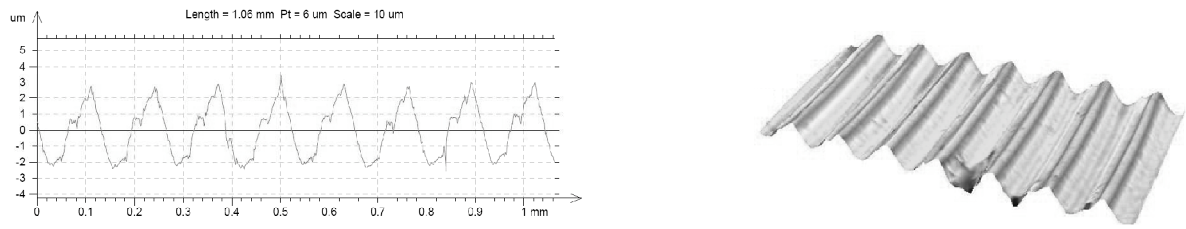


Fig. 6: surface topography of a drilled sample with WLI

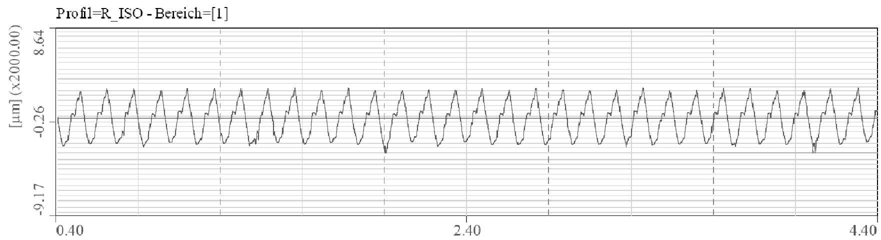


Fig. 7: Result of tactile measurement of the same surface

Pressure sensor

The ability to measure steps greater than the wavelength of light offers interesting applications for white light interferometry. The following example shows the 3D plot of a miniaturized pressure sensor, fig. 8. If the sensor is measured at different pressure states, even deflection of the membrane due to pressure can be shown. The figure shows deflection of the membrane at 3.5 and 5 bar in comparison to the non-deformed reference state at 1 bar, fig. 10.

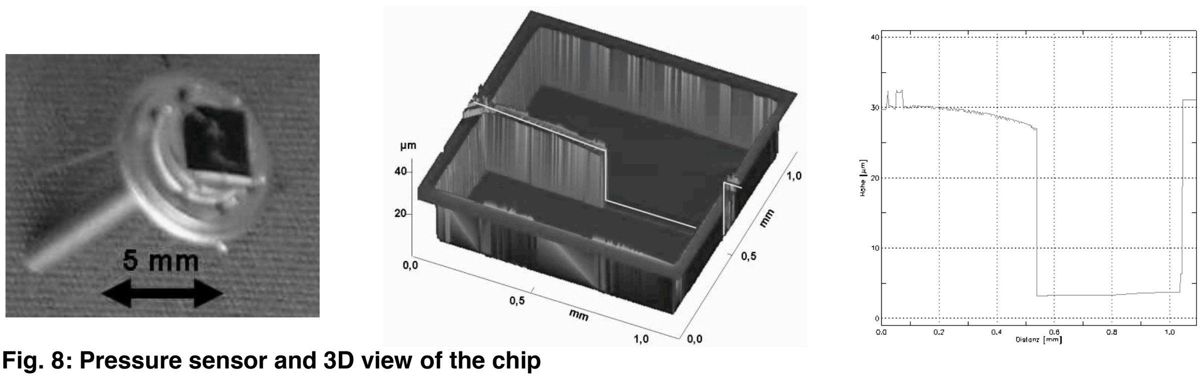


Fig. 8: Pressure sensor and 3D view of the chip

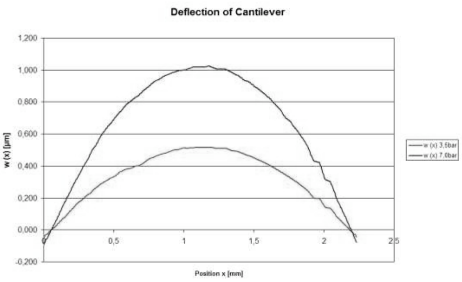


Fig. 10: Deformation of the membrane at different pressure steps

Tunable Etalon

An etalon is in principle a Fabry Perot interferometer. It basically consists of two parallel glass plates. Light waves are partly reflected at the glass plates and can interfere with one another. In this way an etalon serves to select a certain laser wavelength from the bundle of wavelengths offered by the laser. In order to allow a well defined shift of the selected laser wavelength, a tunable etalon has been developed. A silicon structure with capacitive actuator supports a glass window, fig. 11. When a voltage is applied, the glass window is moved towards the glass carrier, thus reducing the gap between window and glass carrier. The glass window can be moved by applying a voltage to the actuator. The symmetric design guarantees parallel movement of the glass window. If the etalon is observed through the digital holography microscope, the tilt of the glass window can be quantified, fig. 12. It is well below 30nm, which represents parallelism better than —.

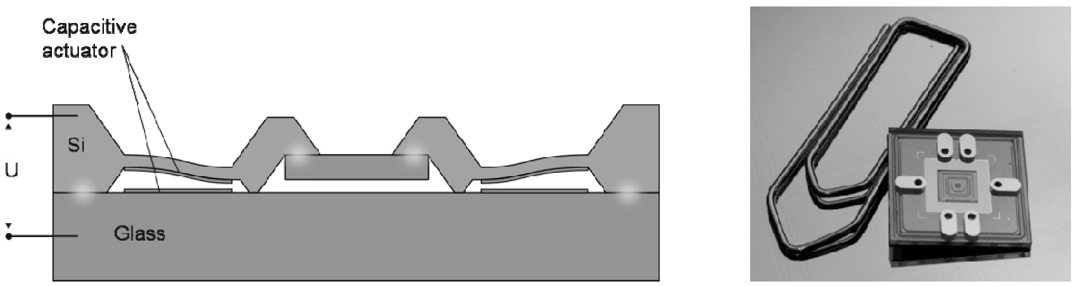


Fig. 11: View and design of a tunable Etalon

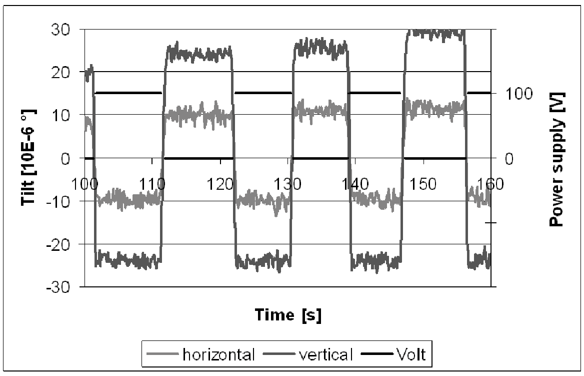


Fig. 12: Tilt of the top etalon surface during movement

Vibration of an Atomic Force Cantilever

In order to record vibrating objects, digital holography can be used in stroboscopic mode. The shutter opening of the camera is synchronized with the vibration excitation signal. Several measurements are taken at different phase positions with respect to the vibration signal. For example, if the phase between vibration signal and camera shutter is shifted by 30°, a total of 12 measurements are required to record a complete vibration cycle.

The example shows the vibration of the cantilever of an atomic force microscope (AFM), fig. 13. The cantilever was mounted on a piezo and excited at 1.000 Hz. The graphs show the object phase at different phase positions of the measurement process, fig. 14. It should be noted that the amplitude phase at the tip of the cantilever is different in each image. The graph shows the amplitude phase over time.

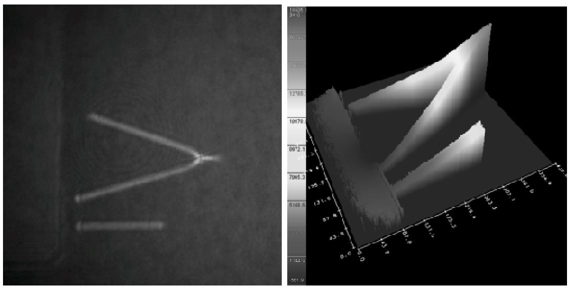


Fig. 13: View and 3D display of an AFM cantilever

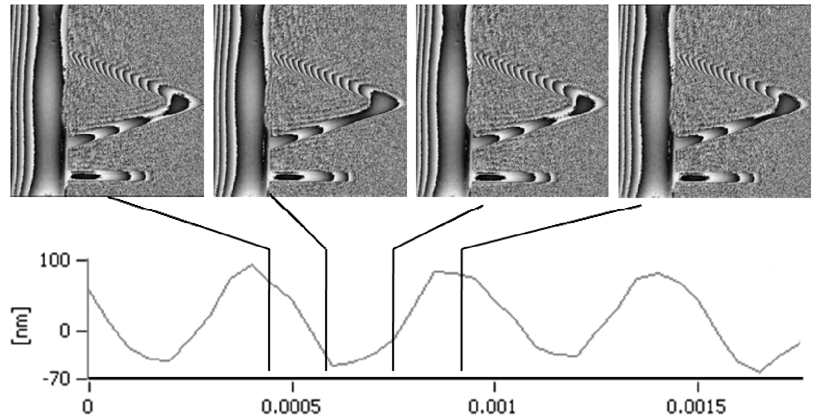


Fig. 14: Phase maps of the cantilever at different positions during the vibration cycle

Thermal lens effect of a laser crystal

The crystal of a NdYAG laser is pumped with the light of a diode laser. As not all pump energy can be converted into laser light, the crystal is heated up. The resulting deformation of the crystal causes a mechanical deformation of the crystal, which can change the optical parameters of the laser beam. This effect is called thermal lens effect and can result in worse performance of the laser. Therefore, the thermal lens effect was investigated by means of digital holography. The microscope looked at the crystal surface via a selective mirror. The mirror was selected to let the wavelength of the pump source (980nm) and laser wavelength of the NdYAG laser (1064nm) pass in transmission and let the measuring wavelength of the holography microscope (682.5nm) reflect to the microscope. An additional band filter blocked any light left over.

With this set-up, the surface of the crystal could be observed during operation. Fig. 16 shows different states of surface deformation of the laser crystal at different pump currents. The peak in the images is caused by some dust on the surface. However, in this experiment the constant position of the peak proves that the surface was not shifted in the lateral direction. The comparison of deformation of the surface and pump current shows a linear relation once minimum offset energy is induced in the crystal.

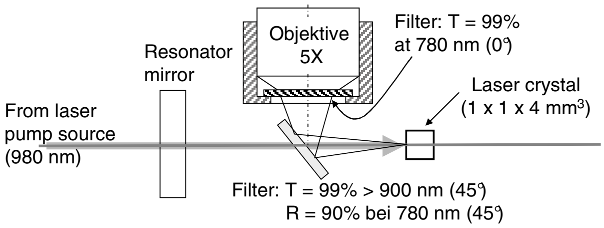
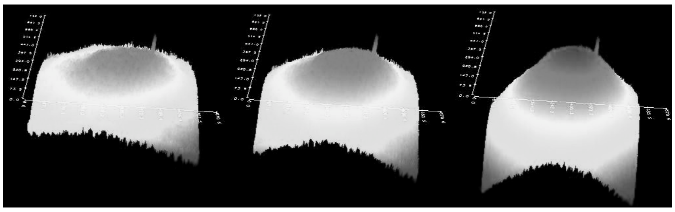


Fig. 15: Experimental set-up



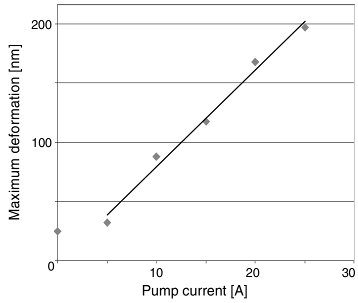


Fig. 16: Deformation of the crystal surface

Summary

White light interferometry and digital holography can be used for non contact and high resolution optical 3D measurement on micro structures. While white light interferometry is capable of measuring steps of several hundred micrometer amplitude, digital holography can work on moving and even vibrating objects. The limitations of both techniques are very much dependent on the quality of the measured surface and the technique has to be carefully selected for each application.

References

/1/ Pedrotti (Vorname???), et. al.: Optik für Ingenieure, Springer Verlag Berlin-Heidelberg, 4. Auflage 2008

/2/ Wyant, W.: Light Interferometry, Proceedings of SPIE Vol. 4737 (2002)

/3/ Cuche, E., Poscio, P., Depeursinge, C.: Optical tomography by means of a numerical low-coherence holographic technique, J. Opt. 28, 260-264 (1997)

/4/ Cuche, E., Bevilacqua, F., Depeursinge, C.: Digital holography for quantitative phase-contrast imaging, Opt. Lett. 24, 291-293 (1999)